IUBAT Review—A Multidisciplinary Academic Journal, 8(2): 264-282
https://doi.org/10.3329/iubatr.v8i2.87283

Assessing the Treatment Efficiency of a Multi-Stage ETP for Pharmaceutical Wastewater: A Case Study in Bangladesh

Md Tarekh Rasul [1*], Nayan Chandra Das[1]

[1]*Department of Civil Engineering, International University of Business Agriculture and Technology (IUBAT).*

Keywords:

Aerobic; Anaerobic; Biological Treatment; Chemical Treatment; Effluent; Reed Bed.

Abstract

This study assessed the treatment efficiency of the physical, chemical, and biological treatment processes to treat effluent discharged for a pharmaceutical factory. The treatment mechanism comprised of equalization tank, neutralization tank, anaerobic followed by aerobic bioreactors, two stage clarification system, reed bed bio-filtration process, and post aeration system. The effluent quality parameters such as pH, turbidity, TDS, TSS, TS, COD and BOD_5 were analyzed in the laboratory with standard methods. The overall pollution removal efficiencies were 100% for turbidity, 97% for TSS, 95% for COD, and 97% for BOD_5. The average reduction ranges of Turbidity, TSS, TS, COD and BOD_5 were 201 FTU to 0 FTU, 512 mg/l to 13 mg/l, 912 mg/l to 530 mg/l, 2034 mg/l to 99 mg/l, and 1126 mg/l to 29 mg/l respectively were observed in the final stage. In terms of performance evaluation of individual treatment units, the anaerobic treatment unit achieved 1%, 17%, and 37% removal efficiencies for turbidity, COD, and BOD_5 respectively; while the aerobic unit achieved 76%, 86%, and 86% removal efficiencies for the same parameters. The chemical treatment process was found effective for TSS and turbidity removal purpose. The Reed Bed performed well in removing BOD_5, COD, and Turbidity.

1. Introduction

The pharmaceutical industries which play a vital role in global health sector but generates complex and diverse toxic wastewater to the streams as well. Such toxic substances induce significant environmental and public health challenges. The pharmaceutical effluents have versatile chemical compositions which create high chemical and biochemical oxygen requirements and contain some residual pharmaceutical substances. Strong treatment strategies are essential to mitigate the biotoxicity, toxicity, and persistence of these substances. The conventional wastewater treatment plants are largely ineffective to remove those pollutants due to their unique chemical structures and biological toxicity of these complex compounds (Li & Yang, 2018). The traditional effluent treatment systems have insufficient removal efficiencies, and even some antibiotics proven to be toxic to

*Corresponding author's E-mail address: tarekhrasul@gmail.com
Article received: October 2025 Revised and accepted: December 2025 Published: December 2025

microorganisms may be present as residue (Patel *et al.*, 2020; Verlicchi *et al.*, 2012; Krzemiński *et al.*, 2018). This insufficiency of the treatment system results in the excessive release of drug residues into the surface water, soil, and groundwater (Tahraoui *et al.*, 2022). These contaminations are accompanied by serious risks, such as toxicity, carcinogenicity, as well as bioaccumulation in the ecosystem (Aziz *et al.*, 2025). The spread of the antibiotic resistant pathogenic microbes poses a threat to the global health condition (Oluwole *et al.*, 2020). The active pharmaceutical substances and other diverse pollutants frequently require a complex treatment strategy (Shah & Shah, 2020). Therefore, an urgent and critical need created for a effective advanced treatment technologies which will be capable to mitigate the environmental impact of pharmaceutical discharges (Iyer *et al.*, 2025; Kato & Kansha, 2024).

The studied Effluent Treatment Plant (ETP) was designed to treat approximately 1.5 cubic meters of wastewater per hour. The source of liquid discharge was various pharmaceutical production units within the factory. It is important to note that effluent originating from the antibiotic units were discharged to the ETP, following a pretreatment system as per the standard protocol established by the company.

The present research seeks to present an overview and comparative analysis of several physicochemical, and biological-based processes that are used to treat pharmaceutical wastewater. This study investigates the performance of a multi-stage effluent treatment plant in Bangladesh, specifically focusing on its efficacy in removing various organic pollutants from wastewater to achieve effluent discharge standard of Department of Environment (DoE) set guideline.

2. Materials and Methods

2.1 Materials

The study was conducted over a consecutive three-month period of time (from December, 2021 to February 2022) in a pharmaceutical industry situated at Comilla district, Bangladesh. Wastewater samples were collected periodically from all treatment units of the effluent treatment plant (ETP) of the factory.

The effluent treatment system of the study plant is sequenced with equalization, pH adjustment, anaerobic followed by aerobic biodegradation, plane sedimentation followed by chemical sedimentation, reed bed bioaccumulation and post aeration. The equalization tank of the effluent treatment plant (ETP) served as the primary treatment unit, receives effluent continuously throughout the day. To maintain the optimal pH level, an automated pH adjustment system had been integrated into the equalization tank. A two-stage biological treatment process, started with the up-flow anaerobic sludge blanket (UASB) system and followed by the activated sludge process were employed. Initially, the effluent from the equalization tank is pumped into the Bioreactor-1, where anaerobic biodegradation takes place through the UASB process. Next, the partially treated effluent is discharged to Bioreactor-2, where further biodegradation of excess organic matter occurs with Activated Sludge Process (ASP). To clarify the effluent of Bioreactor-2, a plane sedimentation system was employed with Clarifier-1. The settled sludge is then partially returned to Bioreactor-2 to maintain the desired concentration of biomass in the reactor.

