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THE INFLUENCE OF SOME FACTORS ON THE SELECTION OF THE OPTIMAL DOSE OF COAGULANT (FERRIC CHLORIDE) USED TO REMOVE WATER TURBIDITY

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Abstract

Turbidity is one of the main problems for drinking water treatment, especially in arid or semi-arid areas where limited high-quality raw water resources coexist with large amounts of poor-quality raw water. Abstract Optimisation of ferric chloride dosage for efficient turbidity removal from Tigris river water under different operational conditions. Jar tests were done to investigate the influences of (1) pH (3–12), (2) a coagulant dose (10–60 mg/L), (3) rapid mixing speed (200–300 rpm), and slow mixing speed (10–20 rpm) operating parameters through 10 experiments being executed with various levels of initial turbidities in a range of 116 to 1172 NTU. The maximum removal efficiency of 99.2% was achieved at the conditions of pH 4.0, coagulant dose 50 mg/L, rapid mixing (250 rp/m) and slow mixing (20 rp/m). They maintained the efficiency of Phadebas blue as high as 98.4% within the best window (pH 4–5, dose 50–60 mg/L) but fell substantially to 85.3–93.7% values regularly measured at strongly basic conditions of pH ≥ 12. These results provide owners and operators of plants with practical, quantitative guidance in that — to achieve sustained high-efficiency turbidity removal — simultaneous control of pH and mixing conditions is required. Results are directly relevant to microíYltration-based and other innovative sustainable water-treatment technologies. The pH (3–12) over which the coagulation response of $FeCl_3$ was

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characterized in this work was artificially adjusted using HCl/NaOH, however, the natural Tigris River water range (≈7.5–8.5) is within the range tested. They confirm practical feasibility (removal remains high (at pH 7.0–8.0 ≥97–98%) with limited adjustment of extreme pH). The pH 4.0–5.0 optimum is the chemically ideal and could be realised on a larger scale only by incorporating upstream pH adjustment systems as described in Recommendations.

Keywords: Water treatment, turbidity removal, coagulation, ferric chloride, optimization, jar test method.

1 Introduction

Quality and availability of water are essential for human health, economic growth and environmental sustainability. Although traditional water treatment strategies (employed for 5,000 years) targeted sensory properties including turbidity, taste and odor of source waters, contemporary forms of water treatments are increasingly required to treat an ever-broader spectrum of contaminants introduced by the intensification of industrial activities, agricultural practices and climate change. Of these, water turbidity (resulting from the drop in water clarity due to suspended and colloidal particulate material) is still one of the most difficult problems that prevent provision of drinking water in the Middle East and North African region [1-4]. Turbidity has various origins, such as inorganic substances, including clay, silt, and sand; organic substances from decomposition of vegetations, which include tannins and algae biomass; and biological pollutants, such as bacteria, algae, and viruses [5]. Not only is high turbidity visually unattractive, but it also might be an indicator of the existence of pathogens and adsorbed pollutants, which pose danger to public health. WHO defines the maximum permissible turbidity of drinking water at 5 NTU, whereas the limit in the developed countries is lower, e.g., 1 NTU in the United States [6]. Concerning the global problems of turbidity control, there are many studies devoted to this issue. In most Arab countries, including Iraq, the wastewater treatment systems serve as pre-conventional plants without strict control. It results in high need in

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practical information on how to improve performance of current treatment technologies [7-10].

Process Unit Consolidation has traditionally been considered as the main unit operation aimed at removing turbidity-forming components of the source water using their chemical destabilization [11]. During coagulation, a rapid mixture of the raw water with the chemical coagulant is made to change the electrostatic charge of the colloids, thus destabilizing them [12]. Following coagulation, flocculation takes place during which the destabilized colloids unite into larger flocs possessing enough weight to precipitate down through the water body and be sedimented [13–15]. This cascaded process requires a proper control of some parameters: type and dosage of the coagulant used, initial pH, mixing time and speed, temperature, and general water quality [13–15]. Ferric chloride ($FeCl_3$) has found use as a coagulant in many treatment plants due to its wide range of action, quick reaction, and relatively low price compared to other reagents, like alum [16]. However, the effect of the combination of various parameters on the $FeCl_3$ optimum dose is not well-studied for high-turbidity waters (like in Iraqi sources) [17,18].

The following comparative context is contained in a more targeted review of past studies of $FeCl_3$ coagulation: (i) Cao et al. Optimal coagulation of $FeCl_3$ occurred at pH 4–6 for Yellow River water Liu et al. [43] (50–500 NTU) which is consistent with the present findings. (ii) Tran et al. Tannery wastewater [42] obtained optimal poly ferric chloride (PFC) dosage of 30–50 mg/L which pH is 5-6. (iii) Solmaz et al. At pH 5–7,>95% turbidity removal was achieved using $FeCl_3$ originated from industrial waste as shown by [16]. (iv) Hameed et al. $FeCl_3$ is better than alum on Iraqi wastewater at acid pH as [17].

Turbidity Removal The last case that will be discussed on turbidity removal relates to Nasier & Abdulrazzaq [35], where they were able to achieve turbidity removal at Al Muthanna WTP, and used conventional coagulation with natural pH.

