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Analysis of the Effects of Chlorine Dosage and Detention Time on the Removal Efficiency of Iron (Fe), Total Dissolved Solids (TDS), and Turbidity

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ABSTRAK

Kadar besi (Fe) pada air baku di Instalasi Pengolahan Air (IPA) PDAM Kotagede Yogyakarta masih relatif tinggi sehingga berpotensi menyebabkan kualitas air tidak memenuhi standar air bersih. Sistem pengolahan yang diterapkan berupa kombinasi aerasi menggunakan *multitray aeration* dan klorinasi. Namun, pada kondisi pengolahan yang ada, proses klorinasi memiliki waktu detensi yang relatif terbatas sehingga efektivitas penyisihan besi belum optimal. Penelitian ini bertujuan untuk menganalisis pengaruh variasi dosis klorin dan waktu detensi terhadap efektivitas penyisihan besi (Fe), total dissolved solids (TDS), dan kekeruhan, serta menentukan kondisi pengolahan optimum. Penelitian ini menggunakan metode eksperimen kuantitatif dengan rancangan percobaan berupa variasi dosis klorin sebesar 0, 2, 4, dan 6 mg/L serta waktu detensi sebesar 0, 30, 45, dan 60 menit, dengan menghasilkan 16 kombinasi perlakuan. Parameter yang dianalisis meliputi besi (Fe), TDS, dan kekeruhan melalui pengujian laboratorium. Data dianalisis secara deskriptif dan menggunakan regresi polinomial untuk menentukan pola hubungan antara dosis klorin, waktu detensi, dan efektivitas penyisihan parameter kualitas air. Hasil penelitian menunjukkan bahwa efektivitas penyisihan besi (Fe) memiliki hubungan nonlinier terhadap dosis klorin dan waktu detensi, dengan koefisien determinasi (R^2) masing-masing sebesar 0,985 dan 0,934. Penyisihan besi tertinggi yang teramati diperoleh pada dosis klorin 4 mg/L dan waktu detensi 60 menit. Parameter TDS menunjukkan penyisihan yang relatif rendah, dengan konsentrasi terendah sekitar 254 mg/L, sedangkan kekeruhan menurun hingga sekitar 23,02 NTU pada kondisi perlakuan yang sama. Hasil tersebut menunjukkan bahwa dosis klorin 4 mg/L dan waktu detensi 60 menit merupakan kondisi perlakuan yang paling mendukung penyisihan besi, sedangkan pengaruhnya terhadap TDS dan kekeruhan relatif terbatas.

***Kata kunci*:** Besi (Fe), Dosis Klorin, Kekeruhan, Pengolahan Air, TDS, Waktu Detensi

ABSTRACT

Iron (Fe) concentration in raw water at the Water Treatment Plant (WTP) of PDAM Kotagede Yogyakarta remains relatively high and may cause treated water quality to fail compliance with drinking water standards. The treatment system applied consists of a combination of multitray aeration and chlorination. However, under the existing treatment conditions, the chlorination process has a relatively limited detention time, resulting in iron removal effectiveness that has not yet reached optimal performance. This study aimed to analyze the effect of chlorine dosage variation and detention time on the removal effectiveness of iron (Fe), total dissolved solids (TDS), and turbidity, as well as to determine the optimum treatment condition. This study employed a quantitative experimental method with experimental design consisting of chlorine dosage variations of 0, 2, 4, and 6 mg/L and detention times of 0, 30, 45, and 60 minutes, resulting in 16 treatment combinations. The analyzed parameters included iron (Fe), TDS, and turbidity through laboratory testing. Data were analyzed descriptively and using polynomial regression to determine the relationship pattern between chlorine dosage, detention time, and removal effectiveness of water quality parameters. The results showed that iron (Fe) removal effectiveness exhibited a nonlinear relationship with chlorine dosage and detention time, with coefficients of determination (R^2) of 0.985 and 0.934, respectively. The highest observed iron removal was achieved at a chlorine dosage of 4 mg/L and a detention time of 60 minutes. TDS showed relatively low removal, with the lowest concentration of approximately 254 mg/L, while turbidity decreased to approximately 23.02 NTU under the same treatment condition. These results indicate that the treatment condition of 4 mg/L chlorine dosage and 60 minutes detention time provided the most favorable observed condition for iron removal, while its effect on TDS and turbidity was relatively limited.

***Keywords*:** Chlorination, Detention Time, Iron (Fe), Turbidity, TDS, Water Treatment

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1. INTRODUCTION

The provision of clean water that meets quality standards remains one of the major challenges in the drinking water service sector. Access to clean water is a fundamental need that is essential for human and environmental well-being. From a quality perspective, adequate water supply and sanitation services are essential in supporting long-term environmental protection. The provision of clean water that meets quality standards is also an important aspect of drinking water services and the achievement of the Sustainable Development Goals (SDGs), particularly Goal 6 concerning Clean Water and Sanitation. One of the challenges in water treatment is maintaining the quality of raw water to comply with health requirements. Optimization of water treatment processes is therefore necessary to improve treated water quality and ensure access to safe and adequate clean water (Harlin et al., 2024).

One of the common water quality problems encountered in Indonesia is the high concentration of iron (Fe) in groundwater. Increasing urbanization and land-use changes may affect raw water quality by increasing the concentration of dissolved metals, including iron (Fe). Under reducing conditions, groundwater generally contains Fe in the form of relatively soluble Fe^{2+}, whereas exposure to oxygen can oxidize Fe^{2+} to Fe^{3+} and subsequently form insoluble iron compounds. This process may produce iron oxide particles that contribute to increased water color and turbidity (Buamah et al., 2009). Excessive iron concentrations can cause problems related to water color, taste, and turbidity, thereby reducing the quality of clean water. Based on operational data from PDAM Tirtamarta, the iron concentration in the raw water at the Kotagede Water Treatment Plant (WTP) remains above the maximum limit of 0.2 mg/L stipulated in Regulation of the Minister of Health of the Republic of Indonesia No. 2 of 2023 concerning the Implementation Regulation of Government Regulation No. 66 of 2014 on Environmental Health. This condition indicates the need to optimize the water treatment process to improve iron removal efficiency.

