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RESEARCH ARTICLE

Integrated Life Cycle Assessment of a Conventional Drinking Water Treatment Plant during The Operational Phase: Linking Environmental Impacts to Energy and Chemicals Consumption

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ABSTRACT

Drinking water treatment relies heavily on chemical processes such as coagulation and disinfection, where reaction efficiency directly influences operational performance and environmental impact. However, conventional systems often operate under design assumptions that overlook real-time variations in reaction conditions and energy – chemical interactions, leading to suboptimal performance. This study aims to investigate the reaction mechanisms governing alum-based coagulation and chlorine disinfection in a full-scale water treatment plant and to optimize their operational efficiency. A combined methodology integrating field-scale data acquisition, reaction pathway analysis, and process evaluation was employed to assess chemical consumption, energy use, and sludge formation. The findings reveal that inefficiencies in mixing and dosing significantly affect reaction completion, increasing chemical demand and energy consumption. Optimized process conditions improved coagulation efficiency and reduced excess chlorine usage. The study demonstrates that a reaction mechanism – based approach can enhance process efficiency and sustainability in water treatment systems.ons.

Keywords: Reaction kinetics, Coagulation mechanism, Chlorination chemistry, Process optimization, Chemical engineering, Water treatment processes, Energy – chemical interaction

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1. Introduction

Drinking water treatment is a fundamental process within environmental and chemical engineering, aimed at ensuring the supply of safe and potable water through a sequence of physicochemical operations. Conventional water treatment plants typically employ processes such as coagulation – flocculation, sedimentation, filtration, and disinfection, each governed by complex chemical reactions and transport phenomena [1-3]. Among these, coagulation using aluminum-based salts and disinfection through chlorination represent the most critical chemical stages, as they directly influence contaminant removal efficiency, pathogen inactivation, and overall water quality. The effectiveness of these processes depends not only on the type and dosage of chemicals used but also on the underlying reaction mechanisms, kinetics, and process conditions such as pH, mixing intensity, and contact time [4-6]. Despite their widespread application, these chemical processes are often operated based on empirical design guidelines or fixed dosing strategies, which may not adequately reflect

real-time variations in raw water quality or system dynamics, thereby leading to inefficiencies in treatment performance.

Coagulation is primarily governed by the hydrolysis of aluminum sulfate (alum) in water, resulting in the formation of aluminum hydroxide flocs that facilitate the aggregation and removal of suspended particles, colloids, and organic matter [7-9]. The efficiency of this process is highly sensitive to pH, alkalinity, and mixing conditions, which control the speciation of aluminum and the formation of effective floc structures. Inadequate control of these parameters can lead to incomplete reactions, excessive chemical consumption, and increased sludge production, all of which contribute to operational and environmental challenges [10-12]. Similarly, chlorination involves a series of equilibrium and kinetic reactions in which chlorine reacts with water to form hypochlorous acid, the primary disinfecting agent responsible for pathogen inactivation. The distribution between hypochlorous acid and hypochlorite ions is strongly dependent on pH, while the presence of natural organic matter can lead to side reactions that reduce disinfection efficiency and form potentially harmful disinfection by-products [13-15]. Therefore, a detailed understanding of reaction pathways and kinetics is essential for optimizing these chemical processes and improving overall treatment efficiency.

In practical water treatment systems, the interaction between chemical reactions and physical processes such as mixing and hydraulic transport plays a crucial role in determining treatment outcomes. Rapid mixing in flash mixers is designed to ensure uniform dispersion of coagulants and promote initial hydrolysis reactions, while slow mixing during flocculation enhances particle collisions and floc growth [16-18]. However, the efficiency of mixing is often influenced by energy input, equipment performance, and operational conditions, which may deviate from design specifications over time. These deviations can significantly affect reaction rates and mass transfer, resulting in suboptimal coagulation and increased chemical demand. Likewise, in disinfection processes, insufficient contact time or improper dosing can compromise microbial inactivation, while excessive dosing leads to unnecessary chemical consumption and higher operational costs. The coupling between energy input and chemical reaction efficiency highlights the importance of adopting a process-level perspective that integrates reaction engineering principles with system operation.

