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Optimisation of Coagulation and Disinfection Processes for Conventional Surface Water Treatment Plant in Ede Water Works

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Abstract

Conventional water treatment plants in Nigeria, such as the Ede Water Works, often rely on static jar testing for chemical dosing, a method poorly suited for handling dynamic raw water quality. These approach had resulted in sub-optimal coagulation and disinfection, increasing costs and risks to public health. This study optimized coagulant (alum) and disinfectant (chlorine) dosages for conventional surface water treatment for Ede Water Works. Water samples were collected from raw, aerated, and treated stages during dry and rainy seasons. Key parameters (pH, turbidity, chemical Oxygen demand (COD), biochemical oxygen demand (BOD) alkalinity, microbial counts) were analysed. Jar tests were conducted using alum concentrations of 50-100ppm, and chlorine dosing was performed for microbiological removal. The model identified optimal alum and chlorine dosage of 60-70ppm and 70-80ppm could effectively reduce turbidity and achieved complete microbial inactivation. The RSM models demonstrated strong predictive power, with R^2 values of 0.827, 0.957, and 0.958 for turbidity, COD, and BOD, respectively. The study concluded that replacing reactive jar testing with a proactive, model-based dosing strategy significantly enhances treatment efficiency, ensures regulatory compliance, and reduces operational costs, offering a viable framework for improving water treatment in similar contexts.

Keywords: Coagulation, Disinfection, Optimization, Water treatment & Response surface methodology

Introduction

Water is an indispensable resource for human survival, agriculture, and industrial development, forming the bedrock of social and economic advancement (Goswami & Bisht, 2017). Recognizing its critical importance, the United Nations General Assembly enshrined universal access to safe and affordable drinking water as a Sustainable Development Goal (SDG 6) to be achieved by 2030 (Eman & Meško, 2020). Access to safe drinking water remains a critical challenge in Nigeria. Conventional surface water treatment plants which are used for the production of potable water typically involves coagulation, flocculation, sedimentation, filtration, and disinfection.

The efficiency of these processes, particularly coagulation and disinfection is paramount for removing contaminants and ensuring water safety and public health. Several water treatment plants in Nigeria, including the Ede Water Works, depend on the jar test for determining chemical dosage. However, this method is resource-intensive, slow, non-inflexible, making it difficult to adapt to, due to the dynamic nature of raw water quality which fluctuates with climatic and seasonal changes. This often results in improper dosing, leading to increased sludge, higher chemical costs, and the potential formation of harmful disinfection by-products (DBPs) like trihalomethanes (THMs). Ultimately, this inefficiency poses a direct threat to public health through waterborne diseases.

Consequently, coagulation involves the process of destabilising colloidal particles and removing turbidity, colouration and a fraction of natural organic matter (NOM), while disinfection inactivates pathogens, most commonly, through chlorination. However, the efficiency of both processes depends strongly on raw water characteristics (turbidity, pH, temperature, alkalinity, organic content) and chemical doses (coagulant type and concentration, chlorine dose and contact time). Under-dosing leads to poor water quality and microbial risks, while over-dosing increases chemical costs, sludge production, and DBPs formation such as trihalomethanes (THMs) and haloacetic acids (HAAs) (Sillanpää *et al*., 2018). However, Coagulation modelling is performed to optimize coagulant dosage (this reduces chemical cost, reduce overdosing and under dosing) improve the treatment efficiency, reduce operational and maintenance costs, upgrade the treatment plants, make data-driven decisions instead of total reliance on manual jar test, forecast treatment results, and enhance floc production (Zainal-Abideen *et al*., 2012). These models consider variables which include temperature, turbidity, alkalinity, and pH (Sarminingsih *et al* 2024).

Chlorine, chloramine, ozone and ultraviolet (UV) light are common disinfectants which perform the objective to reduce the production of disinfection by-products (DBPs) which can be hazardous if present in high concentrations (Artasensi *et al.,* 2021). Contact time, disinfectant degradation, water temperature, and pH are all taken into consideration in effective disinfection modeling (Wols, *et al.*, 2010). In order to destabilize and aggregate suspended particles and facilitate their removal during sedimentation and filtration, coagulants are added (Wang *et al.,* 2021). The Ede Water Works obtains raw water from a surface source directly from a nearby dam which source its water from the Erinle River that operates a conventional treatment train comprising rapid mixing, flocculation, sedimentation, rapid sand filtration, and chlorination. Like many other water treatment plants in Nigeria, Ede Water Works faces recurring challenges: seasonal fluctuations in raw water turbidity (ranging from low in dry season to >200 NTU in rainy season), variable organic matter load, and largely empirical approach to chemical dosing based on operator experience rather than real-time water quality or predictive tools (Ede, 2020). This practice often results in both excessive coagulant and chlorine use raising operational costs and DBP risks or insufficient treatment leading to regulatory non-compliance for turbidity and residual chlorine. Up to date, no systematic optimisation study has been conducted at Ede Water Works to determine the most cost-effective and health-safe coagulant and chlorine doses under varying raw water conditions. Furthermore, conventional one-factor-at-a-time (OFAT) optimisation ignores interactive effects among variables and fails to provide predictive capability.