Groundwater containing Fe is commonly treated through oxidation followed by separation using sedimentation or filtration. Aeration is one of the widely applied methods because it supplies oxygen to oxidize Fe^{2+} into Fe^{3+}. Buamah et al. (2009) reported that iron removal from groundwater through aeration and filtration involves Fe^{2+} oxidation, floc formation, and adsorption onto the filter media. Febriyana and Masduqi (2020) also demonstrated that the combination of aeration and filtration can be applied to reduce Fe concentrations in groundwater. In addition to aeration, chemical oxidants such as chlorine can accelerate the oxidation of Fe^{2+}. The addition of chlorine may also be affected by the presence of chlorine-demanding substances in raw water. Iron and other reducing substances can consume chlorine, thereby reducing the amount of chlorine available for oxidation and disinfection. A positive relationship between iron concentration and chlorine demand has been reported in drinking water, indicating that water with higher iron concentrations may require greater chlorine consumption (Islam and Hossain, 2014). The chlorine demand is also influenced by the characteristics of the raw water and the concentration of reducing substances.

The formation of Fe oxidation products is also associated with changes in the physical characteristics of water, particularly turbidity. Fe oxidation can produce iron oxide or iron hydroxide particles that may initially occur as fine or colloidal particles. If these particles are not effectively separated through sedimentation or filtration, their presence may increase water turbidity. Shi et al. (2021) reported that iron particle formation during chlorine-related treatment processes can affect water turbidity and color. The relationship between Fe and turbidity has also been observed in water treatment systems, where iron particles can constitute one of the particulate components contributing to turbidity.

The Total Dissolved Solids (TDS) parameter differs in characteristics from Fe and turbidity. TDS represents the accumulation of various dissolved substances in water; therefore, changes in TDS are not solely determined by Fe but also by other dissolved ions. TDS was included as a supporting water quality parameter to evaluate whether the application of chlorine dosage and detention time resulted in measurable changes in dissolved substances during the treatment process. Although chlorination is primarily intended for disinfection and oxidation, monitoring TDS provides additional information on changes in the overall dissolved-solids characteristics of the treated water. Studies on groundwater quality have shown that TDS is associated with the presence of various inorganic ions and the hydrogeochemical characteristics of the water source. Unlike Fe and turbidity, TDS represents the total concentration of dissolved substances in water and is influenced by various inorganic ions and hydrogeochemical characteristics of groundwater (Valiallahi and Yazdani, 2025). Therefore, changes in TDS during Fe oxidation may differ from changes in Fe concentration and turbidity.

The Kotagede Water Treatment Plant (WTP) in Yogyakarta is one of the clean water treatment facilities that utilizes groundwater as its raw water source. The raw water at the Kotagede WTP contains naturally occurring iron resulting from interactions between groundwater and geological formations or soil layers, presenting a significant treatment challenge. The treatment system consists of a multitray aeration unit, sedimentation, filtration, and a reservoir. In the aeration unit, raw water containing dissolved iron (Fe) is brought into contact with atmospheric oxygen through multitray aeration. Oxidation occurs when Fe^{2+} reacts with oxygen to form Fe^{3+}, which subsequently forms insoluble $Fe(OH)_3$ precipitates that can be removed through

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filtration. However, under conditions of relatively high initial Fe concentrations, natural oxidation through aeration may not be sufficiently effective. Therefore, the Kotagede WTP applies chlorination as an additional oxidizing process to accelerate the oxidation of Fe^{2+} to Fe^{3+}. Chlorination is carried out in the sedimentation unit, which consists of two compartments: the first compartment is used for the sedimentation process, while chlorine is injected into the second compartment. The water then flows into the filtration unit and is finally stored in a reservoir before distribution. According to Kalvani et al. (2021), chlorine as a chemical oxidant can accelerate oxidation compared with natural oxidation by atmospheric oxygen. The combination of open aeration and chlorination has been reported to achieve an iron removal efficiency of 77.7%, which is higher than physical aeration without a chemical oxidant, which achieved only 57%.

Nevertheless, under the existing conditions at the Kotagede WTP, the chlorination process has a relatively limited detention time, resulting in suboptimal iron removal efficiency. In addition, chlorine addition to support the oxidation process may increase the residual chlorine concentration, which has shown fluctuations during certain periods and tends not to consistently meet the required quality standards. This condition indicates that chlorine application in the treatment system has not yet been fully optimized and requires further evaluation of the applied chlorine dosage and detention time.

Several previous studies have investigated Fe removal through the combination of aeration and filtration and the influence of operating conditions on Fe oxidation. Rosidah et al. (2025) reported that air–water contact and detention time affect the reduction of Fe concentration. Müller et al. (2024) also demonstrated that iron removal in groundwater treatment can involve multiple oxidation pathways, including homogeneous, heterogeneous, and biological processes, with the relative contribution of these pathways influenced by operational conditions such as aeration intensity. However, studies that specifically evaluate the combined effects of chlorine dosage and detention time on raw water at the Kotagede WTP while simultaneously assessing Fe, TDS, and turbidity remain limited. Previous studies have primarily focused on Fe removal or the combination of Fe with selected water quality parameters, whereas changes in TDS as an indicator of dissolved substances and turbidity as an indicator of the formation and separation of oxidation products have not been extensively investigated within a single chlorination treatment scheme.

Based on this research gap, this study aimed to evaluate the effects of chlorine dosage and detention time on Fe removal efficiency and changes in TDS and turbidity in aerated water from the Kotagede WTP, Yogyakarta. The study also aimed to determine the treatment condition associated with the highest observed Fe removal efficiency based on the tested chlorine dosages and detention times. TDS and turbidity were included as supporting water quality parameters to analyze changes in water quality during the treatment process. The results are expected to provide a basis for improving the treatment configuration at the Kotagede WTP and enhancing treated water quality.

2. METHODOLOGY

2.1. Study Area and Research Period

Administratively, the study was conducted in Prenggan Village, Kotagede District, Yogyakarta City, Special Region of Yogyakarta, Indonesia. The study site is located approximately 9 km from Universitas Pembangunan Nasional "Veteran" Yogyakarta. Geographically, the study area is located at coordinates X = 433200–433470 mE and Y = 9135600–9135920 mN. The research was conducted over a period of approximately four months, from December 2025 to March 2026. The study activities included water sampling, experimental treatments involving variations in chlorine dosage and detention time, and water quality analyses. Laboratory-scale experiments were carried out at the Waste and Pollution Management Laboratory, Department of Environmental Engineering, Universitas Pembangunan Nasional "Veteran" Yogyakarta.