The supernatant of Clarifier-1 is passed to Clarifier-2 to remove any remaining unsettled colloidal particles using a chemical sedimentation system i.e. coagulation and flocculation. Any excess sludge from Clarifier-1 and all sludge from Clarifier-2 are discharged into the Sludge Drying Bed. Finally, the sludge is disposed as solid waste after proper dewatering. The clarified effluent from the Clarifier-2 is spread over the Reed Bed followed by a Post Aeration system for polishing with combined physical and biological processes. This comprehensive multi-stage treatment approach ensures maximal removal efficiencies of pharmaceutical compounds, thereby mitigating their environmental impacts and safeguard to the public health.

The Up-flow Anaerobic Sludge Blanket (UASB) system was designed considering Organic Loading Rate (OLR) = 4 – 5 kg COD/m^3-day, Hydraulic Retention Time (HRT) = 12 hours, Sludge Retention Time (SRT) = 60 days. The Activated Sludge Process (ASP) was designed considering Hydraulic Retention Time (HRT) = 12 hours, Sludge Retention Time (SRT) = 12 – 13 days, food and microorganism ratio F/M = 0.33 and oxygen requirement = 25 – 30 kg/day. Dissolved Oxygen (DO) concentration was maintained 24 hours 2 – 4 mg/l in the Bioreactor-2 for the survival of the aerobic bacteria. Coagulant and flocculent doses were fixed periodically (at least once in a week) by Jar Test in the chemical sedimentation system. PAC (Polyaluminium Chloride) and PAM (Polyacrylamide) were used as coagulant and flocculent at the dosing rate of 40 to 70 mg/l and 1 to 2 mg/l respectively.

2.2 Methodology

Water sample collection, transportation, preservation, and laboratory analysis was conducted with the Standard Method (APHA, 2017; Jenkins, 1982). All tests were conducted in the Environmental Engineering Laboratory of IUBAT, with the exception of dissolved oxygen and pH, which were performed on-site.

Samples were collected in every two weeks' interval. Three samples from each of the treatment units were collected for laboratory test. The sample were collected from the outlet portion the treatment units except for Bioractor-2. To evaluate the performance of Bioreactor-2, the clarified sample was collected from the outlet of Clarifer-1 but, to analyze MLSS and SVI sample was collected from the Bioractor-2. After field and laboratory test the concurrent result from the three samples of the same unit were recorded in the data sheet. One-liter size HDPE bottles were used to collect sample from the Bioreactor-2 for MLSS and SVI tests and 500 ml size HDPE bottles were used for the samples from other units. Sample were carried with ice box to maintain temperate below 4^oC.

The studied pharmaceutical industry pre-treats the antibiotic contaminated effluent before discharging to the ETP. Alkaline hydrolysis with sodium hydroxide solution followed by neutralization with hydrochloric acid process were used to disintegrate the antibiotic molecules. In high pH (10–13) antibiotic molecules lose structural integrity and antimicrobial activity and the complex molecules convert into smaller, more biodegradable compounds.

The key effluent quality indicators (KEQI) were assessed in different treatment units of the effluent treatment plant (ETP). The tested water quality parameters are like pH, turbidity, total dissolved solids (TDS), total suspended solids (TSS), total solids (TS), mixed liquor suspended solids (MLSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5) and sludge volume index (SVI). Each of the parameters were meticulously measured and analyzed to evaluate the performance and effectiveness of the treatment process at various treatment stages within the ETP. The status of the overall effluent treatment efficiency of different units of the treatment system are mentioned in Table 1.

Table 1. Effluent Parameters Tested in Different Units.

Unit No	Name of the Treatment Unit	Effluent Parameters
1	Equalization Tank (Eqn. T)	pH, Turbidity, TDS, TSS, TS, BOD_5 and COD
2	Bioreactor-1 (BR-1)	pH, Turbidity, TDS, TSS, TS, BOD_5 and COD
3	Bioreactor-2 (BR-2)	pH, Turbidity, TDS, MLSS, TS and SVI
4	Clarifier-1 (Clr-1)	pH, Turbidity, TDS, TSS, TS, BOD_5 and COD
5	Clarifier-2 (Clr-2)	pH, Turbidity, TDS, TSS, TS, BOD_5 and COD
6	Reed Bed (RB)	pH, Turbidity, TDS, TSS, TS, BOD_5 and COD
7	Post Aeration Tank (PAT)	pH, Turbidity, TDS, TSS, TS, BOD_5 and COD

During the three months' research period, effluent quality data were collected in five times from all the units of the ETP. The obtained data from different treatment units were accumulated and prepared for statistical analysis using Microsoft Excel and finally the relevant inferences were drawn. The comprehensive dataset generated a robust evaluation approach of the multi-stage treatment system based ETP.