This study further enhances this knowledge by simultaneously investigating all four major operational variables (pH, coagulant dosage, rapid mixing speed and slow mixing speed) on high turbidity Tigris river water (up to 1,172 NTU) which

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has led to enabling a full operational optimization in the specific context of the chemical enhancement of Iraqi water supply.

The current work focuses on the influence and optimization of ferric coagulation in the treatment of turbid water sources, which is an extremely challenging endeavor. Traditionally, academic studies have been focused on the analysis of only one variable like pH or dosing rate. Yet, there is a lack of thorough studies regarding the simultaneous influence of all variables in the case of turbid water sources, where the NTU value falls within the range from 750 to 4,000 (or even above 500 NTU) [19–21]. In addition, there is a lack of information on how the best values of pH, mixing speed, and coagulant dosing can be synchronized. Finally, although the models of the process of coagulation are known quite well, the influence of interactions between the high and low mixing rates (determining dispersion kinetics and floc formation rate, respectively) is still not studied [22].

In order to bridge these voids, this study provides a systematic and well-controlled experimental study) that:

(1) Quantitative relations of turbidity removal efficiency relying on $FeCl_3$ dosage (10–60 mg/L), pH (3–12), rapid mixing speed (200–300 rpm) and slow mixing speed (10–20 rpm) in terms of the jar tests; and

(2) Determining the appropriate dosage range of FeCl3 for various qualities of water, starting with an initial turbidity range of 116 to 1,172 NTU, characteristic of indigenous and pilot-plant water samples with the goal of formulating standard procedures for iron dosing, pH correction, and mixing techniques. These standard procedures must consider the Iraqi environment and have the capability to reduce turbidity to about 98%, conforming to WHO guidelines on drinking water standards [23].

2 Methodology

2.1 Water Samples and Source

Water samples in their raw form were obtained from the Tigris River in Tikrit, Iraq. The lower turbidity tests were carried out using untreated water samples, but to investigate other scenarios, other water samples were prepared by adding

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standardized amounts of clays to make their initial turbidity values ranging between 116 and 1172 NTU [24-26]. With this method, a more extensive investigation could be made since only by changing the season of collecting the samples was not enough..

The natural pH of the Tigris River at the Tikrit site is roughly 7.5–8.5, which meets the regulations of Iraqi Law No. 25 (1967) for surface water to be treated (pH 6.5–9.5). All pH values < 6.0 (including pH 3.0) were obtained. The $FeCl_3$ obtained is experimentally characterized by adding HCl and thus artificially imposed. Performance at a diverse pH range. These situations do not exist in the natural Tigris River. The only acid that you would not expect to come across in the traditional treatment of water quality without a specific addition is SOx, because life at 500ppm tries everything it can to avoid marching into the buffer, but we do know that this is not the case for others dosing.

2.2 Materials

Analytical grade ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) was used as a coagulant. The range of the dose 10–60 mg/L included suboptimal and saturating concentrations [27]. For the decrease of the initial pH of the water (pH = 7.5–8.5) to the target pH ≤ 3, a 0.1 N HCl solution was used [28], whereas 0.1 N NaOH solution was used to reach the alkaline pH up to 12 [29]. All these changes in the pH were made exclusively for the purposes of experiments. Because $FeCl_3$ is a salt of strong acid, it automatically decreases the pH of the solution. Thus, $FeCl_3$ was added to the jars, and then the pH was measured again and adjusted to the target pH within ±0.1 pH units by means of HCl or NaOH.

2.3 Apparatus and Equipment

Table 1 lists the apparatus and equipment used in the experimental study. The jar test unit permitted coagulation, flocculation and settling to occur simultaneously in 6 parallel units of 2 l capacity with the facility for varying the rate of mixing at rapid and slow speeds. The turbidity of samples before and after treatment was measured by a calibrated portable turbidimeter in Nephelometric Turbidity Units

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(NTU). Water pH was determined with a pH meter (Precision Scientific, model 63) to a quoted accuracy of ±0.01 pH units. Coagulant weight was determined by an analytical precision balance sensitive to 0.001 g.

Table 1. Equipment specifications and functions employed in the experimental investigation.

Equipment	Specifications	Function	
Jar Test Apparatus	PHIPS	PIRD RICHMOND, USA	Simultaneous coagulation, flocculation, and sedimentation in six parallel units (2 L capacity each); variable mixing speed control (rpm)
Turbidity Meter	Lovibond TB 210 IR	Measurement of turbidity before and after treatment (units: NTU)	
pH Meter	HANA Instruments HI22PH/ORP	Measurement of water acidity/alkalinity; accuracy ±0.01 pH units	
Analytical Balance	Swiss-made; 310 g capacity	Measurement of coagulant mass with 0.001 g precision	

2.4 Experimental Design and Test Protocol

Ten experimental runs were carried out varying some of the operational parameters and constraining others, allowing for main effects and interaction effects between factors to be evaluated [30,31]. The experimental phase matrix and the range of the parameters are given in Table 2, where each experiment is intended as an individual test to verify the removal efficiency of turbidity for some determined operating parameters.

