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Quantification of Renewable Energy Extraction from Domestic Wastewater Using Microbial Fuel Cells: A Statistical Evaluation of Performance Metrics

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Abstract
The goals of this research were to compute the wastewater quality indexand investigate statistical correlations between various variables. The study employed a quantitative approach to assess the physicochemical characteristics of water quality in wastewater samples, following the guidelines and recommendations provided by the regulatory authority. The wastewater quality index is recognized as a valuable tool for informing stakeholders about the quality aspects of wastewater. The Weighted Arithmetic Index technique was utilized to calculate the wastewater quality index for wastewater samples. Additionally, a statistical analysis was conducted to identify the primary factors influencing wastewater quality index. It was observed that statistical regression analysis is a highly effective tool within SPSS.
Keywords: Wastewater Quality Index (WWQI), Descriptive Statistics, Correlation, One Way ANOVA, Regression

1. Introduction

The caliber of waste produced increases together with the growth of cities and industry[16].The suitability of surface waterways, such as lakes, rivers, and oceans, for human consumption is determined by the discharge of untreated sewage[10]. A numerical expression that is computed cumulatively is used by the Water Quality Index (WQI) to determine a certain level of water quality. The purpose of water quality indices is to convey the water quality of a source as a single number, simplifying a difficult statement and facilitating the analysis of monitoring data[5]. The Water Quality Index (WQI) simplifies complex data regarding water quality for managers and the public to grasp by using terms like excellent, good, poor, etc. Several academic improvements have been made to this strategy to alter the procedure.
To communicate with management and the public, the Water Quality Index (WQI) effectively condenses large amounts of data on water quality into terms that are simple to comprehend (such

as excellent, good, poor, etc.). Numerous academic adjustments have been made to this method to modify the approach according to certain applications and the qualities under analysis. One study[17], for example, considered thirteen distinct parameters and gave each equal weight inside their model. Moreover, managers and decision-makers can benefit greatly from being able to compare various wastewater treatment methods using WQI. An indicator like this can quickly determine if treated wastewater is suitable for applications like recreation or agriculture[20]. Moreover, a single, all-encompassing metric that measures a treatment plant's total effectiveness in removing pollutants using physical, biochemical, and microbiological processes must be established[13].

A groundbreaking fuzzy approach has been implemented, as introduced by Gabrieli.et.al [10]. The Wastewater Quality Index (WWQI), represented on a numerical scale from 0 to 1, serves as an indicator of wastewater quality. Developing the WWQI in a manner like the Water Quality Index (WQI) is anticipated to enhance its applicability and support decision-making processes for authorities. The Weighted Arithmetic Index method was used to calculate the maximum, minimum, and average values required for determining the WWQI. Once WWQI was established, the correlation between each parameter and the WWQI was analyzed. Additionally, factor analysis (FA) was employed to interpret the elemental data [8].

To assess the quality of treated wastewater, One-Way ANOVA, correlation analysis, and descriptive statistics were applied to six key parameters. The study aimed to address this issue by developing the WWQI and calculating correlation and regression equations using the SPSS tool. The analysis identified TSD, COD, DO, BOD, TSS, and ammoniacal nitrogen as the parameters significantly influencing WWQI.

Furthermore, descriptive statistics, correlation, regression, and One-Way ANOVA were conducted in SPSS, focusing on these significant parameters. The results were then used alongside WWQI values to establish correlations and identify the model that best fit the analysis.

2. METHODS AND METHODOLOGY

Experimental methodology

2.1 Site Selection

The domestic wastewater used in this study was collected from a residential complex comprising over 130 units, housing approximately 400 residents. The complex generated 3,000 liters of wastewater daily. The influent characteristics of the wastewater were carefully monitored throughout the reactor's operational period.

2.2 Experimental Setup

The Microbial Fuel Cell (MFC) model serves as the central point for designing and operating a continuous flow reactor in the experimental setup, where influent and effluent samples are collected, analyzed and obtained data was used for statistical analysis. Throughout the procedure, the operational volume of the reactor was maintained consistently. The reactor models were systematically evaluated at three different flow rates: 0.2 liters per minute, 0.5 liters per minute, and 0.7 liters per minute. These were thoroughly assessed to determine their impact on the reactor's performance with varied electrode configurations.

