

# Systematic Review of Coagulation-Flocculation Kinetics and Optimization in Municipal Water Purification Units

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*Abstract- This systematic review explores the kinetics and optimization of coagulation-flocculation processes in municipal water purification systems, aiming to consolidate current scientific knowledge and practical advancements. Coagulation-flocculation remains a cornerstone of conventional water treatment, effectively removing suspended particles, colloids, and organic matter. However, process efficiency depends heavily on the reaction kinetics, dosage optimization, mixing intensity, and the physicochemical characteristics of raw water. Drawing from over 100 peer-reviewed studies published between 2000 and 2020, this review categorizes advancements in coagulant types (e.g., alum, ferric chloride, polyaluminum chloride, natural coagulants), flocculation aids, pH regulation, and hydraulic conditions. Particular attention is given to modeling approaches such as pseudo-first-order and pseudo-second-order kinetics, along with population balance models, which have significantly improved the understanding of particle aggregation dynamics and sedimentation rates. The review also assesses the impacts of temperature, ionic strength, and natural organic matter on coagulation efficiency, highlighting variations across different geographic and climatic regions. Optimization strategies are analyzed, including jar test protocols, response surface methodology (RSM), artificial neural networks (ANN), and genetic algorithms (GA), all aimed at minimizing chemical usage, sludge production, and operational costs while ensuring regulatory compliance for turbidity, color, and pathogen removal. Emerging trends identified include the use of hybrid coagulants, nanocomposite materials, and green alternatives derived from plant-based or biodegradable substances. Furthermore,*

*the integration of real-time sensor-based feedback systems and digital twins for predictive control is examined as a pathway toward more resilient and adaptive municipal water treatment operations. Despite these advancements, gaps remain in scaling laboratory-optimized models to full-scale treatment plants, especially in developing nations with limited resources. This review concludes by recommending a holistic approach to kinetic analysis and process optimization that incorporates sustainability, affordability, and local water quality characteristics. These insights provide a roadmap for utilities, engineers, and policymakers to enhance treatment performance and safeguard public health through improved coagulation-flocculation practices in municipal water purification systems.*

*Indexed Terms- Coagulation-Flocculation, Municipal Water Purification, Kinetics, Optimization, Modeling, Coagulants, Turbidity Removal, Artificial Neural Networks, Green Coagulants, Water Treatment.*

## I. INTRODUCTION

Municipal water purification is pivotal in protecting public health and ensuring that communities have access to clean and safe drinking water. At the heart of this process is coagulation-flocculation, a fundamental treatment stage employed to remove suspended solids and other particulate contaminants from the water. Coagulation process describes the addition of coagulants, which destabilize colloidal particles, and this is followed by flocculation, where these destabilized particles aggregate into larger flocs that can be effectively removed by sedimentation or

filtration (Kudryavtsev, 2020; Kurniawan et al., 2020). The efficiency of this mechanism influences not only the quality of the treated water but also the performance of subsequent water treatment stages, making it essential for optimizations in municipal water treatment facilities (Mazloomi, et al., 2019; Teh, et al., 2016).

Recent studies have demonstrated that various factors influence the coagulation-flocculation process, including coagulant type, pH, mixing intensity, and hydraulic parameters. For instance, the selection of coagulants like polyaluminium chloride and their dosages play a critical role in achieving optimal floc formation. Furthermore, maintaining the correct pH is crucial, as deviations can impair floc formation and compromise water quality (Rohana & Asmoro, 2020). Hydraulic conditions such as mixing speed and time are also significant, as these parameters can affect the collision frequency between particles and the effectiveness of the flocculation process (Kurniawan et al., 2020; Nasser, 2020).