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Table 2. Experimental series design with parameter ranges and specified purposes.

Experiment	Initial Turbidity (NTU)	Ferric Chloride (mg/L)	pH Range	Rapid Mix (rpm)	Slow Mix (rpm)	Purpose
1	694	10-60	3.0 (acidic)	300	20	pH effect-strongly acidic
2	860	10-60	5.0 (mildly acidic)	300	20	pH effect-optimal region
3	896	10-60	7.19 (neutral)	300	20	pH effect-neutral
4	381	10-60	12.0 (basic)	300	20	pH effect-basic
5	1,172	50 (fixed)	4-9 (multipoint)	300	25	Fine-scale pH optimization
6	535	10-60	7.5 (neutral)	200	10	Low mixing speed conditions
7	116	10-60	7.19 (neutral)	200	20	Intermediate mixing speeds
8	170	10-60	7.19 (neutral)	200	10	Natural turbidity; low slow mix
9	170	10-60	7.19 (neutral)	250	20	Natural turbidity; optimized mix
10	170	10-60	7.19 (neutral)	300	10	Natural turbidity; high rapid mix

The test procedure was performed as follows: Raw water which was made standard with desired turbidity by adding regulated aliquots of suspension (if necessary) and/or unaltered was initially measured in terms of turbidity (t0), pH. One litre of water samples were placed in each of six jar test cells. The solution of ferric chloride (10-60 mg/L) was introduced in the first stage of each cell, where rapid stirring has been applied for 1 min allowing fast coagulant dilution and dispersion. After this dispersion process, the stirrer speed was decreased to the slow mixing rate for 20 min in most tests (10 min in some tests) to allow floc agglomeration. All the stirring was then stopped and the solids were allowed to sediment at lab temperature (approximately 20-23 ºC) for around 60 min. After

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sedimentation, 30 mL of supernatant were gently decanted (2 cm below the water surface) and removed settled sludge and surface layer floating material. Turbidity of the treated sample was measured with calibrated turbidity meter. The removal rate (E%) was determined by the following equation [1] [51]:

$$E\% = \frac{T_{initial} - T_{final}}{T_{initial}} \times 100$$

where $T_{initial}$ and T_{final} represent turbidity (NTU) before and after treatment, respectively. Figure 1 illustrates the sequential stages of the jar test experimental procedure.

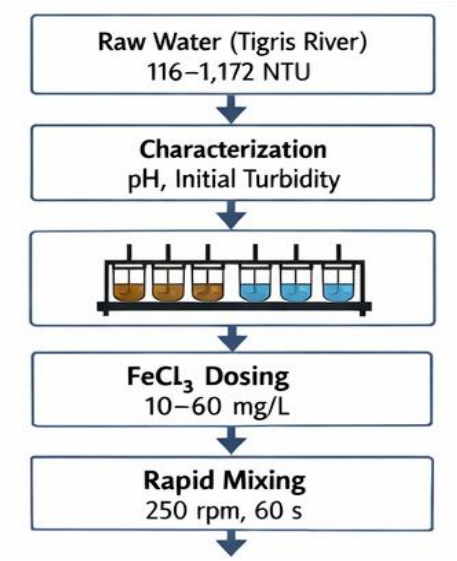

Figure 1. Jar test experimental procedure illustrating the sequential stages of coagulation, flocculation, sedimentation, and sampling.

3 Results and Discussion

3.1 Effect of pH on Turbidity Removal Efficiency

The experimental procedure included the investigation of the effect of pH on the ability of ferric chloride to coagulate. Experiments Series 1–4 were designed to study the efficacy of ferric chloride at different pHs (3.0–12.0), maintaining rapid mixing speed of 300 rpm and low-speed one, which is less than 20 rpm [32].

In experiment 1 (initial turbidity was equal to 694 NTU, pH 3.0), the efficacy of ferric chloride ranged from 95.3% to 97.5%, and turbidities after treatment were in

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the range of 32.5-17.1 NTU for doses of 10-60 mg/L of ferric chloride. A non-linear relation between dose and efficiency was demonstrated: the maximum values of efficiency (97.5%) were detected at the dose of 60 mg/L, however, intermediate doses (e.g., 30 mg/L) resulted in much lower values of efficiency (approximately 69.4%). It can be suggested that the decreased efficiency of coagulation at low doses and strong acidity of water might result from the uneven distribution of the coagulant or the lack of charge equilibrium during the flocculation process [33].

In experiment 2 (pH 5.0, initial turbidity = 860 NTU), the removal efficiency depended on the amount of ferric chloride, increasing with an increase of the dose from 94.2% (10 mg/L) to 98.7% (60 mg/L). The dose-dependent increase of the efficiency is moderate, but greater than those without near-infrared irradiation; these values are significantly better than the results of experiment 1. Turbidities are in the range of 9-50 NTU, which is less than the WHO recommendation (5 NTU) [34].

For near-neutral pH (experiment 3: 7.19; initial turbidity = 896 NTU), removal efficiency was almost equal to the values found in experiment 2, i.e., about 94.0%-98%. Dose-efficiency graphs were similar to those in the experiment 2 [35].