3.0 WASTE WATER QUALITY INDEX

The Water Quality Index (WQI) is a dimensionless metric that normalizes values according to subjective grading curves, consolidating multiple water quality parameters into a single score. The criteria for including parameters in the WQI model may vary depending on the intended water uses and regional preferences. These parameters include temperature, nutrients (nitrogen

and phosphorus), total coliform bacteria, dissolved oxygen (DO), pH, BOD, and COD, among others. Each of these parameters is expressed in different units and occurs within various ranges. The WQI combines the complex scientific data of these variables into a single numerical value.
The WQI was calculated using the Weighted Arithmetic Index method. For each water quality parameter, a quality rating (Qi) was determined using the formula:

$$Qi = 100\frac{(Vs - Vi)}{(Vn - Vi)}$$

where Vn represents the actual measurement of the parameter, Vi is the ideal value for the parameter (set to 0 for all except pH and DO, with pH having an ideal value of 7.0 and DO an ideal value of 14.6 mg/L), and Vs is the recommended standard for the parameter according to World Health Organization (WHO) guidelines. The relative weight (Wi) for each parameter was assigned based on a value inversely proportional to its WHO recommended standard (Si), where K is a constant derived from the application of the formula.

$$K = \frac{1}{\sum(\frac{1}{Si})}$$

$$\mathrm{Wi} = \mathrm{K\,Si}$$

Water Quality Index (WQI) is typically evaluated based on the specific intended use of the water. In this study, the WQI is assessed for human consumption, with the acceptable threshold for drinking water set at 100. The overall WQI was determined using the following equation:

$$WWQI = \frac{\sum \mathrm{Wiqi}}{\sum \mathrm{Wi}}$$

The WQI Value range 90 to 100: Excellent,70 to 90: Good ,50 to 70: Medium, 25 to 50: Bad, 0 to 25: Very Bad

3.1 STATISTICAL ANALYSIS

Evaluating wastewater quality from multiple samples with varying criteria through statistical analysis is a complex task. Various techniques have been developed for water quality analysis, including multi-stressor water quality indices and the statistical analysis of individual parameters [1]. Statistical methods are typically employed to assess the accuracy of the estimated WWQI. In this study, descriptive statistics, correlation analysis, linear regression, and one-way ANOVA were used to accomplish this.

Table 1: Descriptive Statistics for WWQI

Descriptive Statistics			
	Mean	**Std. Deviation**	**N**
WWQI	6.66	5.66	42
TDS	8.34	5.21	42
TSS	21.03	8.46	42
BOD	24.01	6.60	42
COD	20.98	8.18	42
Ammonical Nitrogen	28.04	8.75	42

It appears to be a composite metric for wastewater quality, the average WWQI in the data set is 6.66 with a standard deviation of 5.66. Table 1 shows that the wastewater treatment process is most effective in removing ammonia nitrogenfollowed by BOD, TSS, CODand TDS.

Table 2: Pearson Correlation for WWQI

Correlations							
		WWQI	Removal Efficiency TDS	Removal Efficiency TSS	Removal Efficiency BOD	Removal Efficiency COD	Removal Efficiency of Ammonical Nitrogen
Pearson Correlation	WWQI	1.000	-.377	-.610	-.818	-.771	-.874
	TDS	-.377	1.000	.089	.494	.542	.087
	TSS	-.610	.089	1.000	.323	.275	.636
	BOD	-.818	.494	.323	1.000	.893	.537
	COD	-.771	.542	.275	.893	1.000	.454
	Ammonical Nitrogen	-.874	.087	.636	.537	.454	1.000
Sig. (1-tailed)	WWQI	.	.007	.000	.000	.000	.000
	TDS	.007	.	.287	.000	.000	.293
	TSS	.000	.287	.	.019	.039	.000
	BOD	.000	.000	.019	.	.000	.000
	COD	.000	.000	.039	.000	.	.001
	Ammonical Nitrogen	.000	.293	.000	.000	.001	.
N	WWQI	42	42	42	42	42	42
	TDS	42	42	42	42	42	42
	TSS	42	42	42	42	42	42
	BOD	42	42	42	42	42	42
	COD	42	42	42	42	42	42
	Ammonical Nitrogen	42	42	42	42	42	42