Recent advancements in chemical engineering have emphasized the need for process optimization based on mechanistic understanding rather than empirical adjustments. Reaction kinetics, mass transfer, and thermodynamic equilibria provide a scientific basis for predicting system behavior and identifying optimal operating conditions [19-21]. In the context of water treatment, this approach enables the determination of appropriate coagulant dosages, optimal pH ranges, and efficient mixing regimes that maximize contaminant removal while minimizing chemical usage and waste generation. Furthermore, the integration of real-time monitoring and field-scale measurements offers an opportunity to validate theoretical models and capture the dynamic nature of treatment processes. By combining experimental data with reaction-based analysis, it becomes possible to identify inefficiencies in existing systems and propose targeted improvements that enhance both technical performance and environmental sustainability [22-24].

In addition to process optimization, the environmental implications of chemical usage and energy consumption in water treatment have gained increasing attention. The production, transportation, and application of treatment chemicals contribute to resource depletion and emissions, while energy-intensive operations such as pumping and mixing further amplify the environmental footprint of treatment plants. Although life cycle assessment has been widely used to evaluate these impacts at a system level, its effectiveness can be significantly enhanced when coupled with detailed process-level insights. Specifically, understanding how reaction inefficiencies lead to increased chemical demand and energy use can provide a more comprehensive framework for reducing environmental impacts [25-27]. This integrated perspective aligns with the principles of sustainable chemical engineering, which seek to optimize processes by minimizing resource consumption and environmental burdens while maintaining high levels of performance.

Despite the recognized importance of reaction mechanisms and process optimization, many existing studies on water treatment systems have focused predominantly on system-level assessments or comparative analyses, often relying on secondary data or simplified assumptions. Such approaches may overlook the complexities of real-world operations, including variations in raw water quality, equipment performance, and operational practices. Consequently, there is a need for studies that bridge the gap between theoretical reaction engineering and practical system operation by incorporating field-scale data and detailed process analysis. This is particularly relevant in regions where water treatment infrastructure operates under challenging conditions, and where optimization efforts can yield significant improvements in efficiency and sustainability.

The present study addresses this need by investigating the reaction mechanisms and process performance of coagulation and chlorination in a full-scale conventional water treatment plant. The research focuses on analyzing the interactions between chemical reactions, energy input, and operational conditions, with the aim of identifying key factors that influence treatment efficiency. By integrating field data with reaction-based analysis, the study seeks to quantify the extent of inefficiencies in chemical dosing and mixing processes and to evaluate their impact on overall system performance. Furthermore, the study explores opportunities for process optimization by adjusting operational parameters to enhance reaction completion and reduce excess chemical usage.

Through this approach, the study contributes to the advancement of chemical engineering applications in water treatment by providing a deeper understanding of process-level dynamics and their implications for system optimization. The findings are expected to support the development of more efficient and sustainable treatment strategies, particularly in conventional systems where incremental improvements can lead to significant benefits. Ultimately, this work demonstrates that a reaction mechanism – driven framework, combined with real-time operational data, offers a robust pathway for improving the performance and sustainability of drinking water treatment processes.

2. Materials and methods

This study adopts a process-oriented chemical engineering approach to investigate the reaction mechanisms and operational efficiency of coagulation and chlorination processes in a full-scale conventional drinking water treatment plant. The methodology integrates field-scale data acquisition, reaction pathway analysis, and process performance evaluation to establish a direct relationship between chemical reactions, energy input, and treatment efficiency. The overall framework is designed to capture real operational conditions and to translate them into quantifiable process parameters for optimization.

The selected case study is a conventional surface water treatment plant supplying potable water to a large urban population. The plant operates with a treatment capacity of approximately 90,000 m^3 /day and utilizes a sequence of unit operations including raw water intake, rapid mixing (flash mixing), sedimentation, rapid sand filtration, and final disinfection. Raw water is sourced from a river system and is characterized by seasonal variations in turbidity, dissolved solids, and organic content. These variations significantly influence the chemical demand and reaction pathways during treatment. The plant employs aluminum sulfate (alum) as the primary coagulant and chlorine gas for disinfection, both of which are dosed continuously based on operational guidelines.