However, removal was significantly lower at basic pH 12.0 (Experiment 4; initial turbidity=381 NTU), where the range of removal was between 85.3% and 93.7%, with final turbidities of 24–60 NTU. The maximum performance reached was only 93.7% due to the highest dose of 60 mg/L, which was much lower than the efficiency at neutral and slightly acidic pH [36].

The strong pH-dependence of the process shown is consistent with the underlying thermodynamic and chemical reactions of ferric ion hydrolysis. The hydrolysis of FeCl3 in water occurs via the following consecutive steps [9] 3Fe b Coulometry:

$$Fe^{3+} + 3H^2O \rightleftharpoons Fe(OH)^3 \downarrow + 3H^+$$

The reaction is pH- $^+$ ⇌ $^+$dependent, low pH prevents precipitation and; at increasingly high manganiferous coagulant doses (pH 4–5), parallel development of charge-neutralising ferric hydroxide species occurs.

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This reaction is strongly pH-dependent. Excess of H^+ ions forces the equilibrium to left; thus prevents further precipitation of ferric hydroxide (floc) under acid conditions (low pH). Maximum monomeric and dimeric ferric hydroxide concentrations, and polymeric species in pH 4-5 range which is favorable as they also help to trap and neutralize colloidal particles through charge neutralization mechanism and those beyond a certain age will have deposited. For high values of the starting pH (>12), most of the ferric ions are precipitated into Fe(OH)3 solids that can act to bind the colloidal particles resulting in excessive sludge formation, but these conditions are insufficient to facilitate the operation of the charge neutralization process [37-39].

In order to narrow down the optimal pH region, in Experiment 5 we set ferric chloride at a concentration of 50 mg/L and varied pH between 4.0 and 9.0 with intervals of a single pH unit (initial turbidity = 1,172 NTU; rapid mix = 300 rpm; slow mix = 25 rpm) [40]. As shown in Figure 2, there was a clear pH optimum of response. The maximum turbidity removal efficiency of 99.2% was obtained at pH 4.0 with the final turbidity of 8.84 NTU. The efficiency for pH 5.0 was 98.6% with a final turbidity of 14.6 NTU, for pH 6.0 was 97.5% (29.0 NTU), for pH 7.0 was 97 (26.9 NTU), for pH 8.0 was also achieved a high efficiency of removal of turbidity that reached up to 98% (17,.3 NTU) and lastly to reach the lowest efficiency recorded in this study which is over than acceptable by the regulation (95%). This high-definition description shows that the efficiency decreases in a gradual way with pH between 4.0 and 6.0, and it becomes stable at about 97.4 - 98.5% for pH values higher or equal to 7.0. Theoretical optimum pH for ferric hydroxide formation in the range of 4.0 to 5.0 is thus in close agreement with experimental findings. This increased efficiency in the range pH 8-9 relative to pH 6-7 can be due to a variation of the ferric species distribution upon hydrolysis and polymeric properties of that are favourable for floc formation and settling. Optimal pH for coagulation of ferric chloride is usually between 4-6 as reported in literature [41,42] and was found to correspond with the observed results. The wide pH range tested at three initial turbidity levels (694, 896, and 1,172 NTU) also confirms

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previous results that the optimal pH is not greatly affected by changes in influent water quality when the turbidity is low.

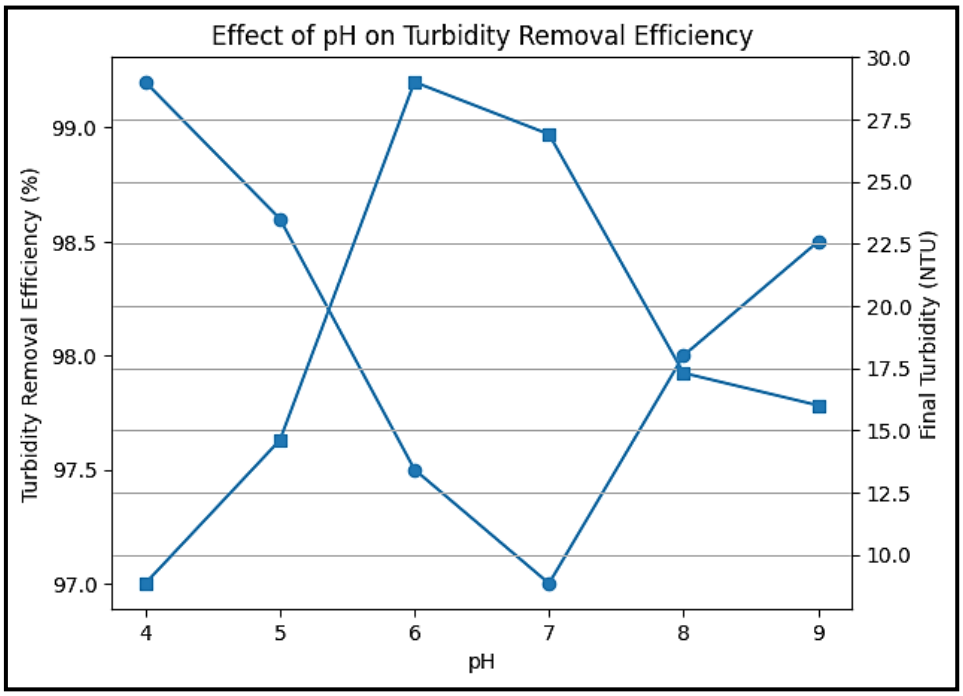

Figure 2. Effect of pH on turbidity removal efficiency (Experiment 5; $FeCl_3$ = 50 mg/L; initial turbidity = 1,172 NTU). The optimal pH range is clearly demonstrated with peak efficiency at pH 4.0.