3. Results and Discussion

The laboratory test results which had been found during the study period from the different treatment units of the ETP are summarized and compared with DoE effluent discharge standards (ECR 2023). The summary of the ANOVA result is shown in Table 2. The laboratory test results with mean and standard deviation (SD) is show in Table 3.1 and Table 3.2. The results show the variation of pollution removal efficiencies of different units. Some significant variations observed in individual processes as well. Several key effluent quality indicators (KEQI) reflect the performance of these treatment units. Based on the characteristics of the effluent and the treatment process, Turbidity, TDS, TSS, COD, and BOD_5 are considered as the KEQI for evaluating the ETP.

Table 2: ANOVA Results Summary

Parameter	F-value	p-value	Statistical Interpretation
pH	6.61	< 0.001	Significant
Turbidity	112.40	< 0.001	Highly significant
TDS	3.58	0.009	Significant
TSS	38.57	< 0.001	Highly significant
TS	38.00	< 0.001	Highly significant
COD	85.25	< 0.001	Highly significant
BOD_5	146.72	< 0.001	Highly significant

pH: The value of pH remains within the limit of effluent discharge standard under all treatment steps. It fluctuated little bit in different chemical and biological treatment units. A statistically significant difference in pH ($F = 6.61$, $p < 0.001$) is show among treatment units by the One-way ANOVA test.

Turbidity: The turbidity of influent water was found as 201±101 FTU, primarily attributed to colloidal pharmaceutical particles. The turbidity of effluent had been significantly and progressively decreased through various treatment stages. Turbidity showed a highly significant difference among treatment units ($F = 112.40$, $p < 0.001$), indicating effective clarification and polishing through downstream units. A significant reduction was observed after aerobic biodegradation in Bioreactor-2 followed by clarification. Chemical coagulation, flocculation, and subsequent clarification proven effective in removing most of the turbidity caused by colloidal particles present in the effluent. Additionally, a reed bed system also played a significant role in removal of turbidity. Ultimately, the discharged effluent became turbidity free. This study demonstrates the efficacy of the multi-stage treatment process to achieve a high degree of clarity to meet the environmental discharge standard. A system based on various treatment processes, including sedimentation, filtration, and plant uptake, can achieve substantial reductions in suspended solids and associated turbidity (Pastor-López *et al.*, 2024). The final effluent from pharmaceutical effluent treatment plants should have an aim to achieve a turbidity of less than 5 NTU (Jegatheesan *et al.*, 2022). The Nephelometric Turbidity Units (NTU) are considered comparable to the Formazin Turbidity Units (FTU) when turbidity is measured by nephelometry calibrated with a formazin standard reference suspension (US EPA Method 180.1).The integrated physical, chemical, and biological processes of the treatment system ensures such removal efficiency of turbidity (Wondim *et al.*, 2023).

TDS: The treatment system could not remove dissolved solids from the effluent at all. On the contrary, after chemical treatment, due to the addition of coagulant and flocculent, TDS increased from 400±33 mg/l to 522±75 mg/l. A statistically significant variation in TDS was observed across treatment units ($F = 3.58$, $p < 0.01$), although the magnitude of change was comparatively low. This observation proves that the chemical treatment methods can elevate the total dissolved solids concentration in the treated water (Makowska *et al.*, 2023). In some cases advanced treatment methods may be required to effectively manage TDS levels before final discharge (Abdelfattah *et al.*, 2022).

TSS: The concentration of total suspended solids differed highly significantly among treatment units ($F = 38.57$, $p < 0.001$), confirming efficient suspended solids removal. The suspended solid concentration in the ETP influent was found as 512±272 mg/l. The TSS concentration had been slightly decried in the discharged effluent from Bioreactor-1. Further, a massive increase occurred in Bioreactor-2, due to the presence of biomass in the aeration tank. The suspended solids in the aeration tank, referred to as mixed liquor suspended solids (MLSS), reached a concentration of 4346±1481 mg/l. Such MLSS value indicates presence of a substantial and active microbial biomass in the reactor. This is crucial for the biological degradation of complex pollutants in pharmaceutical wastewater (Bermúdez *et al.*, 2023; Govindaraju *et al.*, 2022). The concentration of suspended solids decreased abruptly after both the physical and chemical clarification systems. At the final effluent discharge point TSS concentration reduced to 13±6 mg/l. Both physical and chemical treatments are highly effective in reducing TSS to the acceptable discharge levels. The physicochemical process, including coagulation, flocculation, sedimentation, clarification, and various filtration techniques are crucial for suspended solids removal (Chhetri *et al.*, 2016;Konring & Tang, 2016). These physicochemical processes separate colloidal and suspended particles from the effluent and ensure the environmental discharge standards (Konring & Tang, 2016; Ponce-Robles *et al.*, 2022). The multi-stage treatment technique, combination of biological with physical and chemical separation, can effectively remove complex particulate matter in pharmaceutical effluent also (Konring & Tang, 2016; Ponce-Robles *et al.*, 2022).

Both from the field and laboratory test, the sludge from Bioreactor-2 was observed as compact nature. The average sludge volume index from the sample was found as 58±13ml/g. An SVI value below 100 ml/g indicates good settling characteristics and that type sludge settles well in the clarifier without bulking (Khudhair *et al.*, 2023; Rashid, 2024). This efficient settling characteristic of sludge ensured clearer effluent with simple solid-liquid separation system.

