Journal of Engineering Research and Reports

Volume 25, Issue 3, Page 114-125, 2023; Article no.JERR.100121
ISSN: 2582-2926

Assessment of the Efficiency of Wastewater Treatment Plant in Oil and Gas Firm in Eleme Rivers State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2023/v25i3896

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/100121

Original Research Article

Received: 24/03/2023
Accepted: 28/05/2023
Published: 10/06/2023

ABSTRACT

The study aimed to determine the efficiency of a wastewater treatment plant and the quality of effluent discharged by the plant into the receiving water body (Okochiri River) in Eleme, Rivers State. The study lasted for four months. Wastewater samples were collected at various stages of the treatment unit and tested for major water quality parameter such as Biological Oxygen Demand (BOD), oil/grease, phenol, Dissolved Oxygen (DO), Total Suspended Solids (TSS), and sulphide. In general, the composite wastewater treatment system (comprising dissolve air floatation, Rotary Bio-Disk, and sedimentation unit) was effective in pollutant removal, except for sulphide, which had a negative efficiency (-238%). In line with Pearson Correlation, there are strong positive relationships between several parameters, such as pH and Sulphide (0.93), Phenol and Oil/grease (1.00), and Phosphate and Sulphide (0.91). The Principal Component Analysis yielded four principal

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components (PC1-4): PC1 parameters with the highest loadings on the first factor (D1) were sulphates and phenols, whereas Chemical Oxygen Demand and Biological Oxygen Demand had the highest loadings on the second factor (D2). Dissolved oxygen was most strongly associated with the third factor (D3), and pH was the parameter with the highest loading on the fourth factor (D4). It is recommended that the wastewater treatment system's overall efficiency be improved for the system to consistently meet regulatory limits for pollutant control. Recommendations for improving system efficiency include (1) ensuring regular maintenance of individual units in the treatment plant; and (2) maintaining optimal operating conditions for the rotary bio-disk unit.

Keywords: Wastewater treatment plant; BOD; TSS; biological treatment; removal efficiency; principal component analysis.

1. INTRODUCTION

Water is a valuable commodity that is scarce in most countries, and protecting water resources is one of the challenges that engineers, hydrologists, technologists, and scientists face [1]. According to the World Health Organization [2], 80% of illnesses and infections in the world are caused by inadequate sewage treatment, and pathogens living in the aquatic environment kill more than 3.4 million people each year [3]. Wastewater is essentially liquid waste that has been contaminated by a variety of uses. During its application, the water supplied to a specific region or apartment contains several chemical substances and microbial organisms, causing the wastewater to have a polluting potential and become a health and environmental hazard. Untreated wastewater disposal spreads communicable diseases of the gastrointestinal tract such as cholera, typhoid, dysentery, and water-borne diseases such as infectious hepatitis, so the primary goal of sanitary wastewater disposal is to prevent communicable diseases and protect public health [3]. However, due to population growth and a lack of sanitation and wastewater management practices, one of the major challenges confronting developing countries has been the management and handling of wastewater. In developing countries, 80-90% of wastewater is discharged directly into bodies of water [4]. Because of a lack of sanitation infrastructure, 62% of the urban population in Sub-Saharan Africa disposes wastewater directly into water bodies.

Wastewater treatment is the process and technology used to remove the majority of the contaminants found in wastewater to maintain a healthy environment and public health. Wastewater management thus entails handling wastewater to protect the environment and ensure public health, economic, social, and political stability [5]. In most cases involving domestic wastewater, treatment consists of removing total suspended solids and BOD_5, which are the two most important parameters. When treated effluent is discharged into a watercourse or land, the degree of treatment provided to the wastewater is primarily based on the effluent standards prescribed by regulatory agencies. If the effluent is reused, the effluent quality required to support such reuse will indicate the level of treatment required. The complete wastewater treatment procedure involves a sequential combination of several physical unit operations as well as chemical and biological unit processes. The degree of reduction of BOD and suspended solids, which constitute organic pollution, is the general indicator used to evaluate the performance of a sewage treatment plant [6]. The treatment plant's efficiency is determined not only by proper design and construction but also by proper maintenance and operation [3,7].