3.2 Effect of Coagulant Dosage

The relationship between ferric chloride dosage and removal efficiency was examined across multiple experimental conditions. The dosage response across all experiments is presented in Table 3, which summarizes the effect of ferric chloride dosage on removal efficiency under optimal pH conditions.

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Table 3. Effect of ferric chloride dosage on removal efficiency under optimal pH conditions.

Dosage (mg/L)	Experiment 2 (pH 5, turbidity 860 NTU)	Experiment 5 (pH 4, turbidity 1,172 NTU)
10	94.2%	-
20	98.9%	-
30	98.4%	-
40	97.7%	-
50	98.6%	99.2%
60	98.7%	-

Within Over the ideal pH range (4-5), removal efficiency showed a steady improvement as ferric chloride dose increases. At pH 5, efficiency was between 98.4% and 98.9% for › 20 mg/L and showed that it had an asymptote at around 20 mg/L of SEI IV before seeing marginal returns on the increased dosage level, under optimal conditions (pH 4.0), such efficiency reached as high as approximately 99.2% in a dose of 50 mg/L or more; however, dosages over this range provided no additional gain in efficiencies due to excessive use which is uneconomical considering chemical cost/sludge production in the given decrease in cost effectiveness with increasing dose.

The dose response mechanism is characterized by two antagonistic effects. The primary positive effect of charge neutralization is that higher coagulant dosage increases hydrolyzed ferric species concentration, which allow more colloidal particles to meet the charge-neutralized species and then to be destabilized resulting in a reduction of residual turbidity [43]. With the exception of overdosing effects that are not significant in the range of 10-60 mg/L, a reverse effect may occur at very high dosages: excess charge is introduced by excess coagulant and some particles which have already been destabilized could potentially re-stabilize via charge reversal—a phenomenon reported in literature at concentrations beyond 100 mg/L but not observed here [43,44]. In the range of doses that are studied, charge neutralization is the main process that is responsible for this steady increase in efficiency beyond which a plateau is reached.

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Both the lowest and highest pH levels (pH 4, pH 9) were used; specifically, experiment 5 was deliberately assessed on this parameter with czl02 dose at a constant dose of 50 mg/L equivalent to an initial NTU value of 1,172. Since this experiment was not designed as a dose-response study, the complete dosage range (10-60 mg/L) at pH 4.0 was not investigated in this part of our research. It is, therefore, correct that Table 3 only presents the result for Experiment 5 at 50 mg/L. The data obtained from Table 3 are in line with the pH effect visible at a fixed dosage (Figure 2). The caption of Table 3 has been followed by the following clarifying remark:

Experiment 5 only tested the 50 mg/L condition (fixed-dose pH-variation study); no full dose-response data at pH 4.0 were obtained in this series of experiments.

Figure 3 shows the dose-response curve of the relationship between FeCl 3 concentration and removal efficiency at pH 5.

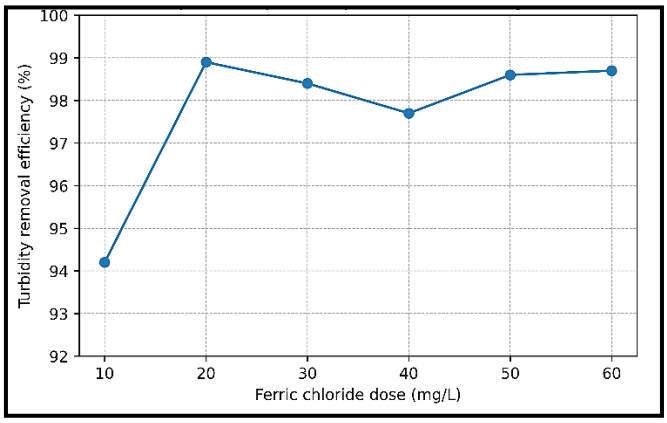

Figure 3. Dose-response curve at pH 5 (Experiment 2; initial turbidity = 860 NTU), showing the relationship between ferric chloride concentration and removal efficiency.

3.3 Effect of Mixing Parameters on Coagulation Efficiency

Mixing parameters during both rapid and slow mixing phases exert significant influence on coagulation efficiency. Rapid mixing speed during the initial 60-second stage is critical because it governs uniformity of coagulant dispersion and initial contact between ferric ions and colloidal particles. Slow mixing speed during the subsequent 20-minute flocculation stage controls gentle particle aggregation that promotes formation of large, readily settleable floc masses.