Table 3.1: The Effluent Test Results of Different Treatment Units and DoE Standard

Sapling Units	pH			Turbidity (FTU)			TDS (mg/l)			TSS (mg/l)		
	Value	Mean	SD	Value	Mean	SD	Value	Mean	SD	Value	Mean	SD
Eqn. T	6.76	6.48	0.42	298	201	101	410	400	33	60	512	272
Eqn. T	7.08			92			350			670		
Eqn. T	6.12			288			410			640		
Eqn. T	6.28			233			440			730		
Eqn. T	6.18			95			390			460		
BR-1	6.18	6.28	0.21	164	199	94	480	398	76	320	480	136
BR-1	6.58			350			330			620		
BR-1	6.39			188			310			610		
BR-1	6.02			199			460			480		
BR-1	6.21			92			410			370		
BR-2	6.73	7.03	0.65	31	53	34	510	436	65	5340	4346	1481
BR-2	6.62			37			390			6260		
BR-2	6.43			112			350			4040		
BR-2	7.41			53			470			2480		
BR-2	7.98			32			460			3610		
Clr-1	7.05	7.20	0.52	64	47	29	500	410	82	140	68	50

Clr-1	6.72			64			350			40		
Clr-1	6.82			40			300			20		
Clr-1	7.40			69			450			100		
Clr-1	7.99			0			450			40		
Clr-2	5.74			0.55			620			50		
Clr-2	6.09			0.48			520			20		
Clr-2	6.03	6.33	0.54	0.42	0.49	0.17	400	518	78	30	26	15
Clr-2	6.82			0.74			520			20		
Clr-1	6.98			0.28			530			10		
RB	6.62			0.45			630			15		
RB	6.93			0			520			10		
RB	6.6	6.99	0.43	0	0.09	0.20	420	522	75	35	20	12
RB	7.2			0			510			30		
RB	7.62			0			530			10		
PAT	7.35			0			630			20		
PAT	7.58			0			520			10		
PAT	7.52	7.78	0.43	0	0.00	0.00	420	522	75	17	13	5
PAT	8.07			0			510			10		
PAT	8.38			0			530			10		
DOE Standard	6.0 – 9.0			-			≤ 2100			≤ 100		

Table 3.2: The Effluent Test Results of Different Treatment Units and DoE Standard

Sapling	TS (mg/l)	COD (mg/l)	BOD5 (mg/l)	SVI (ml/g)

Units	Value	Mean	SD	Value	Mean	SD	Value	Mean	SD	Value	Mean	SD
Eqn. T	470			1378			788					
Eqn. T	1020			2014			1128					
Eqn. T	1050	912	272	2326	2034	441	1230	1126	224			
Eqn. T	1170			1918			1086					
Eqn. T	850			2532			1398					
BR-1	800			1368			417					
BR-1	950			1414			860					
BR-1	920	878	81	1928	1691	275	916	708	245			
BR-1	940			1874			880					
BR-1	780			1872			465					
BR-2	5850			323			65			36		
BR-2	6650			114			81			69		
BR-2	4390	4782	1470	224	219	76	127	94	23	59	58	13
BR-2	2950			241			98			59		
BR-2	4070			193			101			69		
Clr-1	640			284			162					
Clr-1	390			162			70					
Clr-1	320	478	127	167	238	97	53	99	62			
Clr-1	550			387			171					
Clr-1	490			192			41					
Clr-2	670	544	85	183	145	36	74	40	20			

Clr-2	540			124			33					
Clr-2	430			134			28					
Clr-2	540			183			38					
Clr-1	540			103			27					
RB	645			140			58					
RB	530			108			36					
RB	455	542	68	104	104	23	25	35	14			
RB	540			82			33					
RB	540			88			25					
PAT	650			129			41					
PAT	530			109			29					
PAT	437	535	76	94	99	30	21	29	7			
PAT	520			51			27					
PAT	540			114			28					
DOE Standard	-			≤ 200			≤ 30			-		

COD: The concentration of COD decreased significantly along the treatment train ($F = 85.25$, $p < 0.001$), demonstrating strong organic matter removal efficiency. The concentration of chemical oxygen demand in the influent was found as 2034±441 mg/l. The COD concentration of raw effluent shows presence of a typical organic load in wastewater (Makowska *et al.*, 2023). A remarkable reduction of COD occurred in the Bioreactor-1, where the it decreased to 1691±275 mg/l through anaerobic biodegradation. Such COD reduction signifying the initial efficacy of the UASB system by metabolizing readily biodegradable organic compounds as other studied also found (Bazedi *et al.*, 2023). This reduction was more significantly enhanced after treatment in Bioreactor-2, in an aerobic biological stage. The subsequent clarification, leading to a substantial decrease in COD to 238±97 mg/l. This treatment stage effectively removes biodegradable organic pollutants through aerobic microbial degradation and removes associated suspended solids via clarification (Chalaris *et al.*, 2023; Shtepa *et al.*, 2021). Bacterial treatment processes have demonstrated significant

COD reductions, with some studies reporting reductions to 134 ± 0.74 mg/l from initial values of 2035 ± 0.61 mg/l (Bhargawa *et al.*, 2024).

