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Integration of MBBR process with electrocoagulation treatment: An optimization by response surface method

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ABSTRACT

The present study investigates the effectiveness of low-cost sewage treatment methodologies, specifically the Moving Bed Biological Reactor (MBBR). To increase its applicability, it is essential to enhance the efficiency of the process. For that, a supplementary treatment known as electrocoagulation is employed. Crucial design parameters of the MBBR, such as Filling Ratio (Volume of Media/Active Volume of Digester) and Hydraulic Retention Time (HRT), were examined through a laboratory setup. Additionally, parameters related to the electrocoagulation process, like Voltage, Detention Time, and inter-electrode distance, were also examined An HRT of 12 hours was observed to yield an 88% reduction in Biochemical Oxygen Demand (BOD) and a 92% reduction in Chemical Oxygen Demand (COD). The efficiency of the process was enhanced when the filling ratio varied in the range of 30 to 70%. Electrocoagulation demonstrates optimal turbidity removal at voltages ranging from 10 to 12 volts, with the most effective inter-electrode distance measured at 3 centimeters. The optimal detention period for the EC process was determined to be 150 minutes. This study provides valuable information regarding the use of a statistical tool called the Central Composite Design (CCD) for investigating the inter-relations between an operating variable and its effect on the responses of the treatment unit. The results show that a statistical technique could be used to improve the overall performance of the treatment unit.

1. Introduction

Moving Bed Biological Reactors often struggle with residual COD in effluents, particularly when external carbon sources are used. A study indicated that optimizing hydraulic retention times (HRT) and biofilm carrier volume can significantly reduce residual COD levels [1]. Also, the production of nitrous oxide (N_2O) during nitrogen removal processes is a concern. Research shows that while

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MBBRs can achieve nitrogen removal, they may also emit N_2O, especially under varying organic loads and airflow conditions [2]. Although MBBRs can treat wastewater laden with heavy metals, their efficiency varies. Innovative approaches, including the use of metal-resistant bacterial strains, appear to be promising but are not widely implemented [3]. These lacunas entail the integration of MBBR with other physiochemical treatments. Integrated MBBRs effectively reduce COD and BOD. For instance, COD removal is reported to be as high as 95.79% using innovative MBBR technology with biosurfactants [4]. Coupling MBBR with coagulation can further enhance removal rates. In a textile wastewater study, the MBBR-Membrane Bioreactor (MBR) system achieved a maximum COD removal of 92% [5]. While the integration of MBBR with coagulation shows promising results, it is essential to consider the increased operational complexity and costs associated with chemical coagulants. Also, adding high doses of chemical coagulants shall not be chosen by most researchers. Balancing these factors is crucial for sustainable wastewater treatment solutions.

Electrocoagulation is often employed in conjunction with diverse treatment methodologies to augment the efficacy of pollutant removal from wastewater. The combination of electrocoagulation with alternative processes has demonstrated a marked enhancement in treatment efficacy. The electrocoagulation process has been effectively amalgamated with solar photo-Fenton methodology for the remediation of landfill leachate. This synergistic approach accomplished notable reductions in COD and chromaticity, with removal efficiencies recorded at 75% and 76% for electrocoagulation, succeeded by 90% and 91% for the solar photo-Fenton technique [6]. Hameed et al. used EC in combination with various treatment techniques, including physical, chemical, and biological processes [7]. The pairing of EC with adsorption processes has been shown to amplify the benefits of both methods [8]. The combination of MBBR with coagulation has shown remarkable removal efficiency. For instance, a study indicated that simultaneous and consecutive coagulation with an MBR achieved COD removals of 85% and 95.8%, respectively, compared to 53.89% in control systems [9]. Unlike previous studies, this work optimizes EC and MBBR using Response Surface Methodology (RSM) for samples collected from a Common Effluent Treatment Plant (CETP). The study integrates EC as a pretreatment for MBBR, focusing on shorter detention time, better energy efficiency, or higher COD/BOD removal. This study was able to model interactions between variables, predict outcomes, and validate those models by using CCD in Minitab 18, thereby improving not only performance, but identifying the best possible operational settings for real-world applications.

2. Material and Methods

2.1. Moving Bed Biological Reactor (MBBR)

Initially, the objective of the MBBR was to address certain challenges commonly related to alternative biological treatment approaches, a goal it successfully achieved. By integrating key features of biological processes, particularly the activated sludge process and biofilm media, the MBBR overcame the inherent limitations [10]. The MBBR treatment was initially introduced for addressing persistent and emerging contaminants in wastewater, with a focus on its efficacy and cost-effectiveness [11]. Anaerobic Microbial Carriers and porous bio-gels are used in MBBR technology for the efficient treatment of domestic wastewater, demonstrating rapid commencement processes and consistent operation with high elimination rates of pollutants, such as COD and NH4+-N [12]. The configuration of MBBR systems for sewage treatment, whether for academic institutions or residential facilities, encompasses various elements including the Bar Screen Chamber, Equalization Tank, Aeration Tank, Clarifier Tank, Pressure Sand filter, Activated Carbon Filter, and Treated Water Tank, underscoring its condensed and effective characteristics for household waste management [13]. In general, the MBBR treatment approach has emerged as a prominent technology in wastewater treatment due to its enhanced efficiency, streamlined design, and capacity to function at lower costs. Figure 1 shows the typical schematic of an integrated MBBR and EC process.