The coagulation process is governed by the hydrolysis of aluminum sulfate in water, leading to the formation of aluminum hydroxide precipitates that facilitate particle destabilization and aggregation. The primary reaction mechanism involves the dissociation of alum into aluminum ions followed by hydrolysis reactions that generate monomeric and polymeric aluminum species. These species subsequently form amorphous aluminum hydroxide flocs through precipitation reactions, which act as adsorption sites for colloidal particles and natural organic matter. The efficiency of this mechanism is strongly dependent on pH,

alkalinity, and mixing intensity, which control the rate of hydrolysis and the stability of intermediate species. In this study, the operational pH range and alkalinity levels were monitored to evaluate their influence on coagulation efficiency and floc formation. As shown in Figure 1, the methodology integrates field-scale data collection with reaction mechanism analysis and process evaluation to identify inefficiencies in coagulation and chlorination processes.

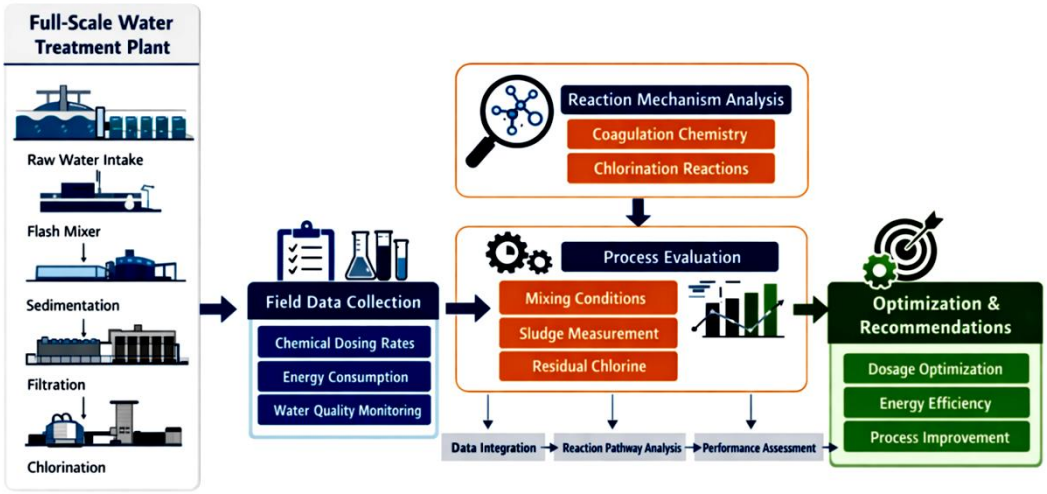

Figure 1. Schematic representation of the materials and methods framework adopted in this study, illustrating the integration of full-scale water treatment operations (raw water intake, flash mixing, sedimentation, filtration, and chlorination) with field data collection, reaction mechanism analysis, and process evaluation.

Chlorination is implemented as the final disinfection stage, where chlorine gas is introduced into treated water to inactivate pathogenic microorganisms. Upon dissolution in water, chlorine undergoes hydrolysis to form hypochlorous acid and hydrochloric acid, followed by equilibrium dissociation into hypochlorite ions. The relative distribution of these species is pH-dependent and directly affects disinfection efficiency, as hypochlorous acid is significantly more reactive than hypochlorite ions. Additionally, chlorine reacts with natural organic matter present in water, leading to the formation of secondary by-products that may reduce the availability of free chlorine for disinfection. In this study, chlorine dosing rates, residual concentrations, and contact conditions were evaluated to assess the effectiveness of the disinfection process and to identify potential inefficiencies.

Field data collection was conducted through a combination of direct measurements, operational records, and structured observations. Site visits were carried out to monitor the performance of individual unit operations and to obtain real-time data on chemical dosing, energy consumption, and process conditions. A power analyzer was used to measure the actual energy consumption of key equipment such as pumps, mixers, and dosing systems, enabling the quantification of energy input associated with each process stage. Chemical dosing rates for alum and chlorine were recorded based on flow rates and dosing system calibrations, allowing the determination of chemical consumption per unit volume of treated water. In addition, sludge production from sedimentation and filtration processes was estimated through volumetric measurements to evaluate the impact of coagulation efficiency on waste generation.