The additional COD value reduction observed following chemical clarification and it decreased to 145±36 mg/l. This physicochemical process plays a crucial complementary role by removing residual organic matter, including colloidal particles and recalcitrant pharmaceutical substances that often present after biological treatment (Guo *et al.*, 2017; Malik *et al.*, 2019; Patel *et al.*, 2020). The sequential application of biological and chemical treatments process is essential for effectively removing the complex, recalcitrant and often low-biodegradable organic elements of pharmaceutical effluents (Khalidi-Idrissi *et al.*, 2023; Malik *et al*., 2019). The Reed Bed and Post Aeration system also removed some amount of COD. The final concentration of COD at the outlet of the Post Aeration Tank was measured as 99±30 mg/l. Other studies have demonstrated that various phytoremediation agents can reduce COD ranging from 52% to 91% and up to 99% using combined physicochemical and biochemical techniques (Fitrisyaah *et al.*, 2025; Bazedi *et al.*, 2023).

BOD: The biochemical oxygen demand reduction pattern of the effluent was similar to those observed for COD. The reduction of BOD_5 showed the highest statistical significance among all parameters ($F = 146.72$, $p < 0.001$), highlighting the effectiveness of biological treatment processes. The BOD_5 of influent was initially measured as 1126±224 mg/l. This concentration successively decreased to 708±245 mg/l in Bioreactor-1, then to 99±62 mg/l after Bioreactor-2 and subsequent clarification, and further to 40±20 mg/l following chemical clarification. A slight reduction was also observed after passing through Reed Bed, culminating in a final BOD_5 concentration of 29±7 mg/l at the Post Aeration Tank discharge point. The overall BOD reduction scenario demonesses the effectiveness of the integrated treatment system to mitigate the pollution and ensures the effluent quality within acceptable limits for discharge. The various pre-treatment methods, such as chemical oxidants like hydrogen peroxide, Fenton's reagent, potassium persulfate etc. can significantly improve biodegradability of pharmaceutical compounds(Iyer *et al.,* 2025) . Different Biological processes, particularly bacterial treatment or plant-based systems, have demonstrated substantial efficiency in reducing biochemical oxygen demand and chemical oxygen demand in pharmaceutical wastewater (Bazedi *et al.*, 2023; Bhargawa *et al.*, 2024; Pandya *et al.*, 2022).

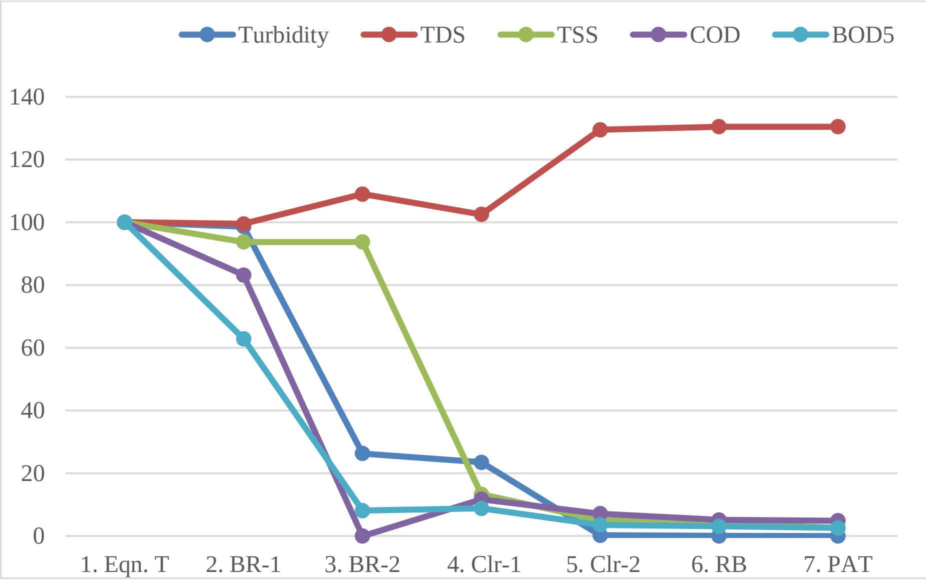

Figure 1: Percentile Pollution Removal Efficiency Curve of Different Units

The Figure-1 demonstrates the gradual removal of pollutants during the treatment process. Most pollutants were effectively removed except TDS at the 5th stage of treatment in Clarifier-2. At the final treatment stage, the water achieved complete removal of turbidity, 97% removal of TSS, 95% of COD, and 97% of BOD_5 from the raw influent. Though 31% increment of TDS after the end process, its final concentration remained within acceptable limits.

The Figure 2 highlights the notable improvements in wastewater treatment achieved by the individual treatment units. Utilizing the UASB technique in Bioreactor-1, it was achieved reductions of 17% in COD and 37% in BOD_5. The Clarifier-1, employing the activated sludge process had achieved 86% removal of TSS, COD, and BOD_5. Turbidity removal efficiency found in Clarifier-1 as 76%, while Clarifier-2 exceeded the expectations with a remarkable efficiency of 99%. The Clarifier-2 also showed pollution removal efficiencies of 62%, 39%, and 60% for TSS, COD, and BOD_5 respectively. The Reed Bed unit had shown its pollution removing effectiveness by 82% turbidity, 23% TSS, 28% COD, and 12% BOD load. No turbidity was found in the post aeration unit, i.e. 100% turbidity removed; other parameters like TSS, COD and BOD was removed 33%, 5% and 17% respectively.