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The experiments 6 to 10 had different speeds of rapid mixing (200, 250, and 300 rpm) under a fixed pH of 7.19 and slow mixing speed of 10 and 20 rpm. In the case where the slow mixing speed was 20 rpm (experiments 2, 3, and 9), the responses of rapid mixing speed were; at 250 rpm efficiency range was between 98.2% and 98.4%; at 300 rpm efficiency range was between 97.3% and 98.1%, while at 200 rpm efficiency range was between 94.6% and 97.0%. In the other condition where the slow mixing speed was 10 rpm (experiments 6, 8, and 10), the responses of rapid mixing speed were similar; at 250 rpm efficiency was 98.9%; at 300 rpm efficiency was 98.5%, while at 200 rpm efficiency range was as follows.
was 96.9%. Figure 4 and Figure 5 illustrate these rapid mixing speed responses under different slow mixing conditions.

Best efficiency (98.4%) was obtained when rapid mixing was set at 250 rpm and slow mixing was at 20 rpm (Experiment 9; natural turbidity = 170 NTU; dosage = 60 mg/L). Further increasing rapid-mixing rate to 300 rpm caused slight reduction in efficiency to 98.1%, which can be attributed to early floc breakage. Lowering rapid-mixing rate to 200 rpm caused significant reduction in efficiency to 97.0%, suggesting insufficient mixing [22].

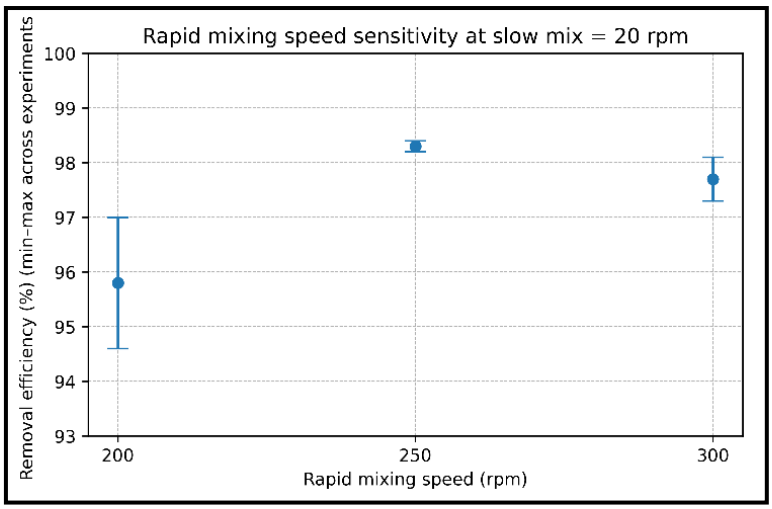

Figure 4. Rapid mixing speed sensitivity at slow mixing = 20 rpm, showing efficiency variation across the (200-300 rpm) range. Optimal performance is observed near 250 rpm.

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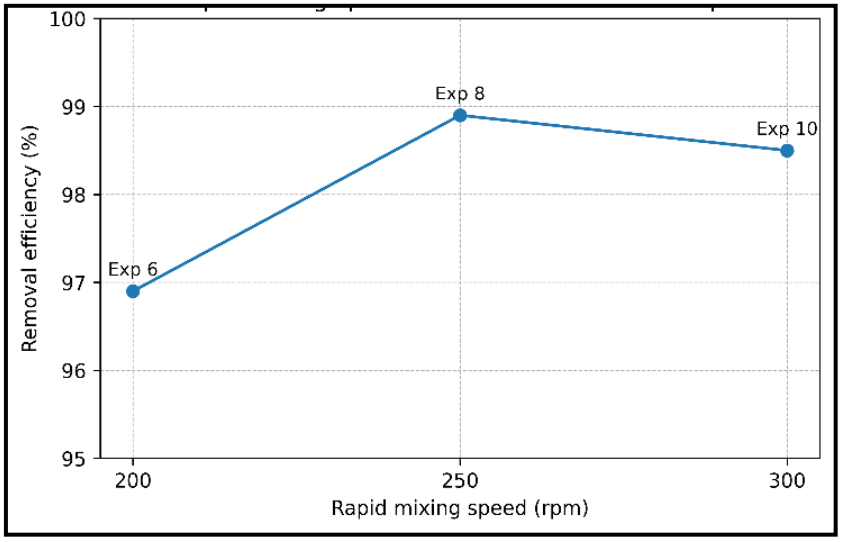

Figure 5. Rapid mixing speed effect at slow mixing = 10 rpm, demonstrating consistent trends with slow mixing = 20 rpm conditions.

Slow mixing speed influences the soft formation of larger settleable floc particles that have been destabilized during the rapid mixing phase. If mixing speed is too slow, fragile floc structures may remain intact but particle aggregation is limited; if mixing speed is too fast, floc may be disrupted or floc contact and growth is insufficient [45]. Comparisons of slow mixing speeds of 10 and 20 rpm under constant conditions (initial turbidity 170 NTU, 60 mg/L dose, rapid mix 250 rpm) revealed that at slow mixing = 20 rpm (Experiment 9) efficiency was 98.4% with final turbidity of 2.72 NTU, while at slow mixing = 10 rpm (Experiment 8) efficiency was 98.9% with final turbidity of 3.2 NTU. Surprisingly, slower mixing at 10 rpm produced slightly higher efficiency (98.9% vs. 98.4%), suggesting that gentler mixing in this turbidity range preserves more fragile flocs. However, the difference is marginal (<0.5% absolute), and both conditions yield excellent removal performance [46]. Figure 6 presents a comparison of the effects of different slow mixing speeds.