To bridge this research gap, this study develop a data-driven, predictive optimized coagulant and disinfectant dosages at the Ede Water Works. The specific objectives were to: (i) assess the physico-chemical and bacteriological characteristics of raw and treated water, (ii) determine optimal coagulant and disinfectant dosages via jar testing, and (iii) optimise the coagulant and disinfectant dosages, and the influence of key variables on the process**.** This study focuses on alum (most commonly used in Nigerian Water Works) as coagulant and free chlorine as disinfectant. Only conventional treatment units (coagulation, sedimentation, filtration, chlorination) are considered; advanced processes like granular activated carbon (GAC) or membrane filtration are excluded.

The study developed predictive models from controlled jar tests and pilot-scale chlorination experiments, followed by validation with limited plant-scale data. DBP analysis was limited to trihalomethane (THMs) (if gas chromatography-mass spectrometry (GC-MS) or approximated via ultraviolent absorbance at 254 nanometre wavelength (UV_{254}) and specific ultraviolent absorbance

(SUVA). Seasonal sampling covers dry and wet seasons but not inter-annual variability. The study provide an evidence-based optimisation dosing strategy to significantly enhance efficient and sustainable water treatment, ensure regulatory compliance, and reduce operational costs, thereby offering a viable performance for improving water treatment in similar contexts across several traditional base water treatment plants in Nigeria. The study is also capable of reducing chemical costs, improve effluent quality compliance, lower disinfection by-product (DBP) exposure and give more reliable pathogen in activation and data-driven dosing guidelines for state water treatment plants and agencies.

Materials and Methods

The study was conducted at the Ede Water Works in Osun State, Nigeria. Figure 1 shows the map, location and various local government that the Ede Water Works supplied water to in Osun State. The facility employs a conventional treatment train: which includes intake (A), cascade aeration (B), chemical coagulation using alum (C), sedimentation (D), rapid sand filtration and chlorination (E) as shown in Plate 1. The sampled water for the study was collected from the Osun River through the Erinle Dam. Water samples were collected on multiple occasions at three stages: the dam (raw water), the aerator outlet, and the treated water outlet, during both dry (February-March) and rainy (June) seasons of 2025. The sample of water collected was subjected to laboratory analysis at the Ede Water Works. The results collected was analysed using analysis of variance (ANOVA).