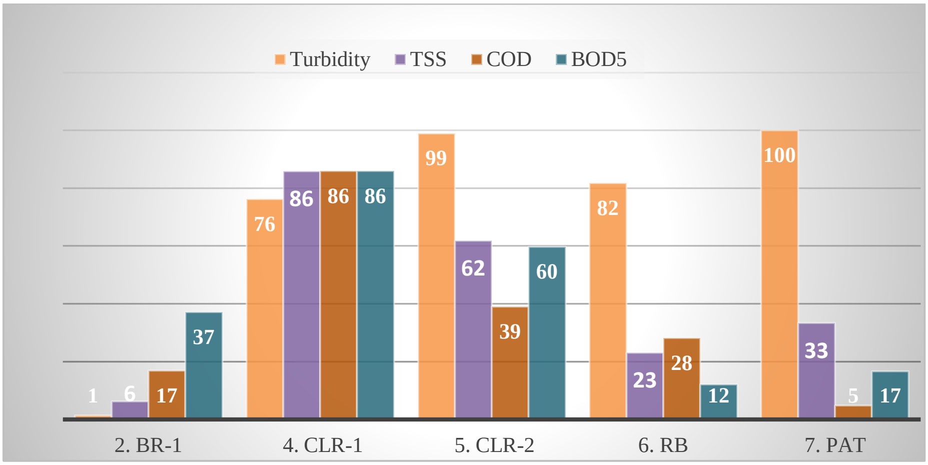

Figure 2: Percentile Pollution Removal Efficiency of Individual Treatment Units

During the study, it was observed that Bioreactor-1 removed 343 mg/l of COD. Assuming the plant operation period of 20 hours per day at a flow rate of 1.5 m^3/hr; the biogas generation rate can be calculated, as mentioned by Tchobanoglous *et al.*, 2003 and He *et al.*, 2019. Specific operational parameters and wastewater characteristics must be kept in account for the calculations predicted biogas yield. The following equation derived at a temperature of 25°C:

Methane Production Rate = COD (g/m3)/day x 382 x 10-6

= m^3 /day

= 1.5 x 20 x 343 x 382 x 10-6 m3/day

= 3.93 m^3/day

A study by (Dai *et al.*, 2019) reported that 1 gram of COD can generate approximately 16.1 kilo-joules of energy. Therefore, the estimated energy production potential of the studied ETP is approximately 166 mega-joules per day. Such integration of treatment system can lead to a new approach of energy savings and some extent of energy neutrality (Dai *et al.*, 2019).

The studied effluent treatment plant meets the discharge quality standards as per the regulations of Environmental Conservation Rules (ECR, 2023). The extent of removal efficiency varies significantly depending on the specific pharmaceutical compounds and the operational efficiency of each treatment unit (Akinwumi *et al.*, 2023). These advanced treatment approaches open an avenue toward more effective elimination of recalcitrant pharmaceutical contaminants from the wastewater streams (Twi-Yeboah *et al.*, 2024).

5. Conclusion

Three months' examination of the effluent treatment plant revealed that the end result of the discharge of the effluent met all the necessary parameters as guided by the department of Environment. In case of COD and BOD_5 removal extremely high F-values confirm biological treatment as the dominant removal mechanism. The significant improvements of TSS, TS, and turbidity removal reflect effectiveness of clarification and reed bed filtration system. The TDS value in the effluent was lower but not efficiently removed by conventional biological treatment system. The statistically significant differences of the pH are operationally acceptable and do not hinder treatment performance. The Water quality results shows that Bioreactor-2 was more effective in removing organic pollutants compared to Bioreactor-1. The aerobic treatment shown better results than anaerobic treatment with the same detention time in removing organic pharmaceutical pollutants. In case of sedimentation, chemical sedimentation process was found more effective compared to plane sedimentation in terms of eliminating BOD, COD, and TSS. But, the level of TDS significantly increased in the course of chemical treatment. Reed Bed system was found mainly effective in the removal of turbidity and suspended solids. The varying physicochemical characteristics of pharmaceutical compounds require different treatment methods. Pollution removal efficiencies of pharmaceutical effluent may vary dramatically even within the same therapeutic group, based on aspects such as biomass concentration, hydraulic retention time, and pH. Treatment of pharmaceutical effluent with biological treatment is usually necessary to obtain complete elimination of all recalcitrant chemicals and to obtain desirable discharge limits.

Acknowledgement

The authors would like to thank the technical staffs of the Environmental Engineering Laboratory, Department of Civil Engineering, International University of Business Agriculture and Technology for their helpful assistance during testing. Special thanks to the authority of NIPRO JMI Pharma Ltd. for their cooperation during the study period.

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, multiple publication and, or submission, and redundancy have been completely witnessed by the authors.

References

Abdelfattah, I., Abuarab, M. E., Mostafa, E. A., Awady, M. H. E., Aboelghait, K. M., & El-Shamy, A. M. (2022). Integrated system for recycling and treatment of hazardous pharmaceutical wastewater. *International Journal of Environmental Science and Technology, 20*(4), 4101–4114. https://doi.org/10.1007/s13762-022-04269-7

Akinwumi, O. D., Dada, E. O., Agarry, S. E., Aremu, M. O., Agbede, O. O., Alade, A. O., Aworanti, O. A., & Alao, A. I. (2023). Optimization of operating parameters for simultaneous bioelectricity generation and treatment of pharmaceutical wastewater using microbial fuel cells. *Research Square*. https://doi.org/10.21203/rs.3.rs-3695023/v1

American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). APHA.