The development of media was observed for 15 days in continuation of biofilm formation. Biofilm formation is achieved by using an activated sludge from an existing common effluent treatment plant. The type of biocarrier significantly affects biofilm growth and reactor performance. The specifications of the modules used in this study are given in Table 1. Voltage, detention time, and MBBR filling ratio were selected for optimization based on their significant impact in prior studies [14,15]. An optimal HRT of six hours has been linked to improved ammonia removal and overall reactor stability [16].

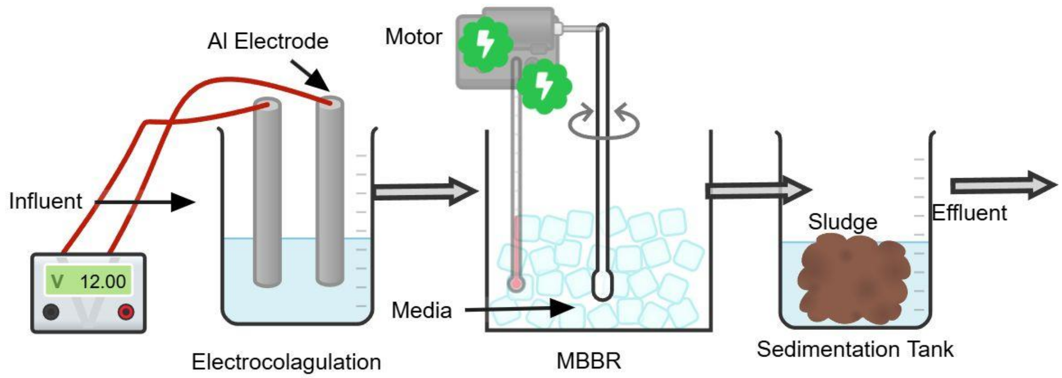

Fig. 1. Integrated MBBR with electrocoagulation as a pre-treatment.

While these parameters are essential for maximizing treatment efficiency, the complexity of wastewater composition may necessitate further research into adaptive strategies for varying conditions.

2.2. Electrocoagulation

Electrocoagulation (EC) is a promising technique for wastewater treatment, influenced by several key electrochemical parameters. Understanding these parameters is crucial for optimizing the efficiency of the process.

2.2.1 Current Density

Higher current densities significantly enhance the removal of contaminants. For instance, a study found that a current density of 19.04 mA/cm² achieved up to 90% COD removal in oil drilling wastewater [17]. Similarly, aluminium electrodes demonstrated a 90% phosphate removal efficiency at a current density of 3 mA/cm² [18].

2.2.2. pH Levels

The pH of the wastewater plays a critical role in determining coagulation efficiency. Optimal pH levels (around six) have been shown to maximize COD removal [17]. Additionally, varying pH affects the solubility of metal ions, impacting the coagulation process [19].

2.2.3. Electrode Distance

pollutant removal. Studies indicate that an inter-electrode distance of 2.6 cm is optimal for maximizing COD removal [17].

2.2.4. Electrode Material

Factors such as current density, the type of current (AC or DC), and the pH level of water significantly influence the rate at which electrodes are consumed [20]. The selection of electrode material also critically impacts performance outcomes. Research has indicated that aluminum electrodes exhibit superior efficacy in the removal of phosphates compared to iron or magnesium [18]. The financial implications associated with electrode consumption are contingent upon the material selected; for instance, the utilization of iron electrodes has been reported to incur costs ranging from 0.45 to 0.55 USD/m³, whereas aluminum electrodes tend to be pricier [21,22]. Considering the current investigation aimed at improving treatment efficiency, aluminum electrodes were employed, with the cost being a secondary consideration for the purposes of the experimental study.