2.2. Tools and Materials

The laboratory stage was conducted using a laboratory-scale experimental design with water samples collected from the outlet of the aeration unit prior to entering the sedimentation unit. The analyzed parameters included iron (Fe), total dissolved solids (TDS), and turbidity. Experimental treatments consisted of combinations of chlorine dosages of 0; 2; 4; and 6 mg/L and detention times of 0; 30; 45; and 60 minutes. The equipment used in this study included a flocculator for mixing, a turbidimeter for turbidity measurement, a TDS meter for TDS measurement, four 500-mL beakers, a measuring pipette, and sixteen 500-mL plastic containers used as sample storage vessels after treatment. The materials used consisted of 10 L of water samples, 12% sodium hypochlorite (NaOCl) solution as the chlorine source, 500 mL of NaOCl stock solution, and twelve sheets of Whatman No. 42 filter paper for sample filtration prior to laboratory analysis. Sodium hypochlorite (NaOCl) was selected because it is stable, easy to handle in laboratory-scale applications, and produces minimal additional residues that could interfere with water quality analyses during the oxidation process. Furthermore, NaOCl is widely used as an oxidizing agent in water treatment plant operations.

2.3. Research Procedure

2.3.1. Experimental Design

The experiment was conducted in the laboratory using a batch jar test method, with beakers serving as the experimental reactors. The jar test method was

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employed to evaluate the effectiveness of the water treatment process under various operating conditions at the laboratory scale (Adiono et al., 2025). In this study, the experimental treatments consisted of variations in chlorine dosage and detention time. The chlorine dosages applied were 0, 2, 4, and 6 mg/L. The selected dosage range was based on the study conducted by Kallista et al. (2023), which reported that chlorine dosages of 1-5 mg/L are sufficient to oxidize iron without causing over-chlorination. Therefore, the dosage variations used in this study were intended to represent low, medium, and high chlorine dosages commonly applied in water treatment processes.

The detention times applied in this study were 0, 30, 45, and 60 minutes. The selection of detention time variations was based on the ratio between the detention basin volume and the actual flow rate in the existing Kotagede WTP system. The calculation results indicated that, at a flow rate of 15.8 L/s, the detention time was approximately 26 minutes. Therefore, a detention time of 30 minutes was used to represent the existing operational condition, while detention times of 45 and 60 minutes were applied to simulate extended oxidation contact times. Longer detention times provide greater opportunities for the oxidation of Fe^{2+} by chlorine to occur, thereby enhancing the formation of $Fe(OH)_3$ precipitates. The experimental design flowchart is presented in **Figure 1**.

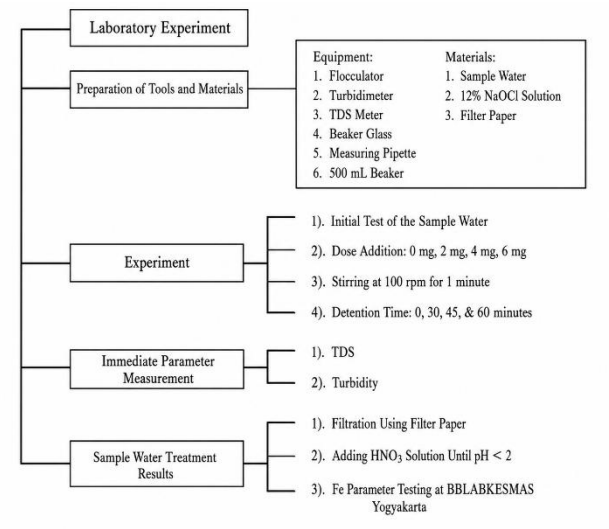


Figure1. Flowchart of Experimental Design

2.3.2. Water Quality Analysis

Water quality analysis was conducted on water samples collected from the outlet of the aeration unit prior to entering the sedimentation unit. Initial iron (Fe) concentration was analyzed at an accredited testing laboratory, namely the "Balai Besar Laboratorium Kesehatan Masyarakat" (BBLabkesmas) Yogyakarta. Meanwhile, measurements of total dissolved solids (TDS) and turbidity were carried out at the Waste and Pollution Management Laboratory, Department of Environmental Engineering.

Before treatment, the water samples were placed into 500-mL beakers for initial parameter measurements. TDS was measured using a TDS meter, while turbidity was measured using a turbidimeter. Prior to use, the TDS meter was calibrated with distilled water to ensure measurement accuracy. The initial parameter values were used as the baseline for evaluating removal effectiveness after treatment with variations in chlorine dosage and detention time.

2.3.3. Treatment with Chlorine Dosage and Detention Time Variations

The water samples were treated with chlorine at dosages of 0, 2, 4, and 6 mg/L. The chlorine solution was homogenized using a flocculator at a mixing speed of 100 rpm for 1 minute to ensure uniform chlorine distribution throughout the sample. After mixing, the samples were allowed to stand according to the predetermined detention times of 0, 30, 45, and 60 minutes. The experimental design consisted of 16 treatment combinations of chlorine dosage and detention time. Each treatment combination was applied to a separate water sample in an individual beaker and conducted once (n = 1). Thus, a total of 16 experimental conditions were analyzed. The treatment combinations applied in this study are presented in **Table 1**.

Table 1. Treatment Combinations

No.	Chlorine Dosage (mg/L)	Detention Time (Minutes)	No.	Chlorine Dosage (mg/L)	Detention Time (Minutes)
1.	0	0	9.	4	0
2.	0	30	10.	4	30
3.	0	45	11.	4	45
4.	0	60	12.	4	60
5.	2	0	13.	6	0
6.	2	30	14.	6	30
7.	2	45	15.	6	45
8.	2	60	16.	6	60

2.3.4. Sample Filtration and Preservation

After the designated detention times, the water samples were filtered using Whatman No. 42 filter paper before being transferred into sample containers. The filtration process was performed to separate $Fe(OH)_3$ flocs formed through the oxidation of Fe^{2+}, thereby preventing these precipitates from being measured as total iron during laboratory analysis. In addition, filtration was intended to minimize the influence of suspended flocs on TDS and turbidity measurements. Following filtration, water quality analyses were conducted to determine changes in TDS and turbidity concentrations. TDS was measured using a TDS meter, while turbidity was measured using a turbidimeter.