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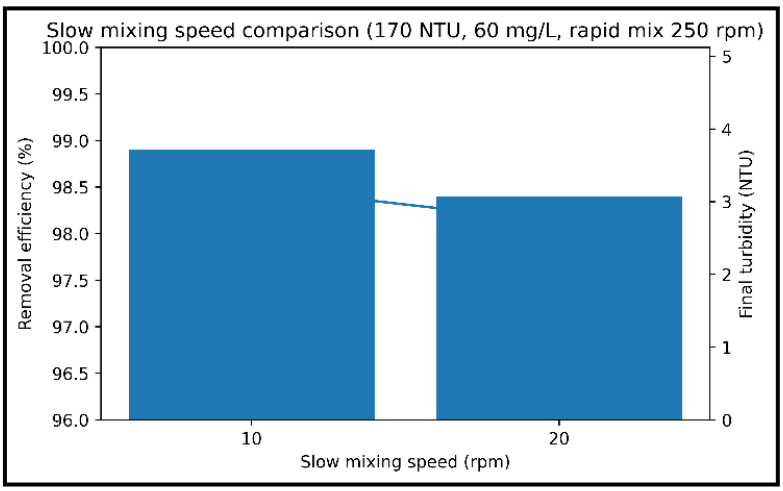

Figure 6. Slow mixing speed comparison (10 vs 20 rpm at matched conditions), demonstrating marginal but measurable efficiency differences.

Integration of all mixing experiments identifies rapid mixing of 250 rpm combined with slow mixing of 20 rpm as the operational optimum. This configuration achieves consistent efficiency exceeding 98% across initial turbidities from 116 to 1,172 NTU and is recommended for field implementation [35].

Here, turbidity has been chosen as the parameter to be studied, which is the removal efficiency (E %). The source has been taken from Behnam et al. A preliminary survey was done to study the structure of tentacles and the size of flocs. But there have been no special studies on the distribution of particles, their sedimentation velocity, and sludge volume index (SVI). These factors would have helped in giving a better understanding of the coagulation efficiency along with the design of sedimentation tanks. It is suggested that the size of flocs be measured in future through laser diffraction or image analysis for estimating sludge volume and settling velocity [3].

3.4 Interaction Between pH, Dosage, and Mixing Parameters

The above discussion has been done parameter-wise; however, interaction effects amongst dosing and mixing parameters and pH are needed to be considered. In cases when pH is between 4 and 5, ferric chloride dosage as low as 20 mg/L can

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ensure removal efficiency above 98%, while the maximum feasible dosage (60 mg/L) at higher pH values (pH ≥ 12) reaches only around 93.7% effectiveness. It is clear from the above data that pH should be controlled and the dosage should be varied according to this value, and not vice versa. Thus, if the high-pH natural water sources are treated, investment into the pH control equipment would be needed to increase the coagulation efficiency.

The dependency between mixing rate and initial turbidity is to be investigated as well. With low initial turbidity (116 NTU, Experiment 7) all dosages under rapid mixing (200 rpm) show efficiencies in the range of 94.6-98.4%. On the other hand, in the case of high initial turbidity (1,172 NTU; Experiment 5) the effect of this combination of parameters is not so critical. Thus, the significant difference in reaction to the variation of these operational conditions proves the necessity for the stricter control of these waters.

The results together conclude the optimum operating window of ferric chloride coagulation for high-turbidity Iraqi water supply. The optimum conditions are: pH range of 4.0-5.0 (target pH 4.0 for highest efficiency); ferric chloride dose of 50-60 mg/L; rapid mixing at 250 rpm for a time span of one minute; slow mixing at 20 rpm over for a period of 20 minutes and settling time over the course of one hour. In this operational range, the removal efficiency is always greater than 98%, and final turbidity values less than 2.7 NTU are achieved, well below the standard of WHO (5 NTU) and in certain source waters competitive with U.S. EPA's limit (1 NTU) [49].

3.5 Comparison with Literature and Standards

The removal efficiency of 99.2% obtained in this study is higher than that for most published results on ferric chloride coagulation. Similar studies using alum as the coagulant have generally offered maximum removal efficiencies of 95-97%, while bio-based coagulants (for example Moringa seeds, tannins) can provide efficiencies from 60% to 99% depending on water chemistry and source [50]. The pH optimum of 4.0 and dose range of 50-60 mg/L are consistent with ferric chloride manufacturers' recommendations and theoretical ferric hydroxide

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chemistry. Nevertheless, the systematic study of mixing parameter effects and their interplay with pH and dose is an original contribution that will be of significant interest to plant operator's eager to improve the performance of existing facilities. The eventual treated water turbidity (≤2.7 NTU) under optimal conditions satisfies or surpasses WHO and most of the national drinking water standards in different countries of the world, indicating that there is a utility of interest for this determined optimum operational range [50].