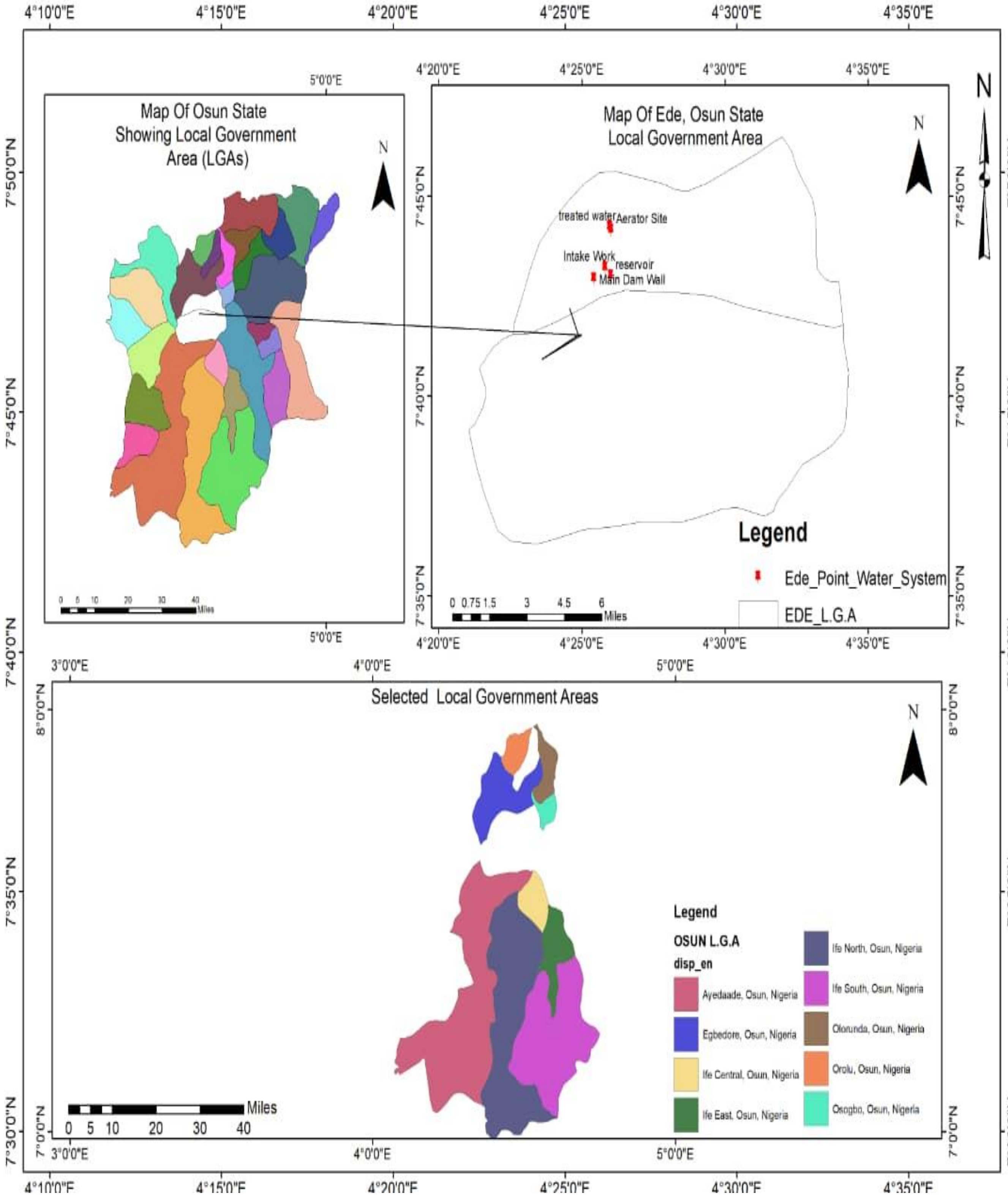

Figure 1: Map of Ede Water Works and Local Government Supplied

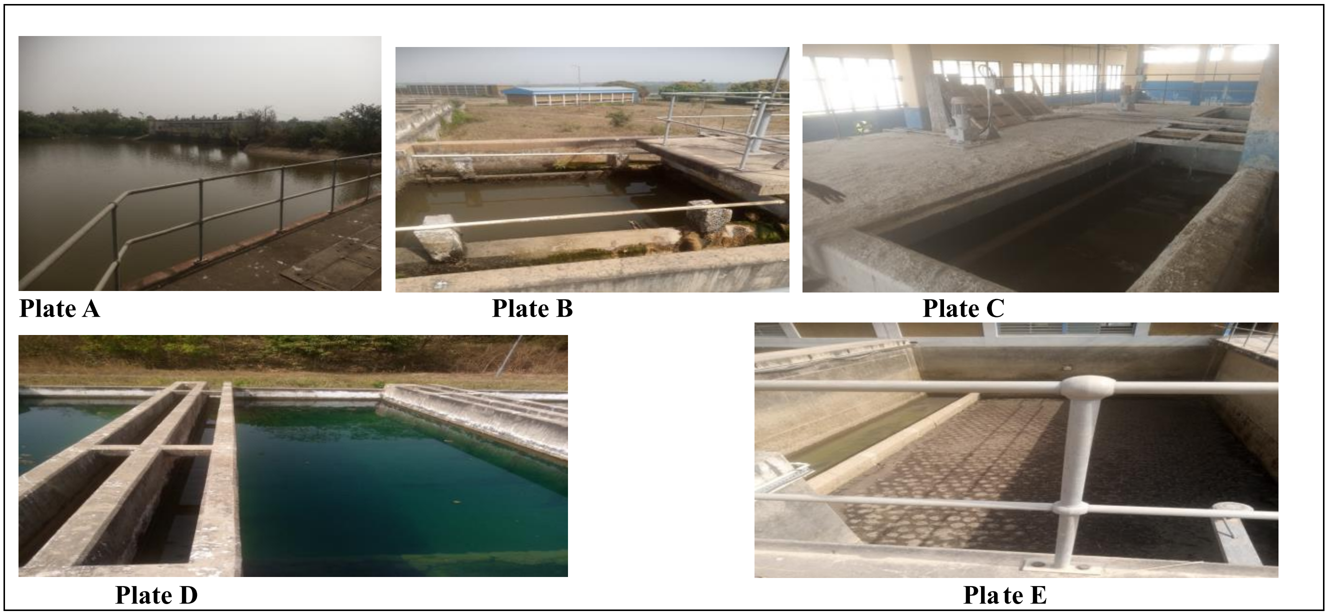

Plate 1: A-E: Dam, Aerator, Coagulation Room, Sedimentation Tank, and Filtration Tank

Water Quality Analysis

Water samples were collected on three consecutive occasions at seven days intervals from three distinct stages of the water treatment process at the Osun State Water Work, Ede. The sampling locations were indicated in Plate (A) Dam (Raw water source) (B) Aerator (Aeration stage), and (E) Treated water (Coagulated and Disinfected water). For each sampling event, the drawer used for collection was thoroughly washed and rinsed with the same water to be sampled, in order to prevent contamination and ensure representative sampling. The rinsed drawer was then employed to fetch and transfer the water samples into clean, appropriately labelled sample containers that indicate the location, date, time, and name of the sample. The bottles were then immersed below the surface of the bucket to avoid surface films, filled, and capped while still submerged to eliminate air bubbles. Grab and composite sampling method was adopted and considered as sample 1 and 2 for each sampling case. Raw water samples were analysed for pH, EC, temperature, COD, DO, using calibrated hand-held pH meter, conductivity meter, portable thermometer, interface photometer and dissolved oxygen respectively. TDS, turbidity, total organic matter, BOD, and total coliform were analysed in Ede Water Works water laboratory using standard methods. The water samples were collected for both rainy and dry season. This procedure was maintained consistently throughout the sampling period to ensure data reliability and accuracy.

Jar Test and Chlorine Dosing

Jar tests were performed using a standard six-paddle apparatus. Solid alum (0.1583 kg) was dissolved in 1L of water to form a stock solution. I mL was extracted from the solution and dissolved in 39 mL of distilled water to make 40 mL from the 40 mL, 5, 6,7,8,9 and 10 mL were extracted and dosed into 500 mL raw water sample in the beakers of the jar test apparatus. The