Subsequently, the samples were preserved with nitric acid (HNO_3) by gradually adding the acid using a dropper until the sample pH reached <2. The preserved samples were then transferred into 500-mL containers, tightly sealed, labeled according to the

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treatment combinations, and stored at room temperature away from direct sunlight prior to laboratory analysis. The preservation process was intended to maintain the stability of Fe concentrations after treatment with different chlorine dosages and detention times until final analysis was performed. Iron (Fe) concentrations were subsequently analyzed at an accredited laboratory.

2.3.5. Data Analysis

Removal effectiveness was calculated by comparing the initial concentration and the final concentration of each parameter after treatment with different chlorine dosages and detention times. The analysis was conducted to evaluate the effect of the treatment variations on the reduction of iron (Fe), TDS, and turbidity concentrations. Removal effectiveness was calculated using the following equation (Kusuma et al., 2019).

$$\sum p = \frac{A - B}{\mathrm{A}} \times 100\%$$

with:
Σp : Removal Effectiveness
A : Sample before treatment
B : Sample after treatment

Table 2. Sample Analysis Methods

Parameter	Unit	Method
Iron (Fe)	mg/L	SNI 06-6989.84-2019
TDS	mg/L	TDS Meter
Turbidity	NTU	Turbidimeter

Data analysis in this study was performed using polynomial regression to model the nonlinear relationship between independent and dependent variables. Polynomial regression is an extension of linear regression that incorporates higher order terms of the independent variable, enabling it to represent curvilinear relationships more effectively (Obidike & Madigoe, 2021). This method was employed to obtain a model that more accurately represents the observed data patterns and to describe the relationship between operational variables and treatment responses in water-treatment processes (Kim et al., 2016).

A second-order polynomial regression (quadratic regression) was applied to analyze the relationships between chlorine dosage and detention time and the removal effectiveness of iron (Fe), TDS, and turbidity. The use of second-order polynomial models is commonly applied in water-treatment experimental studies to describe the relationship between operating variables and treatment responses. The quadratic polynomial regression model is expressed by the following equation (Kim et al., 2016).

$$Y = \beta_0 + \beta_1 \mathrm{X} + \beta_2 \mathrm{X}^2 + \varepsilon$$

with:
Y : Dependent variable
X : Independent variable
β_0 : Constant (intercept)
β_1 : Linear regression coefficient
β_2 : Quadratic regression coefficient
ε : Error term (residual)

The constant term (β_0) represents the estimated value of the dependent variable when the independent variable is equal to zero. The linear regression coefficient (β_1) indicates the initial direction of change in the dependent variable as the independent variable increases. Meanwhile, the quadratic regression coefficient (β_2) is used to identify the nonlinear relationship between the independent and dependent variables. A negative quadratic coefficient indicates a downward-opening parabolic relationship, suggesting the existence of an optimum condition at a certain point. Conversely, a positive quadratic coefficient indicates an upward opening parabolic relationship, suggesting the presence of a minimum point in the relationship between the two variables (Kim et al., 2016).

The use of chlorine as an oxidant for Fe^{2+} removal is supported by previous experimental studies demonstrating that chlorine can effectively oxidize dissolved Fe^{2+} in water and that the oxidation rate is influenced by operational and water quality conditions such as chlorine to iron ratio and pH. Furthermore, factorial experimental approaches have been applied to evaluate factors affecting Fe^{2+} oxidation kinetics in drinking water, demonstrating the relevance of experimental statistical approaches for assessing the effects of treatment variables (Wong et al., 2014).

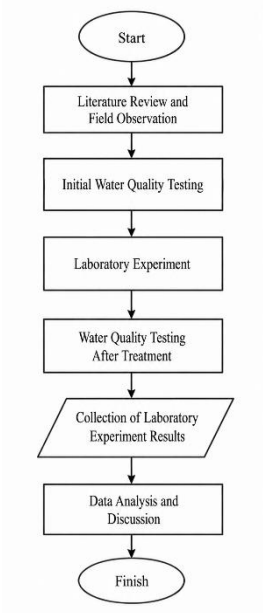


Figure 2. Research Flowchart

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3. RESULTS AND DISSCUSSION

3.1. Raw Water Characteristics

Table 3. Raw Water Test Results

No	Parameter	Unit	Quality Standard*	Result	Status
a. Physical Parameters					
1.	Odor	-	Odorless	Fishy Odor	Non-Compliant
2.	Turbidity	NTU	<3	50.7	Non-Compliant
b. Chemical Parameters					
3.	pH	-	6.5 – 8.5	7.36	Compliant
4.	TDS	mg/L	<300	402	Non-Compliant
5.	Iron (Fe)	mg/L	0.2	4.098	Non-Compliant
6.	Manganese (Mn)	mg/L	0,1	0.845	Non-Compliant
7.	Nitrate (NO_3^-)	mg/L	20	<0.04	Compliant
c. Microbiological Parameters					
8.	Total Coliform	CFU/100 ml	0	103	Non-Compliant

(Source: Balai Besar Laboratorium Kesehatan Masyarakat Yogyakarta, 2026)
**): Refers to Permenkes No. 2 Tahun 2023*

The initial characteristics of the raw water used in the experiment are presented in Table 3. Several water quality parameters exceeded the applicable quality standards, including turbidity, TDS, Fe, Mn, and total coliform. The initial Fe concentration was 4.098 mg/L, which was considerably higher than the allowable limit of 0.2 mg/L. This condition confirms that Fe was the primary water quality concern addressed in this study. The raw water also contained Mn at a concentration of 0.8455 mg/L, exceeding the allowable limit of 0.1 mg/L. The presence of Mn is relevant because Mn, similar to Fe, can undergo oxidation in the presence of chlorine and may therefore contribute to chlorine consumption during the treatment process.

The initial pH was 7.36, which was within the applicable range of 6.5–8.5. This pH condition is favorable for the oxidation and subsequent precipitation of Fe, as the oxidation of dissolved Fe and the formation of iron hydroxide precipitates are influenced by pH. Meanwhile, the turbidity and TDS concentrations were 50.7 NTU and 402 mg/L, respectively, both exceeding the applicable standards. The relatively high turbidity indicates the presence of suspended or particulate matter in the raw water, whereas the elevated TDS indicates a relatively high concentration of dissolved substances. These parameters were included as supporting water quality indicators to evaluate changes in water quality during the treatment process rather than as primary targets of chlorination.