The economic effects of hazardous waste discharge on urban cities can be classified into direct, indirect, and induced impacts [8]. Direct impacts include revenues and added value. Indirect impacts are mainly caused by crude oil and natural gas production activities. Induced effects include income and added-value addition caused by the income of waste management. According to [8], if properly managed, hazardous waste could become a source of huge economic benefit to both the generator and the host community. Waste is a result of businesses, government, and household activities or by material or energy recovery [9]. Hence, the environment and government are affected by waste management. For instance, hazardous waste management can generate employment through job Creation. Countries like India and the United States of America generate between 15-18% of employment (full-time or part-time) employment [10]. The sector applies to individuals throughout the world for high wages to be spent and tax the government. However, Hazardous waste management can pose a great danger to human life if not properly managed. Far be it from exaggeration that between 15-20% of death recorded in a petrochemical-related occupation results from the mismanagement of hazardous chemicals [11]. The corrosiveness of hazardous waste varies in terms of effectiveness, tonnage, combustion, ignitibility, etc. Tonnage is essential in impact assessment, so the more the tonnage increases and the risk probability for humans and animals increases. This implies a relative difference in the level of danger by a particular element in a discharge. In terms of tonnage, some low-tonnage waste may be more dangerous than others with higher tonnage. For instance, Cadmium, Lead, Nitrogen, Zinc compounds, and wastes fall into the higher-risk element category. Alkali's acute results could refer to skin, mouth, throat, or eye burns [12].

Nigeria has four operational oil refineries with an estimated total refining capacity of 445,000 barrels per day [13]. The four refineries came under the ownership and management of the Nigerian National Petroleum Corporation (NNPC) in 1986. The Niger Delta is home to three of these oil refineries. These refineries regularly make use of water for most processes including, distillation, hydro-treating, desalting, boiler feed water required for the generation of steam, cooling water used for water-cooled condensers, product coolers, and other heat exchangers [13]. This results in the production of wastewater which is discharged into the environment after treatment. Typically, the effluent is regulated by environmental protection agencies by setting up the discharge standards as well as performing a regular check. In Nigeria, the Federal Environmental Protection Agency (FEPA) is responsible for setting the minimum standards for industrial effluents and consequently, industries are obligated to monitor and control their effluents to ensure they meet this standard. This involves analysis of the effluents to determine their composition and possible treatment before discharge into inland water [14]. According to [15], a typical refinery wastewater treatment plant consists of three major processes which include the primary treatment, followed by biological treatment, and tertiary treatment (if necessary), commonly known as advanced treatments.

However, these conventional techniques are not adequate and efficient to solve the problem of massive oil contamination. In recent years, nanotechnology is a potential and promising source of novel solutions for oil spill cleanup, with several approaches involving a vast range of nano-materials (nano-catalysts, nano-adsorbents, and nano-membranes), which have been proven to be very effective due to their increase surface area and, in turn, a higher reactivity [16]. As regards oil refinery wastewater treatment, this technology has shown great potential as a low-cost, environmentally friendly, and sustainable treatment technology to remove persistent organic pollutants (POPs) to overcome the shortcomings of conventional technologies. For example, the photocatalytic degradation process has attracted increasing attention during the past decades due to its effectiveness in rapidly degrading and mineralizing recalcitrant organic compounds [17]. This treatment technology has an advantage over other conventional treatments, including other AOPs, such as homogeneous photo-Fenton, UV/H2O2, UV/O3, and UV/H2O2/O3 [18], as it overcomes the problems of incomplete pollutant removal, high consumption of chemical reagent, high treatment cost, long duration, and generation of toxic secondary pollutants [19].

Eleme Urban's wastewater management system is incapable of meeting current demands. The Urban's private residential areas lack an elaborate sewerage network. However, poor plant management has resulted in the discharge of raw untreated and partially treated sewage into the environment. This has resulted in river pollution, poor health, and a lower quality of life within the treatment area and among other users. As a result, it is necessary to assess the efficiency of the wastewater treatment plant and propose any potential improvements or solutions. For any incoming wastewater flow at any wastewater treatment plant; this flow is treated before it is allowed to be returned to the environment, lakes, or streams. Wastewater treatment plants treat waste at a critical point in the water cycle, protecting nature from pollution [20].

2. METHODOLOGY

2.1Study Area

This study was carried out in Alesa-Eleme, in Eleme Local Government Area (LGA) of Rivers State. The community is a satellite town lying 31 kilometres from Port Harcourt (Fig. 1). On the south-eastern Nigeria map, Eleme can be found between coordinates 7E and 8E, 4N and 5N. It is surrounded by different ethnic groups: Igbos to the Northwest, Baan to the west and Gokana to the south. Eleme Local Government is an administrative Subdivision of Rivers State, it covers an area of $138km^2$ and at the last census of 2006, had a population of 190,884 [21]. Eleme has two of Nigeria's four petroleum refineries and one of Nigeria's seaports and the largest seaport in West Africa is located in one of the most populous Towns called Onne [22].

2.2 Sampling Collection

Influent and Effluent grab samples comprising of waste water samples were collected from the different units of the treatment plant comprising of RBD's (A,C,D,E,F), CPI A, CPI B,DAF basin, sedimentation basin of Waste Water Treatment Plant (WWTP) and analyzed for selected physico-chemicalparameters, from May – September (Rainy season).

Samples were collected in bottle containers previously cleaned by washing in non-ionic detergent, rinsed with tap water and later soaked in 10%HNO_3 for 24 hours and finally rinsed with deionised water prior to usage. Before sampling, the bottles were rinsed three times with sample water before being filled with the sample. Samples were accompanied with proper identification and labeling at point of sampling then transported to the laboratory for analysis.