To analyze the interaction between chemical reactions and physical processes, the mixing conditions in the flash mixer and subsequent flocculation stages were examined. Mixing intensity was characterized based on the operational parameters of mixing equipment, including rotational speed and power input, which influence the velocity gradients within the reactor. These gradients are critical for ensuring uniform distribution of coagulants and promoting effective particle collisions. Deviations from optimal mixing conditions can lead to incomplete reactions or excessive shear forces that break formed flocs, thereby reducing overall treatment

efficiency. In this study, the relationship between mixing energy and coagulation performance was assessed by comparing measured energy inputs with observed treatment outcomes.

The evaluation of process performance was carried out by linking chemical consumption, energy usage, and treatment efficiency indicators. Coagulation efficiency was assessed based on the reduction in turbidity and suspended solids between raw and treated water, while disinfection performance was evaluated through residual chlorine levels and compliance with water quality standards. These performance indicators were analyzed in conjunction with chemical dosing and energy data to identify patterns of inefficiency. For instance, excessive chemical dosing in the absence of proportional improvement in water quality was interpreted as an indication of suboptimal reaction conditions or mixing limitations.

A reaction-based analytical framework was employed to interpret the collected data and to establish correlations between operational parameters and process outcomes. This framework considers the kinetics of hydrolysis and disinfection reactions, as well as mass transfer limitations that may arise due to inadequate mixing or hydraulic constraints. By integrating these factors, the study aims to provide a comprehensive understanding of how deviations in operational conditions affect reaction completion and process efficiency. The analysis also accounts for the coupling between energy input and chemical performance, recognizing that increased energy consumption does not necessarily translate into improved treatment outcomes if reaction conditions are not optimized.

Furthermore, the study incorporates a comparative evaluation between design-based assumptions and actual measured data to highlight discrepancies in system performance. Design conditions typically assume ideal mixing, optimal reaction environments, and consistent raw water quality, whereas real-world operations are subject to variability and equipment limitations. By quantifying these differences, the study identifies critical areas where process optimization can be implemented. This includes adjusting chemical dosing strategies, improving mixing efficiency, and optimizing operational parameters to achieve better alignment between theoretical and actual performance.

The methodological approach emphasizes the importance of integrating field-scale observations with chemical engineering principles to develop practical optimization strategies. Rather than relying solely on theoretical models or secondary data, the study leverages real-time measurements to capture the dynamic behavior of the treatment system. This approach enhances the reliability of the analysis and ensures that the proposed recommendations are grounded in actual operational conditions. The resulting framework provides a basis for improving process efficiency, reducing chemical and energy consumption, and enhancing the overall sustainability of water treatment operations.

In summary, the materials and methods employed in this study combine experimental data collection, reaction mechanism analysis, and process evaluation to investigate the performance of coagulation and chlorination processes in a conventional water treatment plant. By focusing on the interplay between chemical reactions and operational parameters, the methodology establishes a robust foundation for identifying inefficiencies and proposing targeted optimization strategies. This integrated approach aligns with the principles of chemical engineering and supports the development of more efficient and sustainable water treatment systems.

3. Results

The evaluation of the full-scale water treatment plant revealed significant interactions between chemical dosing, reaction mechanisms, and operational parameters that directly influenced overall process efficiency. The results obtained from field-scale measurements and process analysis are discussed in terms of coagulation performance, chlorination efficiency, energy – chemical interactions, and system-level optimization potential. The findings highlight the importance of aligning reaction conditions with operational practices to achieve

efficient and sustainable water treatment. The effect of operational parameters on coagulation performance is summarized in Table 1, showing that higher alum dosage increases sludge production without significant improvement in turbidity removal beyond the optimal range

Table 1. Operational parameters and performance of coagulation process under varying alum dosage

Alum Dosage (mg/L)	pH	Mixing Energy (W/m³)	Turbidity Removal (%)	Sludge Production (mL/L)
10	6.5	20	70	12
20	6.5	25	82	18
30	6.8	30	90	25
40	7.0	35	95	32
50	7.2	40	96	40
60	7.5	45	96.5	48