The raw water also exhibited a fishy odor and a total coliform concentration of 103 CFU/100 mL, indicating that the raw water did not comply with the applicable standards for these parameters. Overall, the initial water quality characteristics indicate that the raw water had relatively high Fe and Mn concentrations and contained both suspended and dissolved constituents. These characteristics should be considered when interpreting the Fe removal performance because the presence of other oxidizable substances may affect chlorine availability during the treatment process.

3.2. Iron (Fe) Removal

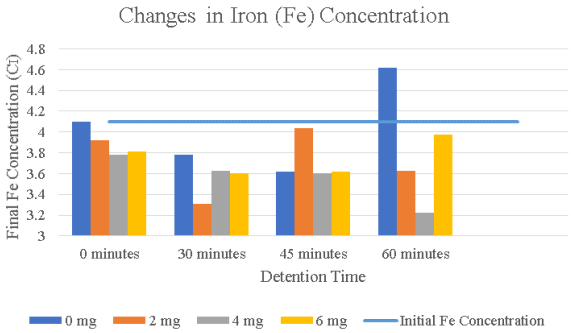


Figure 3. Iron (Fe) Concentrations After Treatment

The initial concentration of iron (Fe) in the sample water was 4.098 mg/L. After varying chlorine doses and detention times, the Fe concentration in most treatments showed a decreasing trend. This decrease in Fe concentration occurred because chlorine acts as an oxidizer that can oxidize dissolved iron (Fe^{2+}) into suspended iron (Fe^{3+}), which then forms a $Fe(OH)_3$ precipitate that can be separated from the water. The iron oxidation reaction by chlorine can be written as follows:

$$2Fe^{2+} + HOCl + 5H_2O \rightarrow 2Fe(OH)_3(s) + Cl^- + 5H^+$$

However, some treatment conditions showed an increase in the measured Fe concentration compared with the initial concentration, particularly at a chlorine dosage of 0 mg/L and a detention time of 60 minutes. Since no chlorine was added under this condition, the increase cannot be attributed to chlorine-induced Fe oxidation. Instead, the variation may be associated with experimental and analytical uncertainty, such as differences in sample homogenization, distribution of suspended Fe particles, or measurement variability during laboratory analysis. Therefore, the increase in Fe concentration in this treatment is interpreted as an experimental variation rather than evidence of an increase in Fe caused by the treatment process.

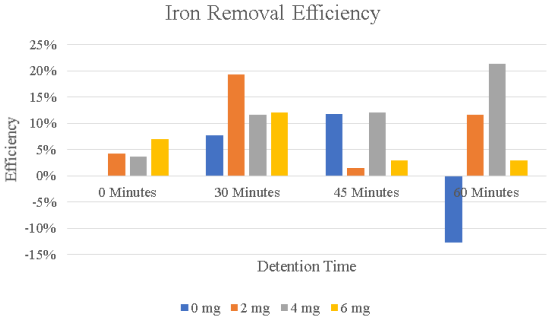


Figure 4. Iron Removal Efficiency

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The effectiveness of the oxidation process is influenced by several factors, including chlorine dosage, detention time, pH, and water characteristics. In general, increasing chlorine dosage and detention time will increase the chance of oxidation reactions, resulting in a tendency for Fe concentrations in the water to decrease. However, in some treatment variations, an increase in Fe concentrations was still found. This condition may be influenced by changes in iron speciation during the oxidation process and the re-release of dissolved iron in the early stages of the reaction. According to Zhuang et al., (2021), iron in water can exist in a complex form with natural organic compounds such as humic acid and fulvic acid, which are included in natural organic matter (NOM). In the initial stages of chlorination, the oxidizer can break the Fe-NOM complex bond, allowing some iron to return to the dissolved phase before undergoing further oxidation to iron oxide particles. This condition causes the measured Fe concentration to temporarily increase before the oxidation process is optimal. Furthermore, fluctuations in Fe concentrations can also be influenced by limitations in the sedimentation/separation process at the laboratory scale. The formed $Fe(OH)_3$ precipitate may not have been completely separated during the filtration process and is therefore still detected as total Fe during laboratory analysis.

The effectiveness of iron (Fe) removal in this study was relatively low. This is influenced by differences in the process systems between laboratory-scale and full-scale experiments. In full-scale systems, the process is continuous. In science systems, the process is continuous, resulting in more even mixing of chlorine and water, and a more stable reaction time. Conversely, on a laboratory scale, the process is conducted in batches with smaller volumes, resulting in less optimal chlorine distribution and formation of $Fe(OH)_3$ flocs. The $Fe(OH)_3$ particles formed in the initial oxidation stage are still fine and tend to remain suspended, resulting in relatively high measured Fe concentrations. Furthermore, the low removal effectiveness is also influenced by the chlorine demand in the sample water. The added chlorine is not entirely utilized to oxidize Fe^{2+} because some reacts with other compounds such as organic matter, ammonia, manganese, and other metal ions. This reaction reduces the amount of free chlorine available for the iron oxidation process (Titriga, 2025). As a result, the oxidation process of Fe^{2+} to Fe^{3+} did not occur optimally in several treatment variations. To determine the pattern of the influence of variations in chlorine dosage and detention time on the effectiveness of Fe removal, a relationship analysis was conducted using polynomial regression, as presented in **Figure 5**.

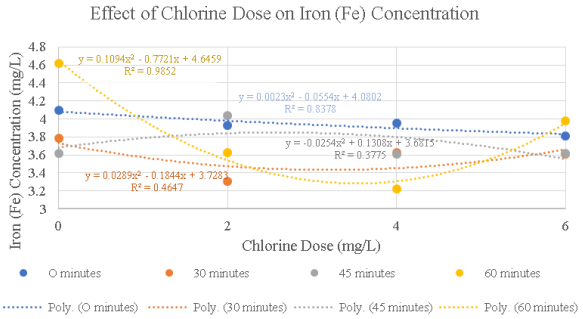


Figure 5. Effect of Chlorine Dose on Iron (Fe) Concentration

Based on the polynomial regression graph, the relationship between chlorine dose and iron (Fe) concentration shows a nonlinear pattern in the form of a parabolic curve. Increasing the chlorine dose at the beginning of the treatment causes the Fe concentration to tend to decrease due to the ongoing oxidation process of Fe^{2+} to Fe^{3+}. However, after reaching a certain condition, increasing the chlorine dose no longer results in a significant decrease in Fe concentration. Despite the relatively low removal effectiveness, the highest observed Fe removal was obtained at a chlorine dosage of 4 mg/L and a detention time of 60 minutes. However, the Fe concentration under this condition remained approximately 3.224 mg/L, which was substantially higher than the applicable quality standard of 0.2 mg/L. Therefore, the highest observed removal condition in this study should not be interpreted as sufficient to achieve regulatory compliance. Rather, it represents the treatment condition that produced the highest observed Fe removal within the experimental range. This finding indicates that variations in chlorine dosage and detention time within the tested ranges alone were not sufficient to reduce Fe concentrations to the applicable standard.