In collecting the samples, airspace was left in the bottles to facilitate mixing by shaking and aseptic techniques were adopted to avoid contamination.

Samples for laboratory analyses were transported in iced-packed coolers to POCEMA and, NNPC laboratories for analysis. Sample storage was carried out according to standard laboratory procedures as recommended by the American Society for Testing and Material (ASTM), [23]. In situ measurements were carried out on some physico-chemical parameters such as, Temperature, pH, Conductivity and DO. Hach Test Kit CE1890 was used for pH, Conductivity and Dissolved oxygen. All these measurements were carried out in-situ after proper calibration of the meters, while the remaining parameters were analyzed in the laboratory.

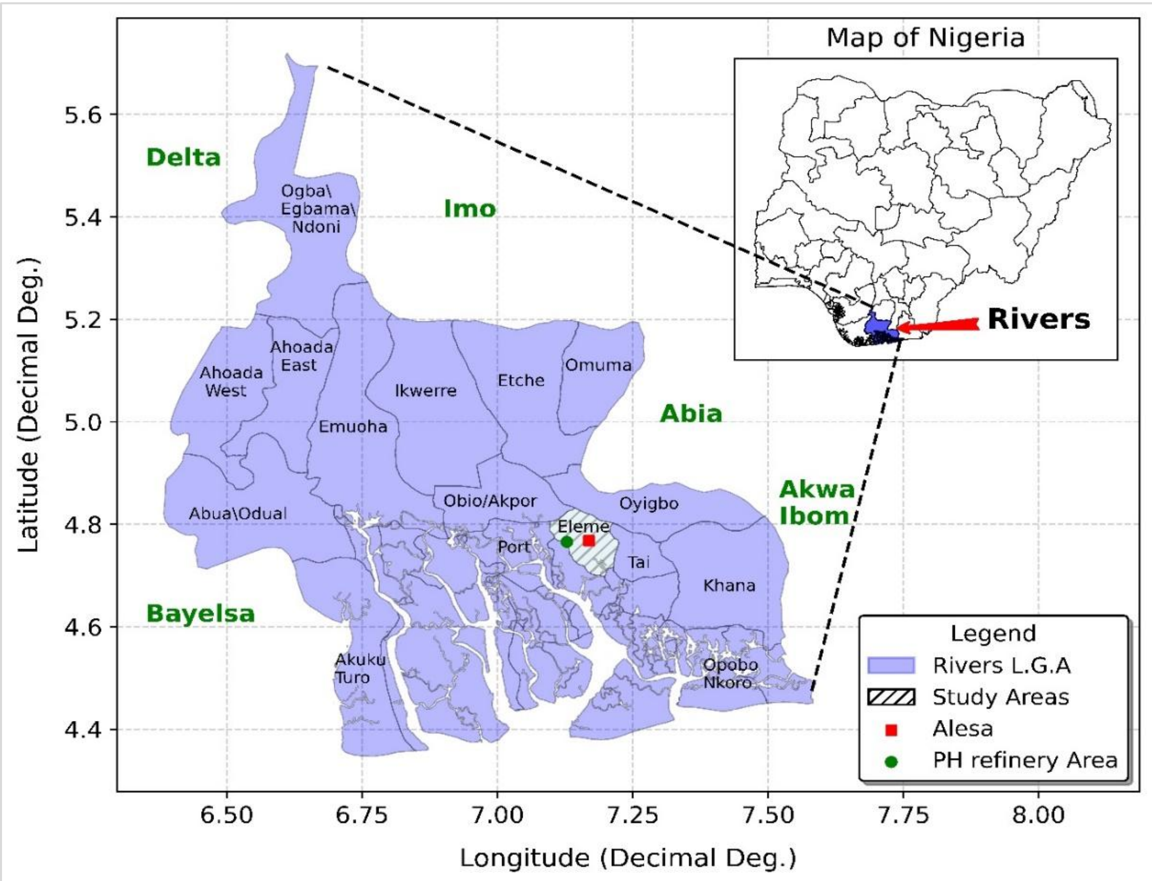

Fig. 1. Map of the study area

2.3 Methods of Data Analysis

The treatment unit efficiency is given as described by the following formula;

$$\text{Efficiency of the unit} = \frac{\frac{Average\ Conc.of\ Oil}{Oil|grease\ in\ RW} - \frac{Average\ Conc.of\ Oil}{Oil|grease\ in\ TW}}{Average\ Conc.of\ Oil|grease\ in\ RW} \times 100 \qquad (1)$$

Pearson Correlation coefficient was carried to establish the relationship between the physiochemical parameters of raw waste water. In order to carry out the Principal Component Analysis (PCA), Bartlett's sphericity test was conducted to assess the suitability of the dataset for PCA computation. The PCA is a factor reduction technique adopted to identify the principal factors adjudged by eigen value greater or equal to one [24].