Aluminum sulfate (alum, Aluminium sulfate ($Al_2(SO_4)_3$) is the most commonly used coagulant in Iraqi water treatment plants. Published studies on However, at more productivepH 6.5–7.5 and doses of 40–80 mg/L compared to alum for Tigris River and similar other sources give maximum turbidity removal:90 -97% [Hameed et al.,2024; Ramal et al.,2022; Nasier & Abdulrazzaq, 2022]. In comparison, in this study $FeCl_3$ resulted in removal of 99.2% at pH 4.0/50 mg/L while retaining >97% efficiency over the pH range (~7–8.5) encountered in natural rivers. $FeCl_3$ hereby may be an significant performance advantage in a high turbidity room (>800 NTU) and in the natural Tigris River pH range. It also had a wider effective pH range, 4 to 9 compared with alum's narrow window of pH 6.5–7.5 makes it that much more resilient to seasonal swings in water quality. The primary trade-offs are higher unit of cost and more acidic sludge in proportion to alum, which ought to be comprise into life-cycle charge assessments for Iraqi treatment facilities.

4 Conclusion and Recommendations

The present systematic study has revealed quantitative correlations between the operating conditions and the performance of ferric chloride as a coagulant for high turbidity water sources in Iraq. It was found that pH plays an important role in the coagulation process. The removal efficiency exceeded 99%, with the highest value obtained in the pH interval of 4.0 to 5.0, which corresponds to the thermodynamic feasibility of ferric hydroxide precipitation. At a pH less than 3.0 and greater than 6.0, the removal efficiency dropped significantly.

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The single most important influent on the optimum ferric chloride dosage was found to be pH. There was a non-linear dose-response relationship; efficiency was less than optimal (94-95%) below the 20 mg/L range and plateaued at approximately 50-60 mg/l with <2% added benefit. Both economically and ecologically, overdose of over 60 mg/L should be avoided since it will result in excessive consumption of chemicals and sludge production with negligible gain in efficiency.

Blending factors were optimized on the basis of relatively narrow but pronounced optimum values. For each of the initial turbidity levels tested (116-1,172 NTU) rapid mixing at 250 rpm followed by slow mixing at 20 rpm resulted in the most uniform and highest removal levels. The mixing velocities other than 200 and 300 rpm caused measurable losses in efficiency with unperfected coagulant dispersion (for less than 200 rpm) or the beginning of floc breakup (more than 300 rpm). Best dosage under the experimental conditions (i.e., at pH 4.0, FeCl3 concentration of 50 mg/L, rapid mixing speed of 250 rpm and slow mixing at 20 rpm) was obtained in parallel with a removal efficiency of 99.2% and final turbidity of 8.84 NTU.

Based on these findings, the following recommendations are made for practical implementation and future research. Water treatment plant operators should maintain real-time pH monitoring with automatic acid (HCl) dosing systems upstream of the coagulation tank, targeting a pH of 4.0 ± 0.5. The ferric chloride dosage must be kept in the range of 50–60 mg/L in controlled pH conditions. An increase in dosage is not an alternative for pH control because such changes do not improve the efficiency but rather increase the cost of chemicals and sludge generation. Mixing apparatuses should be adjusted to work at 250 rpm in the process of fast mixing and 20 rpm in the process of slow mixing; variable frequency drives can be used for the purpose of adjusting speed. Impeller speeds must be verified with calibrated tachometers since theoretical speed values do not always coincide with the measured ones because of friction losses. The sedimentation detention time must be equal to 60 min to guarantee full flocculation under given mixing conditions; the detention times less than 45 min must be avoided to avoid decreasing efficiency. Jar tests must be performed at least once a

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month and once a week during turbid periods in order to make sure that operational parameters of the treatment facility are consistent with laboratory ones.

As for future research and development, the effect of temperature variation (from 15 to 35 °C) on the optimum value of ferric chloride dosage and pH must be investigated since the present research was carried out at the constant laboratory temperature (~20 °C), whereas field treatment facilities experience seasonal changes of temperature, which might affect coagulation process. The supplementary experiments must be carried out with water of Tigris River in different seasons to investigate seasonal variation of source water (turbidity, alkalinity, pH, organic compounds). Also, it is important to evaluate the possible advantages of the combined pre-treatment and post-treatment approach (pH adjustment by CO_2 or alkali addition and polishing filtration/UV disinfection) for the purpose of increasing efficiency of contaminants removal (hardness, color, pathogens). Pilot-scale tests must be conducted in existing treatment facilities in Baghdad and other Iraqi cities.

The study provides the foundation for evidence-based and data-driven optimization of water treatment in developing nations through the provision of quantitative and replicable guidelines for ferric chloride dosage. The guidelines allow operators to use the available conventional infrastructure in order to optimize the performance of treatment processes. Such a consideration is particularly important in the case of Iraqi water treatment facilities because they run on limited financial resources and lack qualified staff. In addition, the performance of the ferric chloride in terms of efficiency levels exceeding 99% suggests that the optimization of conventional coagulation meets the modern requirements for drinking water.

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