Under these conditions, the amount of available oxidizer is sufficient to support the iron oxidation process more effectively. After passing the optimum point, the removal effectiveness tends to experience an oxidation plateau, which is a condition when most of the Fe^{2+} in the water has been oxidized so that the addition of chlorine no longer significantly increases the reaction rate. According to Zhuang et al. (2021), This condition occurs because Fe^{2+} has changed to Fe^{3+} and formed iron oxide particles, so that the amount of Fe^{2+} available for reaction is reduced. In addition to the chlorine dose, detention time also affects the effectiveness of the iron oxidation process because it determines the length of contact time between chlorine and Fe^{2+} in the water. A graph of the effect of detention time on the removal of iron (Fe) concentration is presented in **Figure 6**.

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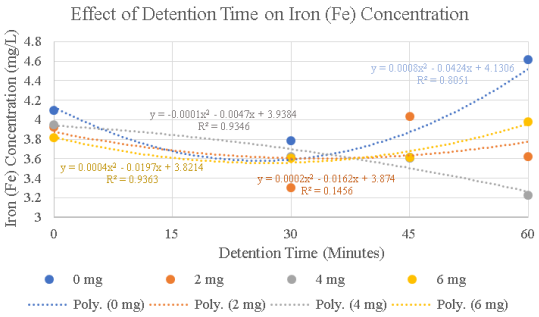


Figure 6. Effect of Detention Time on Iron (Fe) Concentration

Detention time affects the length of contact between chlorine and Fe^{2+}, thus affecting the iron oxidation process in water. The analysis results showed that the optimum condition was obtained at a detention time of 60 minutes with the lowest Fe concentration compared to other detention time variations. At shorter detention times, the oxidation process did not occur optimally because the contact time between the oxidizer and iron was still limited, so some Fe remained in dissolved form. However, after passing the optimum condition, the decrease in Fe concentration no longer showed a significant change. Huang et al. (2024) also explained that with excessively long detention times, the formed iron oxide particles can remain in colloidal or suspended form if the precipitation process is ineffective. This condition causes some iron oxide particles to still be detected when measuring Fe concentrations.

Based on polynomial regression analysis, it was found that chlorine dose and detention time both influence changes in Fe concentration. The most representative relationship between chlorine dose variations was found at a detention time of 60 minutes, with a coefficient of determination (R^2) of 0.985. Meanwhile, with varying detention times, the most representative relationship was found at chlorine doses of 4 mg/L and 6 mg/L, with R^2 values of 0.934 and 0.936, respectively. These values indicate that chlorine dose has a more dominant effect on Fe removal than detention time. However, the effectiveness of chlorine dose is still influenced by the length of contact time available during the oxidation process.

3.3. Total Dissolved Solids (TDS) Removal

Total Dissolved Solids (TDS) is a water quality parameter that indicates the total amount of dissolved solids in water. During the chlorination process, changes in TDS values can occur due to oxidation reactions that occur during the treatment process. The oxidation of Fe^{2+} to Fe^{3+} causes changes in the chemical form of iron, which then forms insoluble compounds. Furthermore, the addition of chlorine can also affect the ion balance in water, although it does not directly function to remove dissolved solids. Observations of TDS concentrations before and after treatment were carried out to determine the effect of variations in chlorine dosage and detention time on changes in the amount of dissolved substances in water. Changes in TDS concentrations after the chlorination process are presented in **Figure 7**.

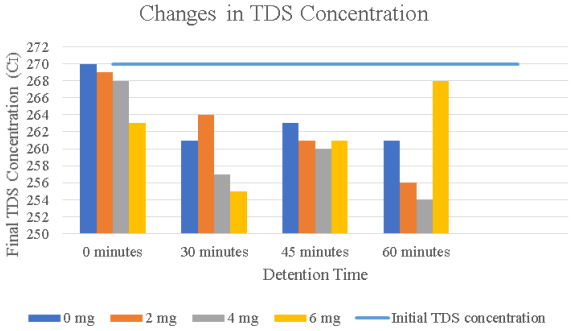


Figure 7. TDS Concentrations After Treatment

Based on the test results, the initial TDS concentration was 270 mg/L. After varying chlorine doses and detention times, the final TDS values for all treatments experienced relatively small changes. This indicates that the chlorination process does not significantly affect the concentration of dissolved solids in water. In general, TDS values tend to decrease slightly with increasing detention time, which may be caused by the oxidation of some dissolved components to suspended form. However, the magnitude of the changes is relatively small, so most of the dissolved substances remain in the dissolved phase throughout the treatment process. In some treatments, especially at higher chlorine doses, TDS values increased. This condition is thought to be related to the addition of chlorine, which contributes to an increase in the number of dissolved ions in the water. To determine the effect of the chlorination process on reducing TDS concentration, an analysis of the removal effectiveness was performed, as presented in **Figure 8**.

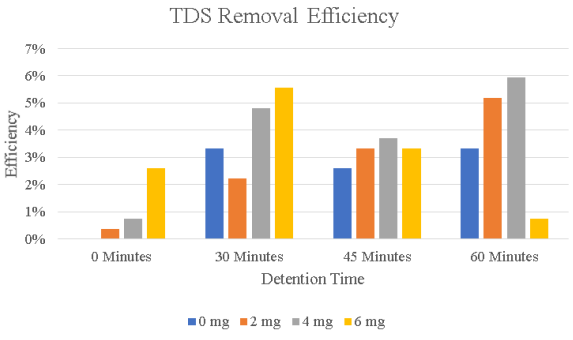


Figure 8. TDS Removal Efficiency

Based on the TDS removal effectiveness graph, the effectiveness value obtained was relatively low and did not show a consistent increase pattern with variations in chlorine dosage or detention time. These results indicate that the chlorination process did not significantly affect the reduction of TDS concentration. This condition occurs because chlorination has a

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primary function, namely for oxidation and disinfection processes, not as a process for removing dissolved solids. In this study, chlorine plays a role in oxidizing Fe^{2+} to Fe^{3+} which then forms $Fe(OH)_3$ precipitate. Meanwhile, most of the components that make up TDS, such as calcium, magnesium, sodium, chloride, and sulfate ions, remain in the dissolved phase and therefore do not experience significant removal during the chlorination process.