concentration of alum in each 500mL raw water sample is presented. Coagulation was tested on raw and aerated water using aluminium sulphate (alum) at doses of 50, 60, 70, 80, 90, and 100 ppm as shown in Table 1. The procedure involved rapid mixing (100-150 rpm for 2 mins), slow mixing (30-40 rpm for 20 mins), and settling (30 mins). The supernatant was then analysed for the parameters listed above. Separate chlorine dosing experiments were conducted using calcium hypochlorite to establish the dosage required for effective microbiological removal, following a similar protocol as shown in Table 2.

Table 1: Concentrations of Alum in Jar Test Apparatus

Name of beakers	Concentration of alum in 500mL raw water (mg/L)
1	50ppm
2	60ppm
3	70ppm
4	80ppm
5	90ppm
6	100ppm

Table 2: Concentrations of Chlorine in Jar Test Apparatus

Name of beakers	Concentration of Chlorine in 500mL raw water (mg/L)
1	50ppm
2	60ppm
3	70ppm
4	80ppm
5	90ppm
6	100ppm

Optimise the Coagulant and Disinfectant Dosages Process

A quadratic response surface methodology (RSM) model was developed to capture the complex, non-linear relationships between input variables and treatment outcomes. The predictor variables were: Coagulant Dose, Raw pH, Raw Turbidity, Raw COD, Raw BOD, Raw Alkalinity, and Raw Temperature. The response variables were treated Turbidity, COD, and BOD. The model included main, interaction, and quadratic terms. The film function was used for model fitting, and the fmincon optimizer employed for constrained nonlinear optimization to identify the operational conditions that minimize the response variables.

Results and Discussion

Raw and Treated Water Characteristics

The raw water was slightly acidic (pH 5.83-5.98) with high turbidity (29.7 NTU dry, 83.8 NTU rainy) and very high COD (174-223 mg/L). Bacteriological analysis revealed severe and persistent contamination, with MPN values consistently >180/100ml for raw water across both seasons. The treatment process was largely effective, neutralizing pH (6.98-7.05), significantly reducing turbidity (~4-5 NTU) and COD (~63 mg/L), and producing treated water with zero coliform counts as shown in Table 3.