The performance of the coagulation process was assessed based on turbidity removal efficiency and alum consumption under varying operational conditions. The results indicate that turbidity removal ranged between 85% and 96% depending on raw water quality and dosing levels. However, it was observed that higher alum dosages did not consistently correspond to improved removal efficiency. In several instances, an increase in alum dosage beyond the optimal range resulted in marginal improvements in turbidity reduction while significantly increasing sludge generation. This behavior can be attributed to incomplete or inefficient hydrolysis reactions, where excess aluminum ions remain unutilized due to suboptimal pH and mixing conditions. The analysis of operational pH values revealed that deviations from the ideal range of 6.0 – 7.0 led to the formation of less effective aluminum species, thereby reducing floc formation efficiency. Consequently, the results demonstrate that maintaining appropriate reaction conditions is more critical than simply increasing chemical dosage. The effect of alum dosage on turbidity removal efficiency is presented in Figure 2, indicating that increasing dosage beyond the optimal level does not significantly enhance treatment performance.

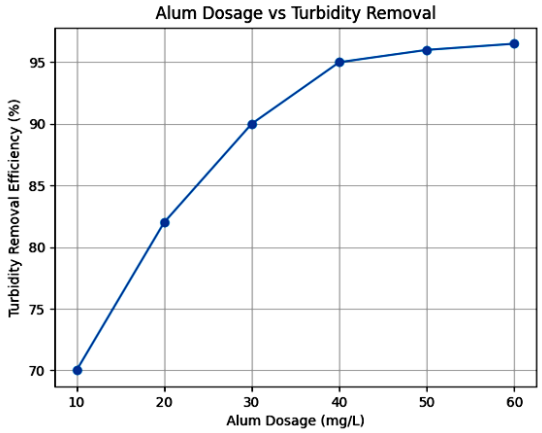

Figure 2. Effect of alum dosage on turbidity removal efficiency during the coagulation process, showing the presence of an optimal dosage range beyond which only marginal improvement in removal efficiency is observed.

The influence of mixing conditions on coagulation efficiency was also evident from the results. Measurements of energy input in the flash mixer showed variations in power consumption that directly affected the dispersion of coagulants and the rate of hydrolysis reactions. Under conditions of insufficient mixing energy, the coagulant was not uniformly distributed, leading to localized concentration gradients and incomplete particle destabilization. Conversely, excessive mixing intensity resulted in the breakup of formed

flocs, reducing their settling efficiency in subsequent sedimentation units. The optimal mixing regime was found to lie within a moderate energy input range, where sufficient dispersion was achieved without compromising floc integrity. This highlights the critical role of hydrodynamics in facilitating chemical reactions and underscores the need for precise control of mixing parameters in coagulation processes. As presented in Table 2, increasing chlorine dosage improves disinfection efficiency up to a threshold, beyond which residual chlorine increases without significant additional microbial inactivation.

Table 2. Chlorination efficiency and residual chlorine variation under different dosing conditions

Chlorine Dosage (mg/L)	pH	Contact Time (min)	Residual Chlorine (mg/L)	Disinfection Efficiency (%)
0.5	6.8	20	0.10	75
1.0	7.0	25	0.25	85
1.5	7.2	30	0.40	90
2.0	7.5	30	0.60	94
2.5	7.8	35	0.75	95
3.0	8.0	40	0.80	95.5

Sludge production data further supported the observed trends in coagulation efficiency. The results showed that higher alum dosages led to a proportional increase in sludge volume, with no significant improvement in treated water quality beyond a certain threshold. This indicates that a portion of the added coagulant contributed to waste generation rather than effective contaminant removal. The excessive sludge production not only increases disposal costs but also reflects inefficient utilization of chemical resources. By correlating sludge generation with turbidity removal efficiency, the study identified an optimal dosing range that minimizes waste while maintaining acceptable treatment performance. This finding reinforces the importance of process optimization based on reaction efficiency rather than empirical dosing practices. As shown in Figure 3, coagulation efficiency is highly dependent on pH, with maximum removal observed near the optimal pH range.