3. RESULTS AND DISCUSSION

3.1 Performance Evaluation of DAF and RBD Units

Results of analysis showing the performance of the wastewater treatment units are presented; two units were evaluated. The Dissolved Air Floatation (DAF) unit and the Rotary Bio-Disk (RBD). Wastewater is first skimmed of oil and grease in the Corrugated Plate Interception CPI and then flows to the Dissolved Air Flotation unit. The oil and grease level in the inlet is usually not monitored and the raw water is pumped into the (CPI).

However, the oil and grease in the outlet before flowing to the DAF unit was measured, thus the performance of the DAF unit and the RBD unit in treating the wastewater was evaluated. Table 1 shows the result of the CPI outlet.

Several parameters such as oil and grease, Total Suspended Solids (TSS) and Sulphides were monitored to evaluate the removal efficiency of the DAF unit. The parameters phenol, phosphate, and ammonia were generally not complaint with the design specifications for the treatment unit. However, for DAF, oil/grease, Total Suspended Solids (TSS), and sulphide removal are of primary importance. The importance of the DAF unit with regards to those parameters are presented in the Figs. 2- 4.

Table 1. Result of CPI outlet

Monitoring Month	Outlet (PPM)
May	2
June	4.5
July	4.4
August	1.5
September	3.75

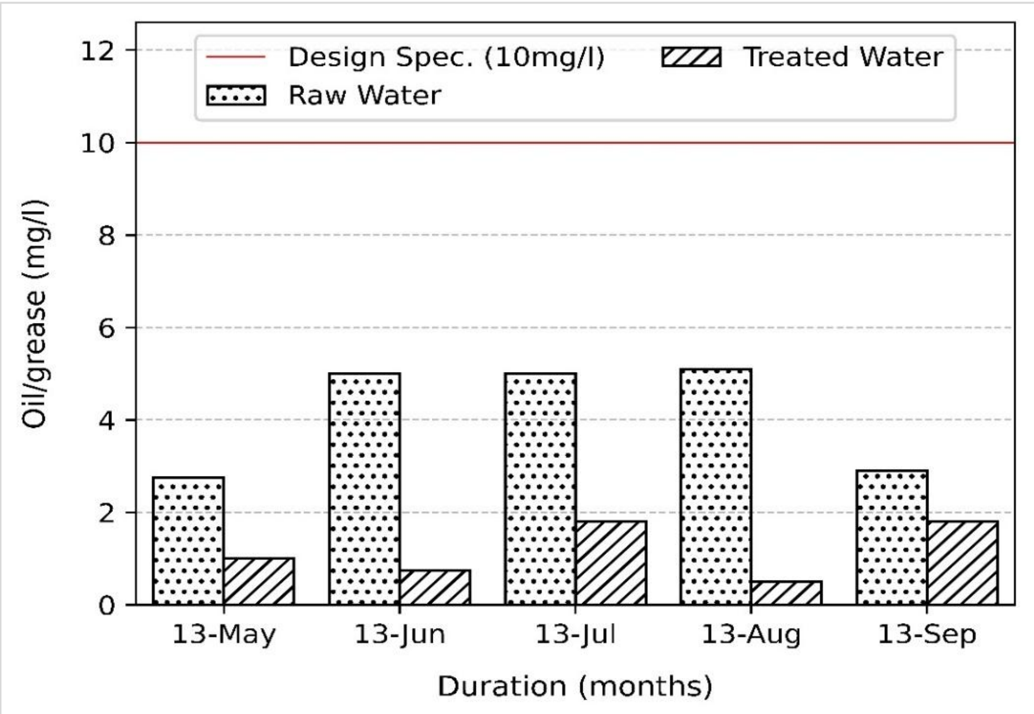

Fig. 2. Performance of DAF unit - oil/ grease removal

The performance of the DAF unit with regards to removal of total suspended solids (TSS) is presented in Fig. 3.The results show a general removal of TSS from DAF unit except for the months of June and September when levels of TSS in treated water were greater than in raw water. This might be associated with increased sediment erosivity and floating matter wash-out because the period coincide with the rainy period which produces high runoff into the river. The average efficiency of unit, was (155-122/155) X 100 =21.3% (POSITIVE EFFICIENCY). On average therefore, the DAF unit was efficient (for the period investigated) with regards to TSS removal. It is noteworthy that the TSS contents of raw water far exceeded the design specification for the DAF unit. It is Similar for the treated water effluent. The performance of the DAF unit with regards to removal of sulphides is presented in Fig. 4.