According to Pushpalatha et al. (2022), TDS in groundwater is generally dominated by dissolved minerals and inorganic salts, such as calcium, magnesium, and other ions derived from the weathering of rocks and soil in aquifers. These components are stable in dissolved form and therefore not easily removed through chemical oxidation processes. The low effectiveness of TDS removal in this study indicates that the chlorination process does not significantly affect the concentration of dissolved solids. Although chlorine is capable of oxidizing Fe^{2+} to Fe^{3+}, the contribution of iron to the total TDS component is relatively small compared to other dissolved minerals. Therefore, changes in Fe concentration do not significantly impact the overall TDS value. To determine the effect of chlorine dose and detention time on changes in TDS concentration, a polynomial regression analysis was performed, as presented in **Figure 9** and **Figure 10**.

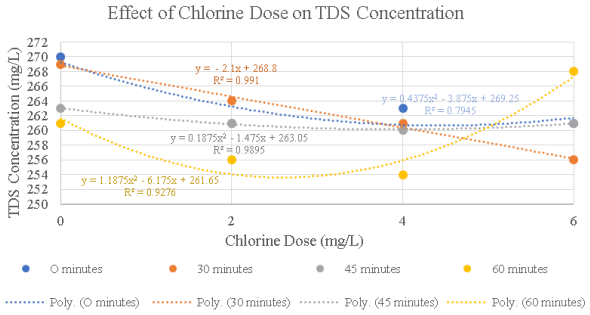


Figure 9. Effect of Chlorine Dose on TDS Concentration

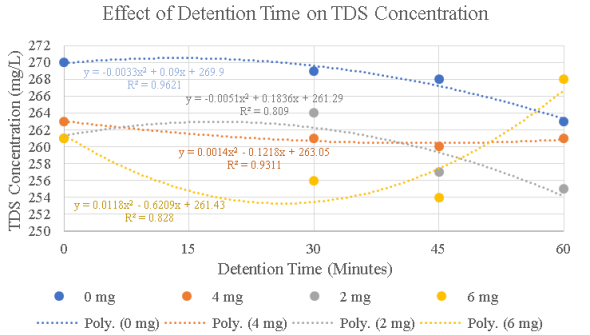


Figure 10. Effect of Detention Time on TDS Concentration

Based on the polynomial graph, the relationship between chlorine dose, detention time, and TDS concentration shows a varying pattern. In the analysis of the effect of chlorine dose on TDS, the highest coefficient of determination (R^2) values were obtained at detention times of 30 minutes and 45 minutes, respectively, at 0.991 and 0.989. These results indicate that changes in TDS concentration in both conditions can be well explained by the regression model used.

Meanwhile, in the analysis of the effect of detention time on TDS, the highest R^2 value was obtained at a chlorine dose of 0 mg/L, at 0.962. Although some models showed high R^2 values, the changes in TDS concentration were relatively small and tended to fluctuate with each treatment. This indicates that variations in chlorine dose and detention time did not significantly affect TDS removal, in line with the characteristics of TDS, which is dominated by stable dissolved ions in water.

Changes in TDS concentration in each treatment showed a relatively small trend. At detention times of 30 and 45 minutes, TDS values tended to decrease slightly with increasing chlorine dose, indicating changes in solute composition due to oxidation. However, the magnitude of the changes was relatively small and did not significantly affect TDS removal. Conversely, at a detention time of 60 minutes, TDS concentrations tended to increase at higher chlorine doses. This condition is caused by the use of sodium hypochlorite (NaOCl) as a source of chlorine which dissociates to produce dissolved ions, such as Na^+ and OCl^-, thus contributing to an increase in the TDS value (Kallista et al., 2023). These results indicate that increasing detention time can prolong the oxidation reaction but does not directly play a role in removing dissolved ions which are the main components of TDS.

3.4. Turbidity Removal

Turbidity parameters were analyzed to evaluate changes in the physical properties of water after the chlorination process. Turbidity describes the presence of suspended particles in water, which can form due to the oxidation process and the transformation of dissolved compounds into solid particles. Changes in turbidity values can indicate the occurrence of physical processes such as particle formation, precipitation, or the coalescence of particles formed after the oxidation reaction. Therefore, observations of turbidity parameters in this study were used to determine how the chlorination process contributed to the physical processes that occurred. Changes in turbidity concentration after treatment are presented in **Figure 11**.

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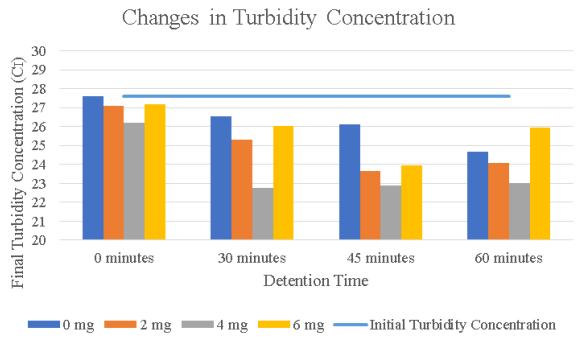


Figure 11. Turbidity Concentrations After Treatment

The initial turbidity of the sample water was 27.6 NTU. Based on the test results, the final turbidity values in most treatment variations showed a decreasing trend compared to the initial conditions. In the treatment without chlorine addition (0 mg/L), the decrease in turbidity was relatively small, indicating that the changes occurred were only caused by the natural sedimentation process during the detention time. In the treatments with chlorine addition, especially at doses of 2 mg/L and 4 mg/L, the decrease in turbidity was more pronounced. This condition indicates that the oxidation process of Fe^{2+} to Fe^{3+} by chlorine produces suspended particles that then form flocs and are more easily separated from the water. In addition, the filtration process using filter paper after the treatment also removed the formed flocs, resulting in a lower final turbidity value. Based on these concentration changes, a removal effectiveness analysis was then conducted to evaluate the ability of the chlorination process to reduce water turbidity. The results of the turbidity removal effectiveness are presented in **Figure 12**.