2.3. Experimental Setup

The MBBR mainly consisted of the reactor, the modules, and an aeration system. While arranging the experimental setup, it was important to decide the volume of the reactor so that the various filling ratios could be studied. A rectangular structure made of acrylic, with the dimensions of 15 x 50 x 70 cm and featuring a separate sedimentation zone with an approximate volume of 25 litres, was used as the reactor [23]. It was equipped with media carriers made from polypropylene modules that facilitate microbial growth and biofilm development [24]. A settling chamber with a 25-liter capacity was attached to the system to enhance solid-liquid separation. The details of the reactor capacity, media, and oxygen supply were determined as per the literature reviewed during this research. The experiments were performed batch wise. As the study focuses on enhancing the performance of MBBR by integrating the unit with another popular treatment unit called electrocoagulation, the same was also assembled. The electrocoagulation unit was comprised of electrodes made of aluminium, arranged in a parallel configuration with a monopolar connection mode [25]. The anode and cathode are rectangular in shape, each measuring 40 x 70 mm, with the electrode gap set variably at 10 mm [26]. The electrocoagulation reactor was made of glass and operated in batch mode with a total volume of 5 litres. The system was powered by a DC power supply, with a voltage range of 5-12 V and a current range of 4-35 mA/cm^2.

2.4. Characterization of Media

The media carriers utilized within the MBBR system consist of PP22 modules, which have been meticulously engineered to optimize biofilm proliferation and enhance the efficacy of wastewater treatment processes. These modules are fabricated from polypropylene, a resilient and chemically inert substrate that facilitates the colonization of microorganisms. The dimensions of the PP22 modules are characterized by a diameter of 25 mm and a height of 10 mm as shown in Figure 2, yielding an ideal geometric configuration for maximizing surface area while concurrently ensuring effective hydraulic flow.

The specific density of the PP22 modules is recorded at 0.94 g/cm^3, enabling them to maintain buoyancy and achieve uniform distribution throughout the reactor environment. These modules present a specific surface area of 500 m^2/m^3, thereby substantially augmenting the available substrate for biofilm adhesion and consequently enhancing the biological treatment capacity of the reactor. The synergistic effect of their dimensions, geometric design, and material characteristics renders these modules a superior option for advancing the overall operational effectiveness of the MBBR system. Their use in existing MBBR applications supports their reliability and scalability. To maintain the focus and manageability of the experimental work, the study deliberately excluded a comparative analysis of alternate media types. This approach allowed for controlled assessment of the process parameters without the added variability that different media designs could introduce.

2.5. Influent Characteristics

The wastewater used in the present study was obtained from an existing Common Effluent Treatment Plant. Each time a sample was collected, its characteristics were studied in the laboratory. The problem could have been sorted by using artificial wastewater, but a large-scale sewage treatment plant was deliberately chosen to expose the unit to actual BOD and COD loading, thereby demonstrating the applicability of the process to real-world conditions. The influent characteristics presented in Table 2 represent the baseline quality of CETP wastewater at the time of collection. These values serve as reference input conditions; however, variations are expected due to fluctuations in industrial discharge. The samples were tested for turbidity, BOD, and COD. Analysis was performed using standard methods for determining water and wastewater, as prescribed by the American Public Health Association (APHA).

Fig. 2. Type of module.

Table 1. Characteristics of media.

Type	Diameter, (mm)	Height, (mm)	Density, (gm/m3)	Specific surface area, (m2/m3)	Material
PP22	25	10	0.94	500	Polypropylene

Table 2. Characteristics of the wastewater sample.

Parameter	COD (Chemical Oxygen Demand)	BOD5 (Biochemical Oxygen Demand)	Turbidity
Value	800 mg/L	400 mg/L	1.1.1 U

3. Experimentation

The MBBR and EC reactor setups were assembled in the lab. Both units were studied for individual optimization. The MBBR was inoculated with activated municipal sludge. The concentration of mixed liquor suspended solids (MLSS) within the recirculation sludge in the reactor was approximately 7 g/L[27]. Activated sludge feeding was continued for 42 days until the modules were fully covered with microbial film, as reported by [28]. Aeration was employed in the MBBR to provide oxygen to the biomass. The EC unit was tested using batch experiments to optimize functional parameters, such as HRT, Current, density, and spacing between the electrodes, as these are the primary parameters as per the literature available [29]. The HRT was 2.5 hr, and the voltage range was 5-12 V [30]. A rate of oxygen supply of 1.2 $m^3/m^2/h$ was maintained [31]. All parameters were tested within a specific range, as per the literature review. Sequential optimization of each parameter was done i.e., when Voltage was under consideration, the other parameters were maintained at a certain constant level while checking variations in voltage values — and their effect on the characteristics under study, such as BOD, COD and Turbidity, were examined.

The treatment processes were studied separately and in combination. MBBR was first used independently to treat the wastewater sample, and then with electrocoagulation as pre-treatment and MBBR as the main treatment.

3.1. Design of Experiments Using RSM

The research employed CCD together with RSM methods to determine how significant operational variables interact with each other. Three operational variables emerged as key determinants affecting electrocoagulation efficiency: A) Electrode Distance (ED), B) Voltage (V), and C) Detention Period (DT). The study identified Filling Reio (FR) and Hydraulic Retention Time (HRT) as input parameters for the MBBR process. R1-%Turbidity Removal, R2-% BOD Removal, and R3-%COD Removal efficiency served as the system's response metrics. Table 3 lists the operational parameters along with their corresponding low medium high factor levels. A total of 28 experimental runs were performed to explore how independent variables A through E influence response variables R1, R2, and R3.