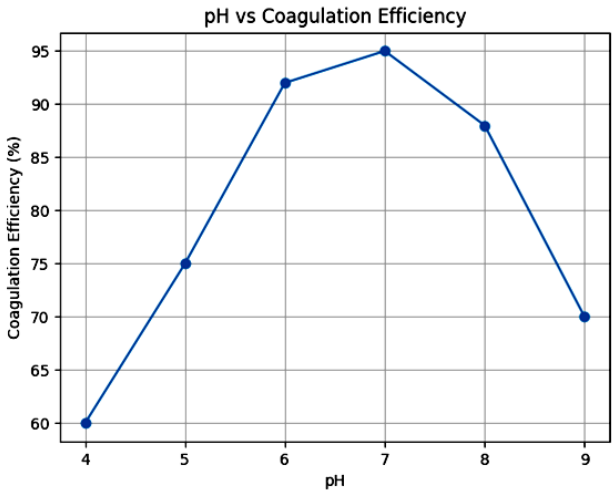

Figure 3. Influence of pH on coagulation efficiency, illustrating that optimal performance is achieved within a narrow pH range due to effective aluminum hydroxide floc formation.

The chlorination process was evaluated based on residual chlorine concentration and disinfection efficiency. The results revealed that the residual chlorine levels at the outlet varied between 0.2 and 0.8 mg/L, depending on dosing rates and water quality conditions. Similar to coagulation, increasing chlorine dosage did

not always result in proportional improvements in disinfection performance. In cases where organic matter levels were high, a significant portion of chlorine was consumed in side reactions, reducing the availability of free chlorine for microbial inactivation. This led to the formation of combined chlorine species and a decrease in overall disinfection efficiency. The pH of treated water was found to play a crucial role in determining the effectiveness of chlorination, as higher pH values favored the formation of hypochlorite ions, which are less effective disinfectants compared to hypochlorous acid.

The relationship between chlorine dosage and residual concentration highlighted the presence of inefficiencies in dosing practices. In several instances, excess chlorine was applied to compensate for variations in water quality, resulting in higher residual levels than required. This not only increases chemical consumption but also raises concerns regarding the formation of disinfection by-products. The analysis suggests that optimizing chlorine dosing based on real-time water quality parameters can significantly improve disinfection efficiency while reducing chemical usage. By maintaining appropriate pH conditions and minimizing organic load prior to disinfection, the effectiveness of chlorine can be enhanced without the need for excessive dosing.

Energy consumption analysis provided further insights into the interaction between operational parameters and process efficiency. The total energy usage of the treatment plant was dominated by pumping and mixing operations, with the flash mixer contributing a significant portion of the overall energy demand. The results indicated that variations in energy input did not always correspond to improvements in treatment performance, particularly in the coagulation stage. In some cases, higher energy consumption was associated with reduced efficiency due to over-mixing and floc breakage. This highlights the non-linear relationship between energy input and process performance, emphasizing the need for optimized energy utilization.

The integration of energy and chemical consumption data revealed a clear coupling between these parameters and treatment efficiency. Inefficient mixing conditions led to increased chemical demand, while excessive chemical dosing resulted in higher sludge production and associated energy costs for handling and disposal. By analyzing these interactions, the study identified opportunities for reducing both energy and chemical usage through process optimization. For example, adjusting mixing intensity to achieve optimal dispersion can enhance reaction efficiency and reduce the need for excess coagulant. Similarly, improving upstream coagulation performance can lower the organic load entering the chlorination stage, thereby reducing chlorine demand. Figure 4 illustrates that both insufficient and excessive mixing adversely affect floc formation, emphasizing the need for optimized energy input during coagulation.

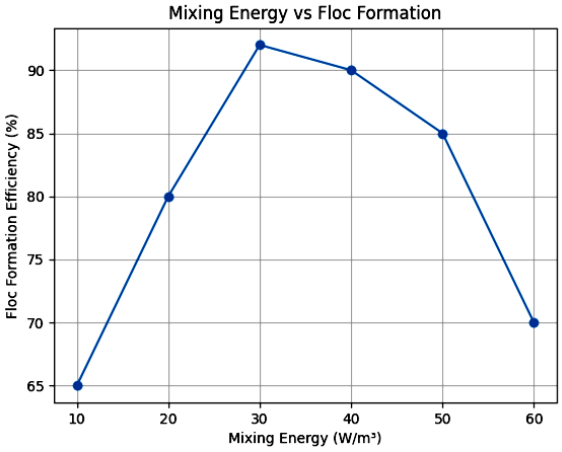

Figure 4. Effect of mixing energy on floc formation efficiency, indicating the presence of an optimal energy range between under-mixing and over-mixing conditions for effective coagulation.