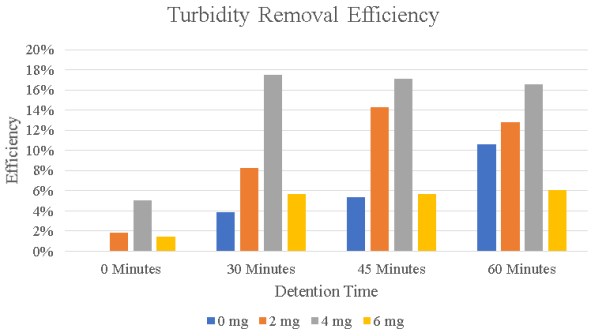


Figure 12. Turbidity Removal Efficiency

Based on the graph of turbidity removal effectiveness, there is a tendency for increased effectiveness in the treatment with chlorine addition compared to the condition without chlorine. These results indicate that the chlorination process not only affects iron removal but also contributes to improving the physical properties of the water as indicated by a decrease in turbidity. In the treatment without chlorine addition, turbidity removal effectiveness is relatively low because changes in suspended particles occur only through natural sedimentation processes during the detention time. Conversely, the addition of chlorine increases the effectiveness of turbidity removal through the oxidation process of Fe^{2+} to Fe^{3+}, which then forms suspended particles and flocs that are more easily separated from the water. This condition contributes to a decrease in turbidity values. However, the removal effectiveness obtained does not always show a consistent pattern of increase in each treatment. This is thought to be caused by the persistence of fine particles resulting from oxidation that remain suspended in the water and are also measured as turbidity. To determine the relationship between chlorine dose and detention time on changes in turbidity, a polynomial regression analysis was performed, presented in **Figures 13** and **14**.

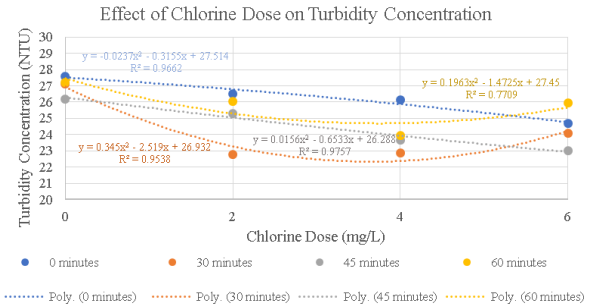


Figure 13. Effect of Chlorine Dose on Turbidity Concentration

Based on polynomial regression analysis, the relationship between chlorine dose and turbidity showed a high level of model fit with a coefficient of determination (R^2) value of 0.975 at a detention time of 45 minutes, 0.966 at a detention time of 0 minutes, and 0.953 at a detention time of 30 minutes. Meanwhile, at a detention time of 60 minutes, a lower R^2 value was obtained, namely 0.770, which indicates that the relationship between chlorine dose and turbidity becomes less consistent at longer contact times.

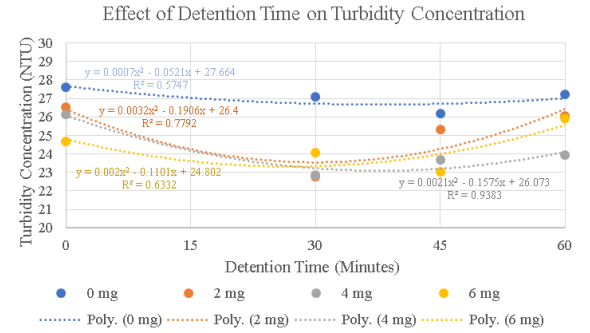


Figure 14. Effect of Detention Time on Turbidity Concentration

Meanwhile, in the analysis of the effect of detention time on turbidity, the highest R^2 value was obtained at a chlorine dose of 2 mg/L of 0.779, while at a dose of 0 mg/L the R^2 value was only 0.574. These results indicate that chlorine dose has a more consistent

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effect on turbidity changes than detention time. It can be seen that the regression curve shows a tendency for a nonlinear relationship with a certain optimum point. Turbidity tends to decrease until a detention time of 30–45 minutes, then increases again at a detention time of 60 minutes. A similar pattern is also seen in variations in chlorine dose, where the best turbidity reduction is obtained at a dose of 4 mg/L, while at higher doses the turbidity value increases again. According to Daud et al. (2023), This condition can be caused by floc instability or the formation of fine particles still suspended in the water, further increasing the turbidity value.

Based on both graphs, the optimum turbidity removal conditions were obtained at a chlorine dose of 4 mg/L with a detention time of 30–45 minutes, resulting in a turbidity of around 22 NTU. However, this condition represents the optimum specifically for turbidity and does not necessarily indicate the overall optimum operating condition for the treatment process. The results also showed that the optimum chlorine dose for Fe removal was 4 mg/L, although the optimum detention time for Fe removal was 60 minutes. Thus, the optimum conditions for turbidity and Fe were similar in terms of chlorine dose but different in terms of detention time.

Considering that Fe removal was the primary treatment objective in this study, the condition of 4 mg/L chlorine dose and 60 minutes detention time was selected as the overall operational optimum for Fe removal. Although the turbidity removal was most favorable at 30–45 minutes, the 60 minute detention time was considered more appropriate for achieving the intended Fe removal performance. Therefore, the determination of the overall optimum condition was based on the combined interpretation of the treatment responses, with greater consideration given to Fe removal as the primary target parameter.

The oxidation of Fe^{2+} to Fe^{3+} produces $Fe(OH)_3$ particles, which then precipitate and are filtered, thus not only reducing the Fe concentration but also reducing the number of suspended particles that contribute to water turbidity (Tabash et al., 2024). Thus, this condition shows that the chlorination process in this study works to oxidize dissolved iron so that it produces particles that can then be separated from water.

4. CONCLUSION

The highest Fe removal effectiveness was obtained at a chlorine dosage of 4 mg/L and a detention time of 60 minutes. In contrast, chlorine dosage and detention time had no significant effect on TDS, as the resulting changes were relatively small and fluctuating. For turbidity, chlorine dosage showed a more consistent effect than detention time, with the best removal achieved at a chlorine dosage of 4 mg/L and a detention time of 30–45 minutes. Considering the overall responses of Fe, turbidity, and TDS, a chlorine dose of 4 mg/L and a detention time of 60 minutes are recommended as the operating condition for the treatment process. This condition provides the most favorable overall treatment performance, particularly for Fe removal, while also considering the responses of turbidity and TDS.

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