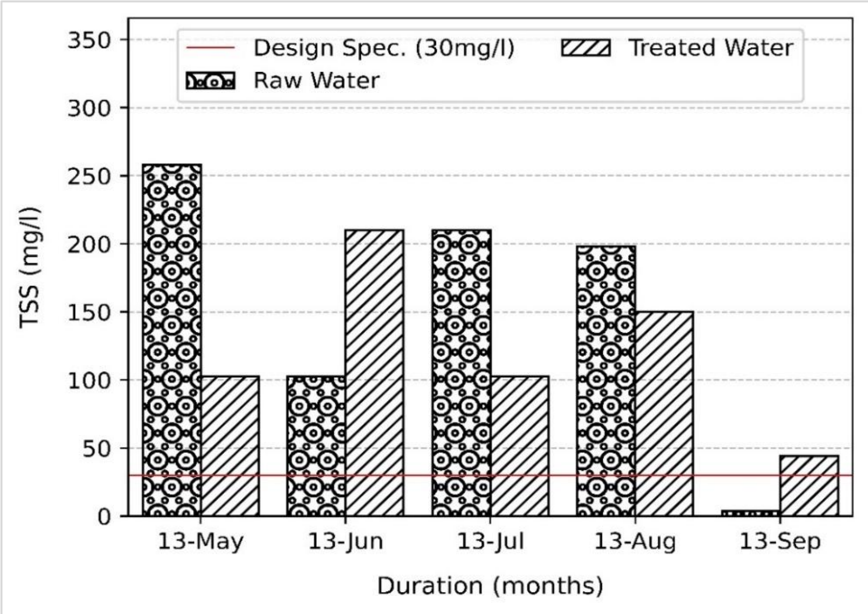

Fig. 3. Performance of DAF unit- TSS removal

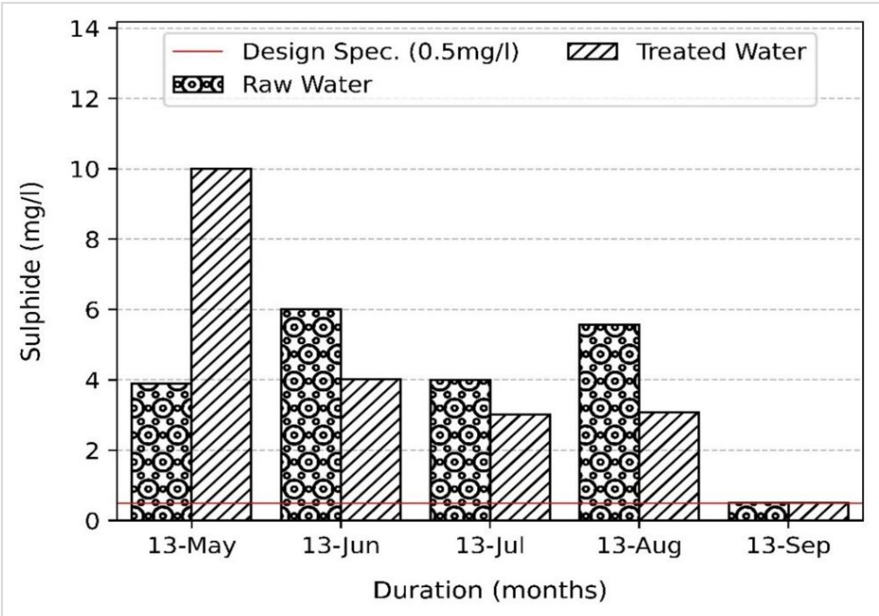

Fig. 4. Performance of DAF unit- sulphide removal

The results show that the DAF unit reduced oil/grease content of wastewater (Positive efficiency) for the months that were investigated. On average, the efficiency was calculated as (3.67-1.34/3.67) x100= 63.5%. Therefore, the DAF unit was efficient with regards to oil/grease removal. The oil/grease content of raw and treated water effluents was within the design specification of the DAF unit. Similarly, TSS removal efficiency was positive as the average removal efficiency was (155-122/155) X 100 =21.3%. Therefore, the DAF unit was efficient (for the period investigated) with regards to TSS removal. It is noteworthy that the TSS contents of raw water far exceeded the design specification for the DAF unit. Conversely, the sulphide content of the treated water was lower than the raw water except for in the month of May and September. The average efficiency of removal of sulphides was, (4-5/4) x 100=-25% (negative efficiency). However, if the exceptionally poor performance in May is ignored, the efficiency of the unit of June-September becomes, (4.02-2.65/4.02) x 100= 39%. The DAF unit therefore removed sulhides but efficiency of removal was inconsistent. It is noteworthy that the levels of sulphides in both raw and treated water effluents were above the design specification for the unit.

3.2 Rotary Bio Disk (RBD) Unit

Only Five (5) out of twelve 12 Rotary Bio- Disks were functional at the period of the research. Three parameters DO, Phenol and BOD_5 were monitored to evaluate their removal efficiency in the RBD.