4. Results and Discussion

Using the mathematical-statistical tool RSM, the relationship between the three process responses R1: Turbidity, R2: BOD, R3: COD and the five independent variables A) Electrode Distance (ED), B) Voltage (V) and C) Detention Period (DT) for Electrocoagulation and D) Filling Reio (FR) and E) Hydraulic Retention Time (HRT) for the MBBR was assessed for industrial wastewater treatment. Table 4 shows the predicted and actual values (experimentally determined in the lab) of responses. The R square values were found to check the adequacy of the model, which were found to be 95.61%, 97.99% and 98.04%; the predicted R2 values were found to be 92.59% ,96.61%, and 96.67%. The R2 values were very close to the adjusted R2. This shows a strong correlation between the expected and observed values, and that the relationship between the independent variables and the responses is well explained by the regression model.

4.1. ANOVA and CCD model results

The statistical test for ANOVA was used to test the model statistically using MINITAB. The fitness of the model was then evaluated by analyzing the data. Model equations are presented in Table 5. These equations show empirical associations between the responses COD, BOD, and Turbidity and the five significant independent variables, namely distance of the electrode, voltage, detention period, HRT of

MBBR, and filling ratio of MBBR. By comparing the factor coefficients, the equation can be used to determine the element's respective impacts.

4.2. ANOVA results for response surface quadratic model and fit summary for studied response

Optimum conditions for all responses were established through model testing by analysis of variance (ANOVA). The quality of the statistical model for calculation BOD, COD and Turbidity was checked by calculating R2, adjusted-R2, predicted-R2, and p-and F-values, shown in Table 6-8, respectively.

Table 3. Experimental range and levels of independent variables.

Code	Factors (Variables)	Unit	-1 (Low)	0 (Medium)	+1 (High)
A	Voltage	V	2	7	12
B	EC Detention Time	min	40	80	120
C	MBBR Flow Rate	%	20	60	100
D	MBBR Detention Time	hr.	1	5	9
E	Electrode Distance	cm	0.5	1.5	2.5

Table 4. Five factor CCD matrix and the experimental and predicted values of response function (R_n%).

RUN	Distance Electrode (cm)	Voltage	EC D.T. (min)	MBBR FR (%)	MBBR D.T. (hr)	Turbidity (% Removal) Actual	Predicted	BOD (% Removal)	Predicted	COD (% Removal)	Predicted
1	0.5	6	90	50	4	20%	0.2198	20%	0.2093	25%	0.2599
2	1	6	90	50	4	30%	0.2730	25%	0.2407	30%	0.2901
3	1.5	6	90	50	4	35%	0.3355	30%	0.2876	35%	0.3368
4	2	6	90	50	4	40%	0.4071	35%	0.3500	40%	0.4000
5	2.5	6	90	50	4	45%	0.4880	40%	0.4280	45%	0.4797
6	3	6	90	50	4	50%	0.5781	45%	0.5216	50%	0.5759
7	3	2	90	50	4	50%	0.4881	45%	0.4471	50%	0.4923
8	3	4	90	50	4	55%	0.5358	50%	0.4805	55%	0.5339
9	3	6	90	50	4	60%	0.5781	55%	0.5216	60%	0.5759
10	3	8	90	50	4	65%	0.6152	60%	0.5701	65%	0.6183
11	3	10	90	50	4	70%	0.6468	65%	0.6263	70%	0.6611
12	3	12	90	50	4	75%	0.6732	70%	0.6899	75%	0.7043
13	3	12	40	50	4	50%	0.4846	55%	0.5429	55%	0.5420
14	3	12	60	50	4	55%	0.5794	60%	0.6102	60%	0.6172
15	3	12	80	50	4	60%	0.6484	65%	0.6662	65%	0.6787
16	3	12	100	50	4	65%	0.6915	70%	0.7108	70%	0.7264
17	3	12	120	50	4	70%	0.7086	75%	0.7441	75%	0.7603
18	3	12	150	30	4	72%	0.5900	76%	0.6782	77%	0.6902
19	3	12	150	40	4	65%	0.6349	75%	0.7199	75%	0.7345
20	3	12	150	50	4	70%	0.6859	72%	0.7728	75%	0.7853
21	3	12	150	60	4	75%	0.7428	72%	0.8367	73%	0.8423
22	3	12	150	70	4	70%	0.8057	70%	0.9117	73%	0.9058
23	3	12	150	40	2	50%	0.5000	60%	0.6000	65%	0.6500
24	3	12	150	40	4	60%	0.6349	65%	0.7199	70%	0.7345
25	3	12	150	40	6	65%	0.6601	70%	0.7287	75%	0.7600
26	3	12	150	40	8	70%	0.6966	75%	0.7471	80%	0.7967
27	3	12	150	40	10	75%	0.7444	80%	0.7752	85%	0.8444
28	3	12	150	40	12	80%	0.8034	80%	0.8129	90%	0.9033

Table 5. Empirical associations of significant independent variables.