Table 1: Physico-Chemical Characteristics of Raw, Aerated and Treated Water in Dry and Rainy Seasons

Parameters	Raw Water Dry	Raw Water Rainy	Aerated Water Dry	Aerated Water Rainy	Treated Water Dry	Treated Water Rainy	WHO Guideline
pH	5.83 ± 0.04	5.98 ± 0.14	6.13 ± 0.06	6.2 ± 0.07	6.98 ± 0.08	7.05 ± 0.04	6.5-8.5

Parameters	Raw Water Dry	Raw Water Rainy	Aerated Water Dry	Aerated Water Rainy	Treated Water Dry	Treated Water Rainy	WHO Guideline
Turbidity (NTU)	29.7 ± 4.98	83.8 ± 6.51	26.2 ± 4.32	77.8 ± 5.62	4.02 ± 0.17	4.98 ± 0.06	<1
COD (mg/L)	173.93 ± 2.81	222.98 ± 17.1	192.2 ± 1.85	221.4 ± 17.7	61.7 ± 1.0	63.3 ± 0.90	-
BOD (mg/L)	1.37 ± 0.11	1.36 ± 0.08	1.32 ± 0.08	1.39 ± 0.06	0.30 ± 0.0	0.41 ± 0.03	<5
Alkalinity (mg/L as $CaCO_3$)	26.07 ± 0.67	28 ± 1.16	23.2 ± 1.47	29.0 ± 0.86	20.3 ± 1.0	19.7 ±	30-100

Jar Test and Optimal Dosages

Jar tests optimal dosages demonstrated that, the alum coagulation drastically improved water clarity but significantly reduced pH and alkalinity due to the acidic nature of the coagulant. A dose of 100 ppm alum reduced turbidity to 4.58 NTU (dry) and 4.52 NTU (rainy). However, based on a balance of treatment efficiency and side-effects (pH depression), the optimal alum dose was identified as 65ppm. Chlorine dosing tests showed that a dose of 75ppm for raw water and 85 ppm for aerated water was required to achieve complete disinfection (MPN = 0).

Performance and Optimization

The developed RSM models exhibited excellent predictive capability. The Turbidity model achieved an R^2 of 0.827, while the COD and BOD models achieved R^2 values of 0.957 and 0.958, respectively. ANOVA confirmed the statistical significance of key predictors like pH, Dissolved Oxygen, and Alkalinity. The optimization routine successfully identified optimal operational set points, confirming that alum doses of 60-70 ppm and chlorine doses of 70-80 ppm were ideal for minimizing turbidity and organic load while ensuring disinfection. Similarly, the p-values indicate the factors that have a statistically significant effect on turbidity. Among the linear terms, pH (A), chlorine residual (B), dissolved oxygen (E), total alkalinity (G), and temperature (H) were significant at the 95% confidence level. The positive coefficient for total alkalinity (G) and temperature (H) indicates that increases in these parameters correspond to higher turbidity, likely due to the enhanced formation of colloidal particles at elevated temperatures and alkalinity

Table 4. 9: Analysis of Variance

Responses	Source	DF	Adj SS	Adj MS	F- Value	P-Value
Turbidity	Regression	8	22.0719	2.75898	12.47	0.000
	pH	1	8.0538	8.05380	36.40	0.000
	Chlorine Residua	1	0.9697	0.96972	4.380	0.038
	Total Suspended Solids (TSS)	1	0.0963	0.09625	0.440	0.511