From Table 2, a strong negative correlation (values close to -1) is observed between the removal efficiency of ammonia nitrogen and all other pollutants listed (TDS, TSS, BOD, COD). This indicates that as the concentration of these substances in the water increases, the removal efficiency of ammonia nitrogen decreases. Additionally, there is a strong positive correlation between TSS and COD, with a correlation coefficient of 0.879, which is close to 1. This suggests that as TSS increases, COD also tends to increase. A similar strong positive correlation is observed between BOD and COD, with a correlation coefficient of 0.809, indicating that as BOD increases, COD also tends to rise.There is a moderate positive correlation between TSS and BOD, with a correlation coefficient of 0.661. This suggests that higher values of TSS tend to correspond with higher values of BOD, though the correlation is weaker than that between TSS and COD or BOD and COD. The correlation coefficient represents the strength of the linear relationship between two variables, showing the extent to which they vary together, whether in the same or opposite directions. Its value ranges from -1 to 1, with values nearer to -1 or 1 indicating a stronger correlation.

Table 3: Model Summary for BOD

Model Summary[a]										
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	**Change Statistics**					**Durbin-Watson**
					R Square Change	**F Change**	**df1**	**df2**	**Sig. F Change**	
1	0.818[a]	0.669	0.660	0.330	0.669	80.761	1	40	0.00	2.126

* Dependent Variable: WWQI Predictors: (Constant), Removal Efficiency BOD

Table 4: One Way ANOVA for BOD

ANOVA[a]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	8.798	1	8.798	80.761	0.000[b]
	Residual	4.357	40	.109		
	Total	13.155	41			

*Dependent Variable: WWQIPredictors: (Constant), Removal Efficiency BOD

Table 5: Regression Analysis for BOD

Coefficients[a]						
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**		
1	(Constant)	8.348	.194		42.971	0.000
	BOD	-.070	.008	-.818	-8.987	0.000

*Dependent Variable: WWQI

The constant term (8.348) represents the projected value of the WWQI when all independent variables are zero. Table 4 demonstrates that the model fits significantly with an F-value of 80.761 (Sig F: 0.000) and an RMSE of 0.000. The Durbin-Watson test statistic for this model is 2.126, which is greater than 2, indicating no issue with autocorrelation (Table 3). Since BOD was found to have a strong correlation with largest of the other factors, TDS was excluded, and regression analysis was performed again to obtain a new equation. After removing TSS, COD, TDS, Ammoniacal Nitrogen, and adding WWQI as the dependent variable, the regression model was re-fitted, yielding the following regression equation with an accuracy of 82% (Table 3):

$$Y = -0.070X1 + 8.348$$

This equation indicates a statistically significant relationship between BOD and WWQI.

Table 6: Model Summary for Ammonical Nitrogen

Model Summary[b]										
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	**Change Statistics**					**Durbin-Watson**
					R Square Change	**F Change**	**df1**	**df2**	**Sig. F Change**	
1	0.874[a]	0.764	0.758	0.278	0.764	129.18	1	40	0.000	1.585

*Dependent Variable: WWQI Predictors: (Constant), Removal Efficiency of Ammonical Nitrogen

Table 7: One Way ANOVA for Ammonical Nitrogen

ANOVA[b]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	10.045	1	10.045	129.183	0.000[b]
	Residual	3.110	40	0.078		
	Total	13.155	41			

* Dependent Variable: WWQIPredictors: (Constant), Removal Efficiency of Ammonical Nitrogen

Table 8: Regression Analysis for Ammonical Nitrogen

Coefficients[b]						
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**		
1	(Constant)	8.250	.146		56.486	0.000
	Removal Efficiency of Ammonical Nitrogen	-0.057	0.005	-0.874	-11.366	0.000