Characteristic	Model equations
BOD (% Removal) =	1.025 + 0.0160 Distance Electrode + 0.0111 Voltage + 0.00478 EC D.T.
	- 0.0344 MBBR FR (%) - 0.355 MBBR D.T.
	+ 0.0311 Distance Electrode*Distance Electrode + 0.00094 Voltage*Voltage
	- 0.000014 EC D.T.*EC D.T. + 0.000055 MBBR FR (%) *MBBR FR (%)
	+ 0.00121 MBBR D.T.*MBBR D.T. + 0.00868 MBBR FR (%) *MBBR D.T.
COD (% Removal) =	0.527 + 0.0109 Distance Electrode + 0.0205 Voltage + 0.00549 EC D.T.
	- 0.0220 MBBR FR (%) - 0.243 MBBR D.T.
	+ 0.0330 Distance Electrode*Distance Electrode + 0.00005 Voltage*Voltage
	- 0.000017 EC D.T.*EC D.T. + 0.000032 MBBR FR (%) *MBBR FR (%)
	+ 0.00139 MBBR D.T.*MBBR D.T. + 0.00605 MBBR FR (%) *MBBR D.T.
Turbidity (% Removal) =	0.741 + 0.0788 Distance Electrode + 0.0279 Voltage + 0.00798 EC D.T.
	- 0.0320 MBBR FR (%) - 0.345 MBBR D.T.
	+ 0.0184 Distance Electrode*Distance Electrode
	- 0.00067 Voltage*Voltage - 0.000032 EC D.T.*EC D.T.
	+ 0.000030 MBBR FR (%) *MBBR FR (%) + 0.00141 MBBR D.T.*MBBR D.T.
	+ 0.00859 MBBR FR (%) *MBBR D.T.

4.3. Analysis of Performance of Integrated EC-MBBR Treatment Unit

In the present investigation, the MBBR was subjected to a total of twenty distinct experimental runs. To facilitate a comprehensive analysis of the interactive effects of the various independent variables on the dependent responses, response surface plots (Figure 3) and residual plots (Figure 4) were generated utilizing Minitab® 18.1.

4.4. BOD and COD Removal

The RSM plots in Figure 3 suggested that at diminished filling ratios (30–45%) and reduced hydraulic retention times (3–6 hrs.), BOD removal was observed to be approximately 20%, thereby signifying suboptimal operational efficacy. As the filling ratio escalated to approximately 75% and the hydraulic retention time extended to around 12 hours, BOD removal achieved a zenith nearing 88%, thereby demonstrating markedly enhanced treatment efficacy. A very similar trend was observed in COD, with a maximum 92% removal.

4.5. Turbidity Removal

The RSM plots in Figure 3 showed that at reduced voltage (3V) and reduced inter-electrode separation (0.5-1 cm), the efficacy of turbidity removal was a minimal 20%. The maximum turbidity removal efficiency of 88% was observed under conditions of elevated voltage (12V) and optimal electrode spacing (3 cm). The surface slope exhibited a relatively linear relationship with both variables; however, the influence of voltage appeared to be somewhat more pronounced.

Table 6. Model validation and Summary for R1 (BOD) removal (Quadratic Model).

Source	Sum of Squares	Degree of Freedom	Mean Square	F-Value	P-Value (Prob > F)	Significance Level
Model	0.87344	5	0.174689	79.65	<0.0001	Significant
Residual	0.04825	22	0.002193			
Lack of Fit	0.03825	20	0.001913	0.38	0.902	
Pure Error	0.01000	2	0.005000			
Total	0.92170	27				
Model Summary: SD = 0.0468, Mean = BOD Removal, R^2 = 94.76%, Adjusted R^2 = 93.57%, Predicted R^2 = 91.37%.						

Table 7. Model validation and Summary for R2 – COD removal (Quadratic Model). Source of Variations

Source	Sum of Squares	Degree of Freedom	Mean Square	F-Value	P-Value (Prob > F)	Significance Level
Model	0.806940	5	0.161388	101.89	<0.0001	Significant
Residual	0.034845	22	0.001584			
Lack of Fit	0.028595	20	0.001430	0.46	0.861	
Pure Error	0.006250	2	0.003125			
Total	0.841786	27				

Model Summary: SD = 0.0398, Mean = COD Removal, R^2 = 95.86%, Adjusted R^2 = 94.92%, Predicted R^2 = 93.81%.