A comparison between design-based assumptions and actual operational data highlighted significant discrepancies in system performance. While the plant was designed to operate under ideal conditions with optimized reaction environments, real-world operations exhibited variations in raw water quality, equipment performance, and operational practices. These variations led to deviations from expected performance, particularly in terms of chemical utilization and energy efficiency. The findings emphasize the importance of continuous monitoring and data-driven decision-making in maintaining optimal process conditions. The variation of residual chlorine with dosage, as shown in Figure 5, indicates that a portion of chlorine is consumed in side reactions, reducing the availability of free chlorine for effective disinfection.

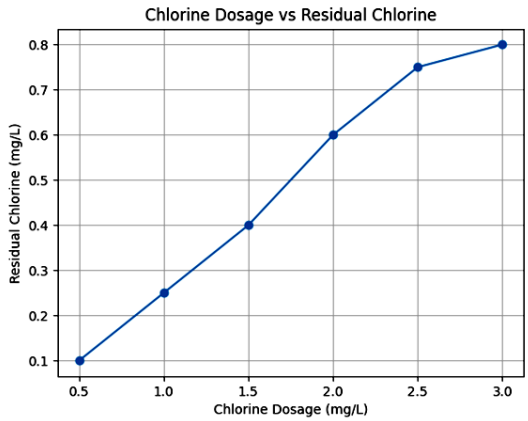

Figure 5. Relationship between chlorine dosage and residual chlorine concentration, demonstrating the influence of competing reactions and organic matter on chlorine demand during the disinfection process

The overall results demonstrate that a reaction mechanism – based approach provides valuable insights into the performance of water treatment processes. By linking chemical reactions with operational parameters and system-level outcomes, the study offers a comprehensive framework for identifying inefficiencies and implementing targeted improvements. The optimization of coagulation and chlorination processes not only enhances treatment performance but also contributes to the sustainability of water treatment operations by reducing resource consumption and waste generation.

In conclusion, the results highlight that effective water treatment is not solely dependent on chemical dosage but on the optimization of reaction conditions and process parameters. The integration of field data with chemical engineering principles enables a deeper understanding of process dynamics and supports the development of efficient and sustainable treatment strategies. The findings of this study provide a strong foundation for further research and practical implementation of optimized water treatment processes in similar systems.

4. Discussion

The present study demonstrates that the performance of conventional water treatment processes is fundamentally governed by the interplay between reaction mechanisms, operational parameters, and energy input. Unlike traditional approaches that rely on fixed dosing strategies and empirical guidelines, the findings highlight that treatment efficiency is strongly dependent on maintaining optimal chemical reaction conditions. This is particularly evident in the coagulation process, where the hydrolysis and precipitation behavior of aluminum species are highly sensitive to pH, alkalinity, and mixing intensity. Deviations from optimal conditions resulted in incomplete reactions, leading to inefficient utilization of coagulants and increased sludge production. These observations reinforce the importance of adopting a reaction engineering perspective in process design and operation.

The results also emphasize the critical role of hydrodynamics in facilitating chemical reactions within treatment units. Mixing conditions directly influence mass transfer, reaction kinetics, and particle interactions, thereby determining the overall effectiveness of coagulation. Insufficient mixing limits the dispersion of coagulants and reduces collision efficiency, while excessive mixing disrupts floc formation and stability. This dual effect highlights the need for precise control of energy input to achieve a balance between reaction completion and floc integrity. From a chemical engineering standpoint, this underscores the significance of coupling reaction kinetics with transport phenomena to optimize process performance.