Aziz, K. H. H., Mustafa, F. S., Karim, M. A. H., & Hama, S. (2025). Pharmaceutical pollution in the aquatic environment: Advanced oxidation processes as efficient treatment approaches. *Materials Advances*. https://doi.org/10.1039/d4ma01122h

Bazedi, G. A. A., Abdallah, H., Ali, S. S., Shalaby, M., Sabry, R., Ali, H. M., & Gadallah, H. (2023). Economic evaluation for anoxic biological system integrated with external membrane for pharmaceutical wastewater treatment. *Applied Water Science, 14*(1), Article 64. https://doi.org/10.1007/s13201-023-02064-4

Bermúdez, L. A., Díaz, V., Poyatos, J. M., Muñío, M. del M., & Martín-Pascual, J. (2023). Effect of pharmaceutical compounds on the heterotrophic behaviors of biomass of a membrane bioreactor to treat urban wastewater. *Environments, 10*(12), Article 198. https://doi.org/10.3390/environments10120198

Bhargawa, P. K., Tiwari, S., Kumar, S., & Kumar, R. (2024). Integrated treatment of textile wastewater and methyl orange azo dye: Constructed wetland-based remediation enhanced by bacterial treatment. *Research Square*. https://doi.org/10.21203/rs.3.rs-5400170/v1

Chalaris, M., Gkika, D. A., Tolkou, A. K., & Kyzas, G. Z. (2023). Advancements and sustainable strategies for the treatment and management of wastewaters from metallurgical industries. *Environmental Science and Pollution Research, 30*(57), 119627. https://doi.org/10.1007/s11356-023-30891-0

Chhetri, R. K., Klupsch, E., Andersen, H. R., & Jensen, P. E. (2016). Wastewater treatment in Kangerlussuaq, Greenland by chemical coagulation and UV disinfection. *Water Science and Technology, 73*(1), 51–59.

Dai, Z., Heidrich, E. S., Dolfing, J., & Jarvis, A. P. (2019). Determination of the relationship between the energy content of municipal wastewater and its chemical oxygen demand. *Environmental Science & Technology Letters, 6*(7), 396–400. https://doi.org/10.1021/acs.estlett.9b00253

Environmental Conservation Rules, 2023 (Bangladesh).

Fitrisyaah, M. R., Fauzi, A. M., & Yani, M. (2025). Bioremediation of petroleum contaminated water using oil spill dispersant and *Lemna minor* in l aboratory-scale constructed wetlands. *Research Square*. https://doi.org/10.21203/rs.3.rs-5885729/v1

Govindaraju, R. A., Parivallal, G., Nagalingam, A. K., & Devarajan, S. (2022). MLVSS/MLSS ratio standard values obtained from different aeration tank samples of sewage treatment plants: A case study. *Indian Journal of Microbiology Research, 9*(2), 144–149. https://doi.org/10.18231/j.ijmr.2022.026

Guo, Y., Qi, P., & Liu, Y. (2017). Advanced treatment of pharmaceutical wastewater: A review. *IOP Conference Series: Earth and Environmental Science, 63,* 012025. https://doi.org/10.1088/1755-1315/63/1/012025

He, H., Ji, X., Xie, X., Ding, X., Wang, F., Ding, J., Hai, Z., & Tang, R. (2019). Energy and economic evaluation of three generations of anaerobic reactors for starch wastewater treatment. *Environmental Pollutants and Bioavailability, 31*(1), 252–260. https://doi.org/10.1080/26395940.2019.1662734

Iyer, A. M., Karande, A. V., & Gogate, P. R. (2025). Treatment of pharmaceutical effluent using ultrasound-based advanced oxidation for intensified biological oxidation. *Processes, 13*(4), Article 1191. https://doi.org/10.3390/pr13041191

Jegatheesan, V., Pachova, N., Velasco, P., Mowjood, M. I. M., Weragoda, S. K., Makehelwala, M., … Jinadasa, K. B. S. N. (2022). Co-development of an integrated assessment framework to evaluate nature-based water treatment technologies. *Environmental Quality Management*, *32*(3), 335–350. https://doi.org/10.1002/tqem.21922

Jenkins, S. H. (1982). Standard methods for the examination of water and wastewater. *Water Research*, *16*(10), 1495–1500. https://doi.org/10.1016/0043-1354(82)90249-4

Kato, S., & Kansha, Y. (2024). Comprehensive review of industrial wastewater treatment techniques. *Environmental Science and Pollution Research, 31*(39), 51064–51089. https://doi.org/10.1007/s11356-024-34584-0

Khalidi-Idrissi, A., Madinzi, A., Anouzla, A., Pala, A., Mouhir, L., Kadmi, Y., & Souabi, S. (2023). Recent advances in the biological treatment of wastewater rich in emerging pollutants from pharmaceutical industries. *International Journal of Environmental Science and Technology, 20*(10), 11719–11740. https://doi.org/10.1007/s13762-023-04867-z

Khudhair, D. N., Hosseinzadeh, M., Zwain, H. M., Siadatmousavi, S. M., Majdi, A., & Mojiri, A. (2023). Upgrading the MBBR process to reduce excess sludge production in activated sludge systems. *Water, 15*(3), Article 408. https://doi.org/10.3390/w15030408