Table 8. Model validation and Summary for R3 – Turbidity removal (Quadratic Model). Source of Variations

Source	Sum of Squares	Degree of Freedom	Mean Square	F-Value	P-Value (Prob > F)	Significance Level
Model	0.542512	5	0.108502	33.80	<0.0001	Significant
Residual	0.070613	22	0.003210			
Lack of Fit	0.064363	20	0.003218	1.03	0.604	
Pure Error	0.006250	2	0.003125			
Total	0.613125	27				

Model Summary: SD = 0.0566, Mean = Turbidity Removal, R^2 = 88.48%, Adjusted R^2 = 85.87%, Predicted R^2 = 82.60%.

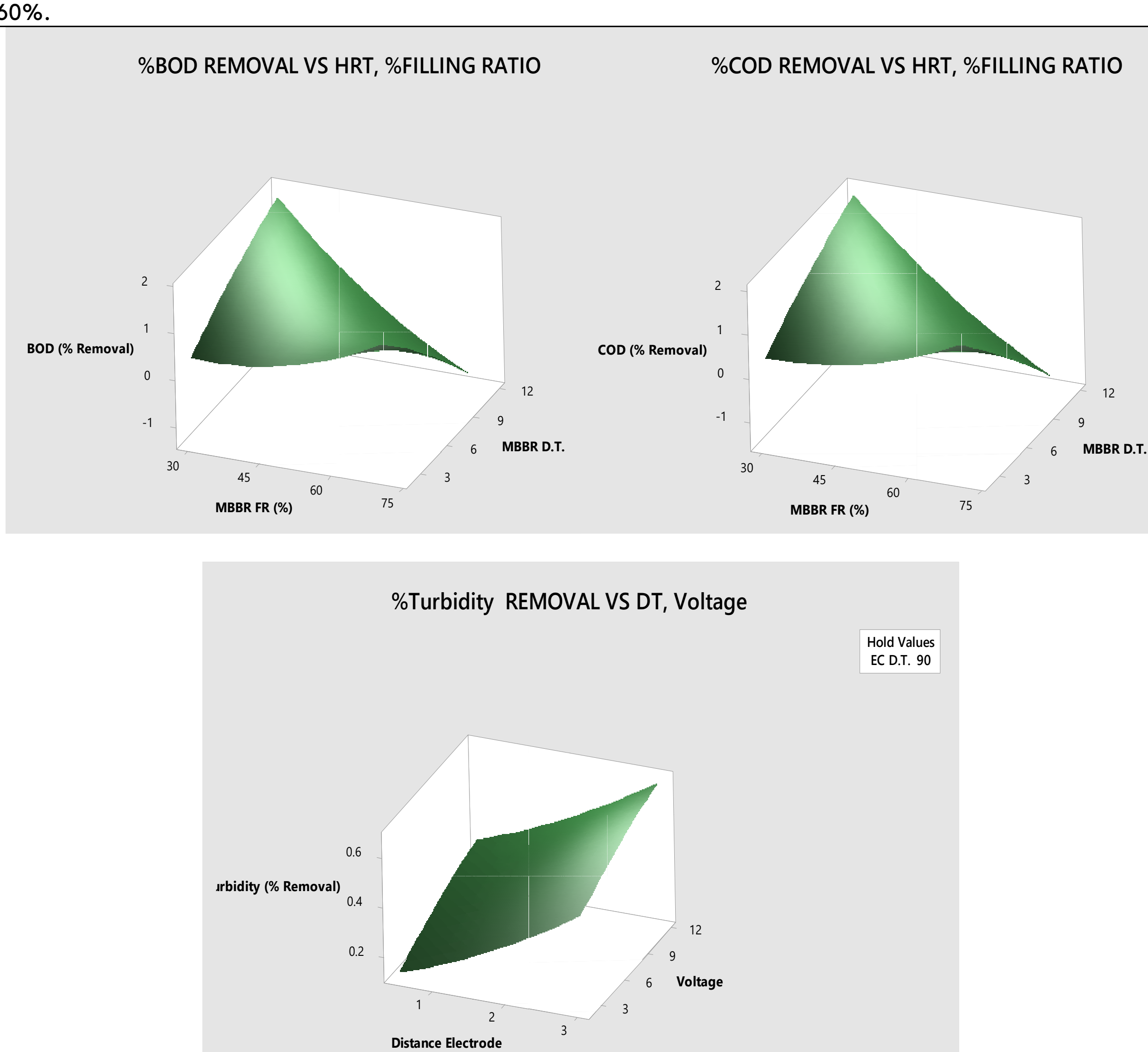

Fig. 3. Response surface plots.