In the context of chlorination, the study reveals that disinfection efficiency is not solely a function of chlorine dosage but is significantly influenced by water chemistry and competing reactions. The presence of natural organic matter leads to side reactions that consume chlorine and reduce the availability of active disinfecting species. Furthermore, the pH-dependent equilibrium between hypochlorous acid and hypochlorite ions plays a crucial role in determining disinfection effectiveness. These findings suggest that optimizing upstream processes, such as coagulation, can indirectly enhance disinfection efficiency by reducing the organic load and minimizing chlorine demand. This integrated approach aligns with the principles of process intensification, where improvements in one stage contribute to overall system efficiency.

Another important aspect highlighted by the study is the coupling between energy consumption and chemical efficiency. The results indicate that higher energy input does not necessarily translate into improved treatment performance, particularly when reaction conditions are not optimized. Instead, inefficient mixing can lead to increased chemical demand, thereby amplifying both operational costs and environmental impacts. This non-linear relationship between energy and process efficiency suggests that optimization efforts should focus on achieving the most effective use of energy rather than simply increasing input. Such an approach is consistent with sustainable chemical engineering practices, which aim to minimize resource consumption while maintaining high levels of performance.

The discrepancies observed between design assumptions and actual plant performance further illustrate the limitations of conventional design methodologies. While theoretical models often assume ideal conditions, real-world systems are subject to variability in raw water quality, equipment efficiency, and operational practices. This gap underscores the need for data-driven optimization strategies that incorporate real-time measurements and field-scale observations. By integrating experimental data with reaction-based analysis, the study provides a more accurate representation of system behavior and identifies practical opportunities for improvement.

Overall, the discussion highlights that a reaction mechanism‐driven framework offers significant advantages over traditional empirical approaches in water treatment. By focusing on the fundamental principles of chemical engineering, including reaction kinetics, mass transfer, and process integration, it is possible to achieve more efficient and sustainable treatment outcomes. The insights gained from this study can be extended to similar treatment systems, providing a basis for optimizing chemical usage, reducing energy consumption, and improving overall process performance.

5. Conclusion

This study presents a reaction mechanism‐driven evaluation of coagulation and chlorination processes in a full-scale drinking water treatment system, emphasizing the critical role of chemical engineering principles in optimizing process performance. The findings demonstrate that treatment efficiency is not solely dependent on chemical dosage but is strongly influenced by reaction conditions, including pH, mixing intensity, and contact time. In the coagulation stage, improper control of hydrolysis conditions and mixing energy resulted in incomplete reactions, leading to excessive alum consumption and increased sludge generation without proportional improvement in turbidity removal. Similarly, in the chlorination process, inefficiencies were

observed due to pH-dependent speciation and competing reactions with organic matter, which reduced the availability of active disinfecting agents and increased chlorine demand.

The integration of field-scale data with reaction-based analysis revealed a clear coupling between energy input and chemical efficiency. It was observed that both under-mixing and over-mixing adversely affected process performance, highlighting the importance of optimizing hydrodynamic conditions to ensure effective reaction completion. Furthermore, discrepancies between design assumptions and actual plant operation underscore the need for real-time monitoring and data-driven process control strategies.

Overall, the study establishes that a systematic approach based on reaction kinetics and process engineering can significantly enhance the efficiency and sustainability of water treatment systems. By optimizing operational parameters, it is possible to reduce chemical consumption, minimize waste generation, and improve energy utilization. The proposed framework provides a practical foundation for advancing conventional treatment processes toward more efficient and environmentally sustainable operation, with potential applicability to a wide range of water treatment facilities.

Author contributions

Conceptualization, Ali T. Alzeyadi and Ahmed M. Al-Sulaiman; methodology, Ali T. Alzeyadi; software, Ahmed M. Al-Sulaiman; validation, Ali T. Alzeyadi, Ahmed M. Al-Sulaiman and Ali W. Al-Attabi; formal analysis, Ali W. Al-Attabi; investigation, Ali T. Alzeyadi; resources, Ali T. Alzeyadi; data curation, Ali W. Al-Attabi; writing—original draft preparation, Ali T. Alzeyadi; writing—review and editing, Ahmed M. Al-Sulaiman; visualization, Ali T. Alzeyadi; supervision, Ahmed M. Al-Sulaiman; project administration, Ahmed M. Al-Sulaiman; funding acquisition, Ali T. Alzeyadi. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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