The performance of the units with reference to dissolved oxygen conditions is presented in Fig. 5. Similar results in waste water treatment performance evaluation, are documented in literature [25], [26] and [27].

3.3 Pearson Correlation

Table 2 presents the relationship between the physiochemical parameters of raw wastewater. There are strong positive relationships between several parameters, such as pH and Sulphide (0.93), Phenol and Oil/grease (1.00), and Phosphate and Sulphide (0.91). These relationships indicate that the presence of one variable is associated with a high presence of another.

Table 3 shows the relationship between the physiochemical parameters of treated wastewater. After treatment, the relationships between several parameters have weakened or changed. For example, the relationship between Phosphate and Sulphide has decreased to 0.72, and the relationship between Oil/grease and Phenol has become negative (-0.14). Additionally, the relationship between Temperature and Conductivity has become strongly negative (-0.68).

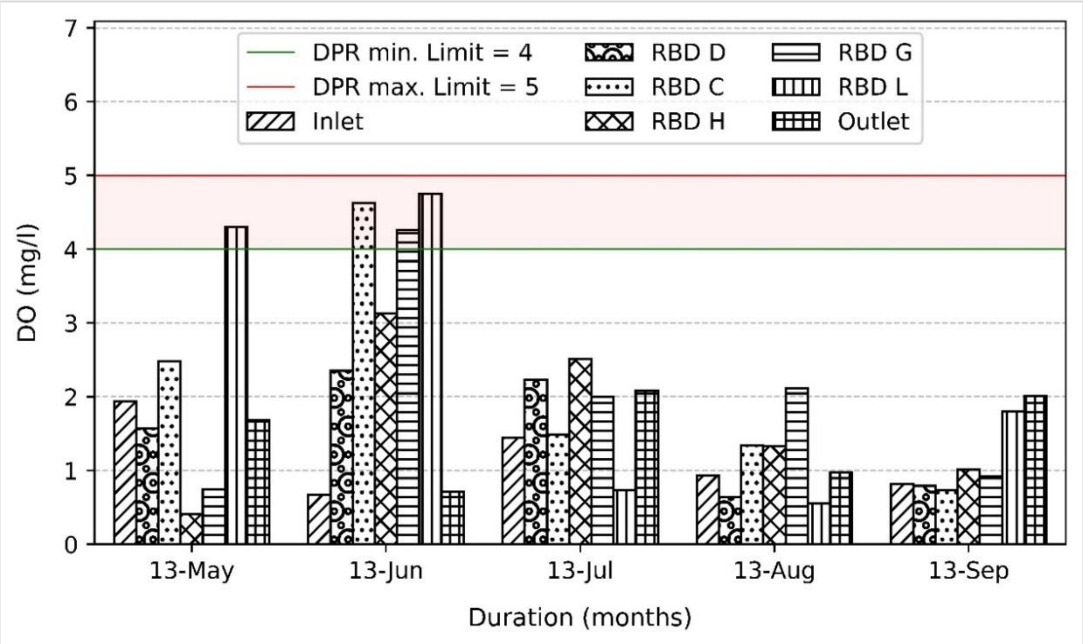

Fig. 5. Performance of RBD units- dissolved oxygen (mg/l)

Table 2. Relationship between the physiochemical parameter of the raw waste water

Variables	PH	Phenol	Oil/grease	Temp	TSS	Cond.	Sulphide	TDS	Phosphate
pH	1.00								
Phenol	0.84	1.00							
Oil/grease	0.83	1.00	1.00						
Temp	0.10	-0.02	0.06	1.00					
TSS	0.62	0.17	0.18	0.40	1.00				
Cond.	0.78	0.84	0.78	-0.50	0.12	1.00			
Sulphide	0.93	0.73	0.74	0.27	0.55	0.63	1.00		
TDS	0.72	0.55	0.56	0.23	0.82	0.41	0.51	1.00	
Phosphate	0.83	0.66	0.64	-0.09	0.29	0.76	0.91	0.23	1.00

Values in bold are different from 0 with a significance level alpha=0.05

Table 3. Relationship between the physiochemical parameter of the treated waste water

Variables	PH	Phenol	Oil/grease	Temp	TSS	Cond.	Sulphide	TDS	Phosphate
pH	1.00								
Phenol	0.50	1.00							
Oil/grease	-0.47	-0.14	1.00						
Temp	0.16	-0.56	-0.57	1.00					
TSS	0.64	0.68	-0.76	-0.06	1.00				
Cond.	0.58	0.79	0.27	-0.68	0.35	1.00			
Sulphide	0.68	-0.27	-0.38	0.55	0.17	0.03	1.00		
TDS	0.54	0.25	-0.57	0.62	0.33	-0.06	0.25	1.00	
Phosphate	0.93	0.43	-0.33	-0.03	0.60	0.66	0.72	0.20	1.00

Values in bold are different from 0 with a significance level alpha=0.05

The results of this study demonstrate that wastewater treatment processes can significantly alter the relationships between physiochemical parameters. The weakened relationship between Phosphate and Sulphide after treatment may suggest that the treatment process has successfully reduced the concentrations of these pollutants in the wastewater. However, the emergence of negative relationships, such as between Oil/grease and Phenol, may indicate that the treatment process has introduced new interactions between the parameters that were not present in the raw wastewater.