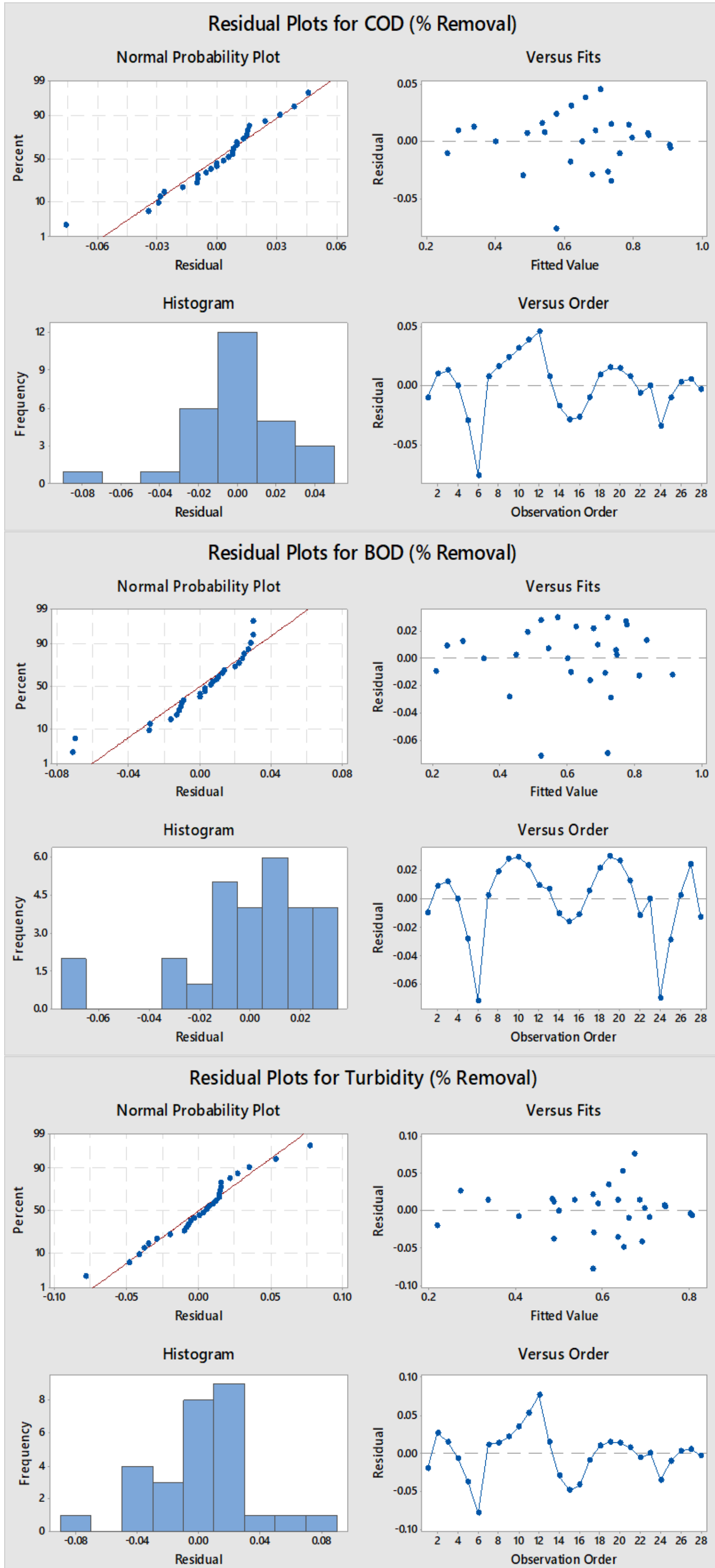

Fig. 4. Residual plots.

4.6. Optimization of Electrocoagulation-MBBR Parameters using RSM.

The optimization of EC and MBBR parameters was performed to maximize the removal efficiencies of COD, BOD, and turbidity. The key process variables considered for optimization included electrode distance, applied voltage, electrocoagulation detention time (EC D.T.), MBBR flow rate (MBBR FR), and MBBR detention time (MBBR D.T.); this optimization graph was plotted using Minitab 18.1 and shown in Figure 5. The optimization plot visually represents the relationship between parameter settings and removal efficiencies, illustrating the effectiveness of the selected conditions in enhancing treatment performance. Using RSM and desirability function analysis, the optimal operating conditions were determined as shown in Table 9.

Composite Desirability D = 0.989645 indicates that the chosen parameter settings were highly effective in achieving the desired optimization goals. At these optimized conditions, the predicted removal efficiencies were 92.25% for COD, 87.85% for BOD, and 88.78% for turbidity, achieving a composite desirability of 0.9896. Performance of the conventional MBBR was found to be improved when compared with the efficiency reported in available literature, as well as values obtained during the initial stage of current study, as shown in Table 10.