Krzemiński, P., Tomei, M. C., Karaolia, P., Langenhoff, A., Almeida, C. M. R., Felis, E., … Fatta-Kassinos, D. (2018). Performance of secondary wastewater treatment methods for the removal of contaminants of emerging concern: A review. *Science of the Total Environment, 648*, 1052–1069. https://doi.org/10.1016/j.scitotenv.2018.08.130

Lalwani, J., Gupta, A., Thatikonda, S., & Subrahmanyam, C. (2020). Treatment strategies for pharmaceutical industry effluent with varying characteristics. *Journal of Environmental Chemical Engineering, 8*(5), 104190. https://doi.org/10.1016/j.jece.2020.104190

Li, Z., & Yang, P. (2018). Physicochemical, chemical, and biological processes for pharmaceutical wastewater: A review. *IOP Conference Series: Earth and Environmental Science, 113*, 012185. https://doi.org/10.1088/1755-1315/113/1/012185

Makowska, M., Spychała, M., & Gajewska, K. (2023). Impact of pharmaceuticals on individual wastewater treatment systems. *Journal of Ecological Engineering, 25*(2), 257–266. https://doi.org/10.12911/22998993/176945

Malik, S. N., Khan, S. M., Ghosh, P. C., Vaidya, A. N., Kanade, G. S., & Mudliar, S. N. (2019). Treatment of pharmaceutical industrial wastewater by nano-catalyzed ozonation. *Science of the Total Environment, 678*, 114–123. https://doi.org/10.1016/j.scitotenv.2019.04.097

Oluwole, A. O., Omotola, E. O., & Olatunji, O. S. (2020). Pharmaceuticals and personal care products in water and wastewater: A review. *BMC Chemistry, 14*(1), Article 58. https://doi.org/10.1186/s13065-020-00714-1

Pandya, K. S., Kodgire, P., & Simon, S. (2022). Combined ultrasound cavitation and persulfate for the treatment of pharmaceutical wastewater. *Water Science and Technology, 86*(9), 2157–2166. https://doi.org/10.2166/wst.2022.304

Pastor-López, E. J., Casas, M. E., Hellman, D., Müller, J. A., & Matamoros, V. (2024). Nature-based solutions for antibiotics and antimicrobial resistance removal in tertiary wastewater treatment. *Water Research, 261*, 122038. https://doi.org/10.1016/j.watres.2024.122038

Patel, S., Mondal, S., Majumder, S. K., Das, P., & Ghosh, P. (2020). Treatment of pharmaceutical industrial effluent by a hybrid advanced oxidation–adsorption process. *ACS Omega*, *5*(50), 32305–32313. https://doi.org/10.1021/acsomega.0c04139

Ponce-Robles, L., Mena, E., Diaz, S., Pagán-Muñoz, A., Lara-Guillén, A. J., Fellahi, I., & Alarcón, J. J. (2022). Integrated full-scale solar CPC/UV-LED–filtration system as tertiary treatment. *Photochemical & Photobiological Sciences*, *22*(3), 641–653. https://doi.org/10.1007/s43630-022-00342-9

Rashid, A. (2024). Nano fullerenes with the ability to store electrostatic energy that can be used as nano supercapacitors with very high capacity. *DOI: https://doi. org/10.55277/researchhub. vq5dnd6h*.

Shah, A., & Shah, M. (2020). Characterization and bioremediation of wastewater: A review. *Groundwater for Sustainable Development, 11*, 100383. https://doi.org/10.1016/j.gsd.2020.100383

Shtepa, V., Balintová, M., Chernysh, Y., Chubur, V., Demčák, Š., & Gautier, M. (2021). Combined use of biological processes and AOPs in wastewater treatment. *Applied Sciences, 11*(16), Article 7551. https://doi.org/10.3390/app11167551

Tahraoui, H., Belhadj, A.-E., Triki, Z., Boudellal, N. R., Seder, S., Amrane, A., … Mihoubi, N. (2022). Mixed coagulant–flocculant optimization for pharmaceutical effluent pretreatment. *Process Safety and Environmental Protection*, *169*, 909–921. https://doi.org/10.1016/j.psep.2022.11.045

Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2003). *Wastewater engineering: Treatment and reuse* (4th ed.). McGraw-Hill.

Twi-Yeboah, N., Osei, D., Dontoh, W. H., Asamoah, G. A., Baffoe, J., & Danquah, M. K. (2024). Enhancing energy efficiency and resource recovery in wastewater treatment plants. *Energies, 17*(13), Article 3060. https://doi.org/10.3390/en17133060

U.S. Environmental Protection Agency. (1993). *Method 180.1: Determination of turbidity by nephelometry*. Environmental Monitoring Systems Laboratory.

Verlicchi, P., Aukidy, M. A., & Zambello, E. (2012). Occurrence of pharmaceutical compounds in urban wastewater: A review. *Science of the Total Environment*, *429*, 123–155. https://doi.org/10.1016/j.scitotenv.2012.04.028

Wondim, T. T., Dzwairo, B., Aklog, D., Janka, E., Samarakoon, G., & Dereseh, M. M. (2023). Wastewater treatment plant performance assessment using effluent quality indices. *Environmental Monitoring and Assessment, 195*(11), Article 1352. https://doi.org/10.1007/s10661-023-11952-w