3.4 Principal Component Analysis

Bartlett's sphericity test was conducted to assess the suitability of the dataset for PCA. The results (Table 2) showed a significant chi-square value (106.644) compared to the critical value (50.998), indicating that the data were suitable for PCA. Four principal components were retained after the PCA, accounting for 75.01% of the total variance in the data (Table 3). The first two factors explained 51.22% of the total variance before Varimax rotation and 40.31% after rotation. The selection of the principal component was based on Eigen One and the proportion of variance retained by each component.

Table 4 presents the factor loadings of the physiochemical parameters onto the four principal components. High factor loadings indicate a strong association between the parameter and the principal component. The parameters with the highest loadings on the first factor (D1) were sulphates and phenols, whereas Chemical Oxygen Demand and Biological Oxygen Demand had the highest loadings on the second factor (D2). Dissolved oxygen was most strongly associated with the third factor (D3), and pH was the parameter with the highest loading on the fourth factor (D4). The PCA results identified four principal components representing different aspects of water quality. The first component was dominated by sulphates and phenols, which are often associated with industrial pollution. The second component was characterized by chemical and biological oxygen demand, indicating the presence of organic matter and the potential impact of microbial activity. The third component was mainly driven by dissolved oxygen, an essential factor for maintaining aquatic life. Finally, the fourth component was heavily influenced by pH, a critical parameter affecting the solubility and availability of nutrients and contaminants in water.

The result of the biplot shows principal components 1 and 2 with the loading of the physiochemical parameters on each component. Also, the loading of the various units of the Rotary Bio Disk unit on the principal axis was also represented in Fig. 6. The result from the biplot showed that unit D of the Rotary Bio Disk unit had a higher concentration of phenol and sulphate compared to other units of the Rotary Bio unit. The result suggests that more industrial waste component was found in the wastewater in that unit. The result indicates that unit D was not efficient at the removal of both phenol and sulphate. Similarly, the result from the biplot showed that the wastewater had higher organic content at the inlet of the Rotary Bio unit than in any other unit of the Bio unit. The result indicates that as the wastewater enters the unit less organic matter can be found in the wastewater.

Table 4. Bartlett's sphericity test

Chi-square (Observed value)	106.644
Chi-square (Critical value)	50.998
DF	36
p-value	< 0.0001
alpha	0.05