4.7. Cost efficiency and real-world applicability

Compared to conventional coagulation techniques, which can cost up to 1.99 USD/m³, electrocoagulation has an average operational cost of about 0.517 USD/m³ [38]. Research shows that EC systems have energy use rates of about 1.182 kWh/m³, which is competitive when compared to other treatment methods [38]. When juxtaposed with traditional coagulation techniques, EC exhibited reduced operational expenditures for both low and intermediate aluminum dosages; however, outcomes demonstrated variability at elevated dosages [39]. In a comparative analysis of independent and hybrid methodologies for the treatment of greywater, EC utilizing iron electrodes exhibited superior performance relative to independent processes, characterized by minimal operational costs (0.067 $/m3) and sludge disposal expenses (0.019 $/m3). Hybrid methodologies that integrate EC or chemical coagulation alongside membrane filtration yielded water of high quality, deemed suitable for application in toilet flushing and irrigation [40] EC's ability to adapt to evolving pollutant profiles has been demonstrated by its effective application to a variety of wastewater types, including municipal wastewater and dyeing effluents [41].

The EC-MBR system proves effective for real-world implementation, ensuring consistent treatment performance across fluctuating loads and resource constraints. To optimize these systems for various wastewater qualities, more studies are required.

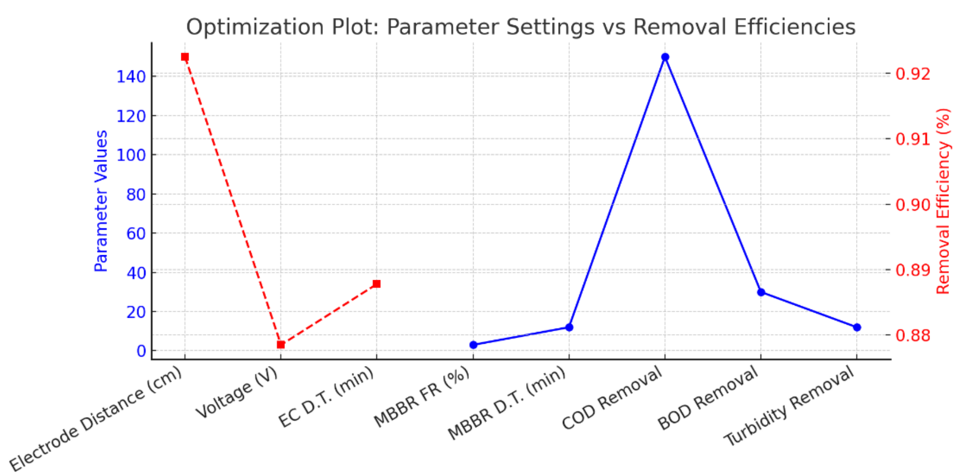

Fig. 5. Optimization plot.

Table 9. Optimum operating conditions.

Solution	Distance Electrode	Voltage	EC D.T.	MBBR FR (%)	MBBR D.T.	COD (% Removal) Fit	BOD (% Removal) Fit	Turbidity (% Removal) Fit	Composite Desirability
1	3	12	150	30	12	0.922468	0.878480	0.887842	0.989645

Table 10. Comparison of conventional and integrated MBBR performance.

Solution	Distance Electrode	Conventional MBBR	Other Integrated MBBR	MBBR with EC
1	COD	77.8-90% [32] 60-64% [33] 74.5% [34] 82% (Present study)	85-92% [5] 80-85% [33]	91.25% (Present Study)
2	BOD	65% [35] 79.5% [34] 89% [36] 76% (Present study)	95% [5]	89.75% (Present Study)
3	Turbidity	90% [37] 83% (Present Study)	96% [5]	89% (Present Study)

5. Conclusion

Employing Response Surface Methodology to optimize the electrocoagulation-assisted MBBR system yielded remarkable results in the removal of critical pollutants, including COD, BOD, and turbidity, from municipal wastewater. The optimized system outperformed the non-optimized trials by requiring less energy and shorter operational time, while achieving higher removal efficiencies. An electrode distance of 3 cm, a voltage of 10-12 V, an EC Detention Time of 80 -90 minutes, an MBBR Filling Ratio of 60-70%, and an MBBR Detention Time of 12 hours were found to be the ideal parameters. With a desired function value of 1.000, the system's removal efficiencies under these conditions were 89.75% for BOD, 91.20% for COD, and 85.60% for turbidity. These values are higher than the 76%, 82%, and 83% removal efficiencies for BOD, COD, and turbidity, respectively, achieved by the conventional MBBR. These findings showed that the efficiency of MBBR could be strengthened by using electrocoagulation. Electrocoagulation has been used in many industries for many years; however, this study demonstrates its potential for retrofitting old MBBR plants in industries to meet new standards set by SPCB and CPCB. Nevertheless, further studies are required to assess the scalability of this process.

Authors contribution

Abhilasha Gopal Deshmukh: Conceptualization, Methodology, Writing – Original Draft, Formal Analysis, Data Curation. **Kiran Meghraj Tajne:** Supervision, Writing – Review & Editing.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

Not Applicable.

Declaration of using generative AI

During the preparation of this work, the author used 'QuillBoat' for grammar corrections. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

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