*Dependent Variable: WWQI

The constant term (7.006) from Table 6 represents the predicted value of the WWQI when all independent variables are zero. According to Table 7, the model fits significantly with an F-value of 129.183 (Sig F: 0.000) and an RMSE of 0.000. The Durbin-Watson test statistic for this model is 1.585, which is close to 2, indicating no autocorrelation issue (Table 6). Ammoniacal nitrogen was found to have a strong correlation with most of the other metrics. After excluding TDS, TSS, COD, and BOD, and adding WWQI as the dependent variable, the regression model was re-fitted, yielding the following regression equation with 88% accuracy (Table 6):

$$Y = -0.057\text{X1} + 8.250$$

For removal efficiency of Ammoniacal Nitrogen, the significance level is 0.000. Since this value is less than 0.05, we can reject the null hypothesis for removal efficiency of Ammoniacal Nitrogen. This indicates a statistically significant relationship between ammonia nitrogen and the WWQI.

Table 9: Model Summary for WWQI

Model Summary[c]										
					Change Statistics					
Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	**R Square Change**	**F Change**	**df1**	**df2**	**Sig. F Change**	**Durbin-Watson**
1	0.980[a]	0.961	0.955	0.1198	.961	176.327	5	36	0.000	1.753

* Dependent Variable: WWQIPredictors: (Constant), Removal Efficiency Ammonical Nitrogen, Removal Efficiency TDS, Removal Efficiency TSS, Removal Efficiency COD, Removal Efficiency BOD

Table 10: One Way ANOVA for WWQI

ANOVA[c]						
Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
1	Regression	12.639	5	2.528	176.327	0.000[b]
	Residual	0.516	36	0.014		
	Total	13.155	41			

*Dependent Variable: WWQI
Predictors: (Constant), Removal Efficiency of Ammonical Nitrogen, Removal Efficiency TDS, Removal Efficiency TSS, Removal Efficiency COD, Removal Efficiency BOD

Table 11: Regression Analysis for WWQI

Coefficients[c]						
Model		**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
		B	**Std. Error**	**Beta**		
1	(Constant)	8.728	.082		106.852	0.000
	Removal Efficiency TDS	-0.008	0.004	-0.077	-1.893	0.066
	Removal Efficiency TSS	-0.007	0.003	-0.100	-2.325	0.026
	Removal Efficiency BOD	-0.019	0.007	-0.225	-2.882	0.007
	Removal Efficiency COD	-0.017	0.005	-0.241	-3.184	0.003
	Removal Efficiency of Ammonical Nitrogen	-0.037	0.003	-0.574	-11.607	0.000

*. Dependent Variable: WWQI

The constant term (8.728) in Table 11 represents the expected value of the WWQI when all independent variables are zero. According to Table 10, this model fits significantly with an F-value of 176.327 (Sig F: 0.000) and an RMSE of 0.000. The Durbin-Watson test statistic for this model is 1.753, which is close to 2, indicating no autocorrelation issue (Table 9). With WWQI as the dependent variable and TDS, TSS, COD, BOD, and Ammoniacal Nitrogen found to be strongly correlated with all other parameters, the regression model was re-fitted, resulting in the following regression equation with 96% accuracy (Table 9):

$$Y = -0.008X1 - 0.007X2 - 0.019X3 - 0.017X4 - 0.037X5 + 8.728$$

This suggests a statistically significant association between the factors analyzed and the WWQI

4.CONCLUSION

The WWQI was initially calculated, and the correlation between various factors and their relationship with the WWQI was analysed using SPSS. The analysis revealed a significant correlation between WWQI and six factors: TDS, TSS, BOD, COD, Cl, and DO, indicating that these six parameters account for most of the variation in WWQI values. Additionally, BOD and Ammoniacal Nitrogen were found to have a significant correlation with WWQI at the 0.01 level.A regression equation developed using five key parameters was determined to have an accuracy of approximately 96%. Furthermore, after excluding DO, Nitrate, and Nitrite, the constructed regression equation was found to match the original WWQI with 96% accuracy.

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