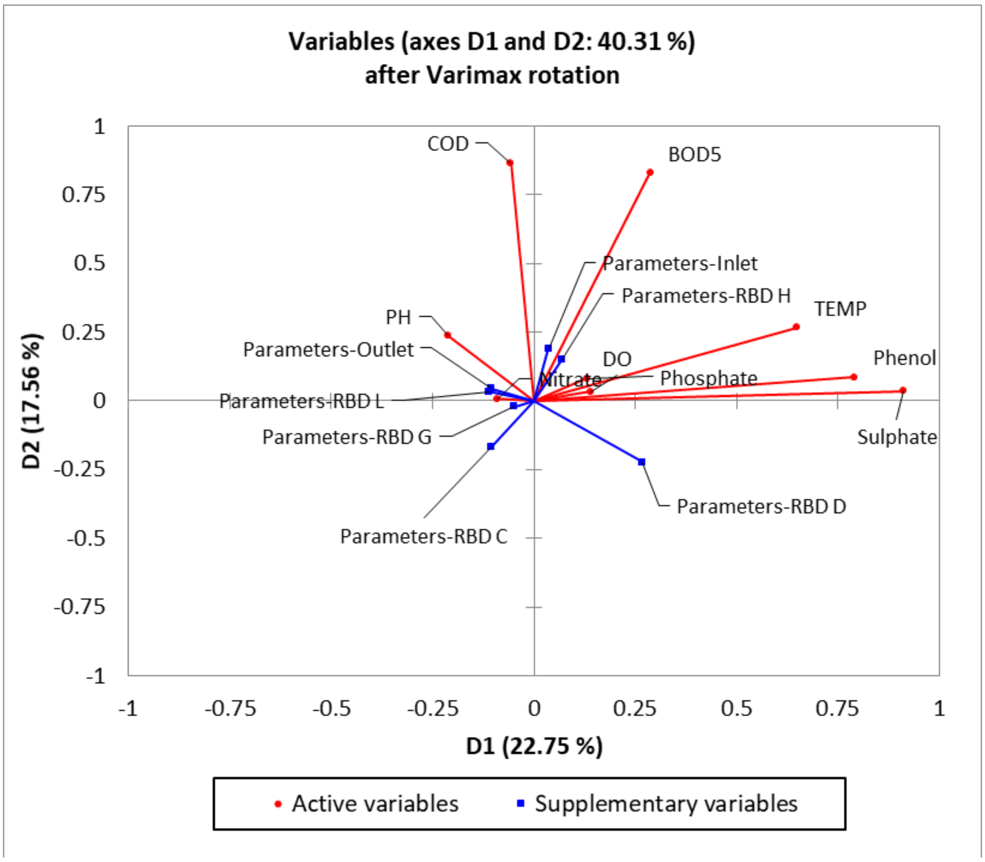

Fig. 6. Biplot

Table 5. Eigen values and proportion of eigenvalue retained

Principal Components	Eigenvalue	Before Varimax Rotation		After Varimax Rotation	
		Variability (%)	Cumulative %	Variability (%)	Cumulative %
F1	2.80	31.12	31.12	22.75	22.75
F2	1.81	20.10	51.22	17.56	40.31
F3	1.20	13.33	64.55	17.00	57.32
F4	0.94	10.46	75.01	17.69	75.01
F5	0.75	8.29	83.30	8.29	83.30

Table 6. Factor loading

Physiochemical Parameters	D1	D2	D3	D4
PH	-0.21	0.24	-0.35	-0.75
TEMP	0.65	0.27	0.51	-0.15
DO	0.14	0.03	0.82	0.13
COD	-0.06	0.87	0.01	0.03
BOD5	0.29	0.83	0.06	-0.10
Phenol	0.79	0.09	-0.19	0.29
Sulphate	0.91	0.04	0.16	0.14
Phosphate	0.13	0.08	0.01	0.85

4. CONCLUSION

Several parameters such as oil and grease, Total Suspended Solids (TSS) and sulphides were monitored to evaluate the removal efficiency of the Dissolved Air Floatation (DAF) unit and the Rotary Bio-Disk (RBD). Phenol levels in the individual RBD units did not show any consistent pattern, as RBD values showed differing values (increases/ decreases) for monthly phenol levels in inlet stream. The levels of BOD_5 in the individual RBD units were within the inlet specification but generally exceeded the outlet design specification. The results show that the DAF unit reduced oil/grease content of wastewater (Positive efficiency) for the months that were investigated. On average, the efficiency was calculated as 63.5%. Therefore, the DAF unit was efficient with regards to oil/grease removal. The oil/grease content of raw and treated water effluents were within the design specification of the DAF unit. Similarly, TSS removal efficiency was positive as the average removal efficiency was 21.3%. Therefore, the DAF unit was efficient (for the period investigated) with regards to TSS removal. In line with Pearson Correlation there are strong positive relationships between several parameters, such as pH and Sulphide (0.93), Phenol and Oil/grease (1.00), and Phosphate and Sulphide (0.91). The Principle Component Analysis yielded four principle components (PC1-4): PC1 parameters with the highest loadings on the first factor (D1) were sulphates and phenols, whereas Chemical Oxygen Demand and Biological Oxygen Demand had the highest loadings on the second factor (D2). Dissolved oxygen was most strongly associated with the third factor (D3), and pH was the parameter with the highest loading on the fourth factor (D4).

Interactions with top management revealed poor management practice in maintaining the RBDs. However, some individual units of the system were inefficient with pollutant levels exceeding regulatory limits. Factors contributing to under performance of some of the system's units include: pH, temperature, and dissolved oxygen instability as well as nutrient dosing. Recipient water (Okochiri River) characteristics were usually within their respective DPR limits except for parameters such as phenol, ammonia, TSS, TDS whose level exceeded DPR regulatory limits.

5. RECOMMENDATION

An improvement in the efficiency of the wastewater treatment system would result in complying with regulatory limits for pollutants, improvement actions should include:

1. Redesigning the CPI, to monitor the amount of oil/grease coming in;
2. Maintaining optimal operating conditions of temperature, pH, nutrient, and dissolved oxygen for the RBD units to ensure effective biological removal of pollutants;
3. Identifying (if any) the source of phenol in the RBD units (considering the phenol levels in the inlet were within design specification but the levels in the RBD units were higher than both inlet and design specifications);
4. Treating wastewater effluent to meet regulatory units before discharge into a recipient water body (as the current practice may result incumulative environmental impact on the Okochiri River and associated health/social implications for water users);
5. By constructing an effluent retention and recycling facility. This will enable in reprocessing of poorly treated effluent; and
6. Ensuring regular and effective maintenance of individual units in the WWTP.

DISCLAIMER

The products used for this research are commonly and predominantly used products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by the personal efforts of the authors.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

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DOI: 10.1007/s41101-020-00081-x

Peer-review history:
The peer review history for this paper can be accessed here:
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