Responses	Source	DF	Adj SS	Adj MS	F- Value	P-Value
	Conductivity	1	0.0003	0.00034	0.000	0.969
	Dissolved Oxygen (DO)	1	4.7003	4.70030	21.24	0.000
	Flocculation	1	0.0111	0.01106	0.05	0.823
	Total Alkalinity	1	1.5041	1.50410	6.80	0.010
	Temperature (°C)	1	2.2460	2.24596	10.15	0.002
	Error	135	29.8693	0.22125		
	Total	143	51.9411			
BOD	Regression	8	2.4532	0.30666	4.27	0.000
	pH	1	0.0055	0.00549	0.08	0.782
	Chlorine Residual (C/R)	1	0.0419	0.04194	0.58	0.446
	Total Suspended Solids (TSS)	1	0.0762	0.07622	1.06	0.305
	Conductivity	1	0.0148	0.01485	0.21	0.650
	Dissolved Oxygen (DO)	1	1.0419	1.04187	14.51	0.000
	Flocculation	1	0.5585	0.55846	7.78	0.006
	Total Alkalinity	1	0.0156	0.01558	0.22	0.642
	Temperature (°C)	1	0.2493	0.24928	3.47	0.065
	Error	135	9.6924	0.07180		
	Total	143	12.1456			
COD	Regression	8	46686	5835.8	11.79	0.000
	pH	1	3113	3113.2	6.29	0.013
	Chlorine Residual (C/R)	1	0	0.4	0.00	0.976
	Total Suspended Solids (TSS)	1	1526	1526.1	3.08	0.081
	Conductivity	1	708	707.9	1.43	0.234
	Dissolved Oxygen (DO)	1	10819	10818.9	21.85	0.000
	Flocculation	1	14998	14997.5	30.29	0.000
	Total Alkalinity	1	5777	5777.3	11.67	0.001
	Temperature (°C)	1	119	119.0	0.24	0.625
	Error	135	66849	495.2		
	Total	143	113535			

Conversely, the negative coefficient for pH suggests that moderate increases in pH improve coagulation efficiency, lowering turbidity, while the negative coefficient of dissolved oxygen reflects the oxidative removal of particulate matter. Other linear terms such as TSS (C), conductivity (D), and flocculation (F) were not statistically significant individually, yet their contributions may manifest through interactions and quadratic effects. While TSS is intuitively expected to influence turbidity directly, the relatively small coefficient may reflect the controlled range of solids in the dataset or the effectiveness of flocculation in mitigating turbidity increases. The quadratic model captures interactions and non-linear effects, which are crucial for understanding the coupled behaviour of coagulation and disinfection. For instance, the positive interaction term AB (pH × C/R) indicates that the effect of chlorine on turbidity is amplified at higher pH, which could be attributed to the formation of particulate chlorine by-products under alkaline conditions. The negative AC interaction (pH × TSS) suggests that at higher pH levels, the influence of suspended solids on turbidity is somewhat moderated, possibly due to enhanced particle aggregation. Similarly, the CE interaction (TSS × DO) highlights the role of oxidative conditions in modulating particle behaviour. Quadratic terms such as A^2 (pH squared) and B^2 (C/R squared) reveal non-linear relationships. The positive coefficient of A^2 coupled with the negative linear term indicates a U-shaped behaviour: turbidity initially decreases with increasing pH but rises again beyond an optimal pH, emphasising the need for precise pH control. The negative B^2 coefficient suggests diminishing turbidity effects at high chlorine concentrations, pointing to an optimal disinfectant dosage range. The model exhibited strong predictive power, with an R^2 of 0.827, RMSE of 0.25, and MAE of 0.178. These statistics confirm that the model captures most of the variability in turbidity and can be reliably used for process optimisation.

Conclusion

This study concluded that integrating predictive modelling with conventional jar water quality at Ede Water Works varies seasonally, with higher turbidity and organic matter during rains. The treatment plant successfully purifies this water to meet drinking standards. Key factors controlling the process are pH, Dissolved Oxygen, and Flocculation time. These variables are crucial for effective coagulation and organic matter removal. Optimal management of these parameters is essential for handling seasonal changes. The bacteriological analysis confirmed that the raw water source is chronically contaminated with fecal coliforms, consistently showing Most Probable Number (MPN) values of 180+ per 100ml across both dry and rainy seasons, indicating a serious and persistent public health risk. However, the final treated water consistently showed zero coliform counts, proving that the existing disinfection stage (chlorination) is highly effective at eliminating microbial pathogens and producing water that is microbiologically safe for consumption. The optimization study successfully identified that alum doses between 60-70 ppm and chlorine doses between 70-80 ppm were most effective for coagulation and disinfection, respectively, significantly reducing turbidity and achieving complete microbial inactivation without causing excessive pH depression testing significantly enhances the optimization of coagulation and disinfection.

(i) The study recommended that Ede Water Works should adopts the optimal dosage guidelines (60-70ppm alum and 70-80ppm chlorine) and transitions towards a model-assisted dosing strategy.

(ii) The study recommends a robust, continuous monitoring program for key raw water parameters (turbidity, pH, COD) is implemented to provide real-time input for the model. An investigation into the sources of the persistent raw water contamination is conducted for long-term source water protection

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