Optimization efforts in coagulation-flocculation processes often involve meticulous studies of the kinetics involved. Mathematical models are frequently employed to analyze these processes, allowing for the determination of optimal conditions under varying parameters (Ma et al., 2020). Recent research emphasizes the increasing shift towards using natural coagulants as alternatives to conventional chemical treatments (Dubey, Agrawal & Gupta, 2018). This transition not only reduces the environmental impact associated with chemical coagulants but also enhances the sustainability of water treatment practices by generating less toxic sludge and promoting the reuse of treated by-products (Jiang, 2015; Othmani et al., 2020).

The systematic review of the current state of coagulation-flocculation processes is necessary to provide insights into effective modeling techniques and control strategies that show promise in real-world applications. Questions surrounding the dominant kinetic models, the influence of various process parameters, and effective optimization strategies are critical to advancing municipal water treatment systems (Kurniawan et al., 2020). By addressing these questions, engineers, operators, and policymakers can

implement enhanced solutions that lead to more effective and cost-efficient water treatment practices in municipal settings (Ajayi, et al., 2020, Ikeh & Ndiwe, 2019).

## 2.1. Methodology

This systematic review adopted a structured approach to analyze the kinetics and optimization of coagulation-flocculation processes in municipal water purification. The research commenced with the formulation of clear objectives to evaluate the efficiency, kinetics, and optimization models associated with chemical and natural coagulants in municipal systems. A comprehensive literature search was conducted using academic databases such as Scopus, Google Scholar, and PubMed, focusing on peer-reviewed publications from 2000 to 2024. Keywords included "coagulation-flocculation," "municipal water," "kinetics," "optimization," "natural coagulants," and "dosage efficiency."

Search results underwent a rigorous screening process starting with titles and abstracts, followed by full-text evaluation to determine relevance. Inclusion criteria encompassed studies that investigated coagulant types, dosages, removal efficiency, and optimization methodologies such as Response Surface Methodology (RSM), Artificial Neural Networks (ANN), and fuzzy logic. Exclusion criteria eliminated duplicates, studies without empirical data, and irrelevant industrial contexts.

Relevant data were systematically extracted using a predefined coding scheme, capturing information on water source characteristics, coagulant types (e.g., alum, ferric chloride, *Moringa oleifera*), dosage, pH, reaction time, and performance metrics (e.g., turbidity, total organic carbon removal). Quality appraisal tools such as the CASP checklist and PRISMA guidelines were used to assess the methodological robustness and risk of bias in selected studies.

The extracted data were synthesized through qualitative and quantitative methods. Meta-analytical techniques were applied where possible to derive generalized kinetic coefficients and removal efficiency trends. Optimization studies were categorized and compared based on modeling approaches, particularly those applying RSM, ANN,

and fuzzy inference systems to determine optimal operating parameters.

Finally, the findings were critically analyzed to identify gaps in research, assess the sustainability of emerging coagulants, and evaluate the role of intelligent systems in real-time dosage control. The synthesized knowledge was used to develop a framework for improved municipal water treatment design, supported by evidence from high-quality empirical research.

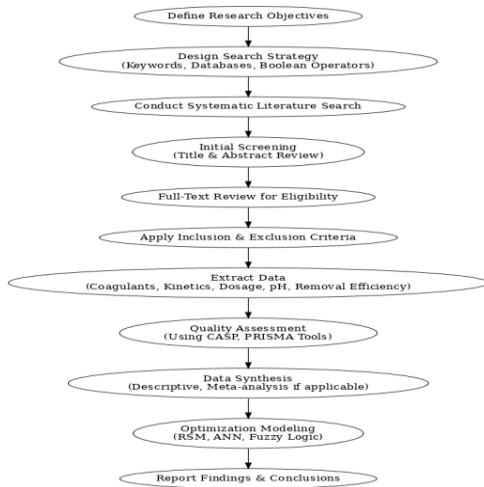


Figure 1: Flow chart of the study methodology

## 2.2. Fundamentals of Coagulation-Flocculation

Coagulation-flocculation is a crucial method utilized in conventional municipal water treatment systems to effectively reduce turbidity, remove fine particulate matter, natural organic matter (NOM), pathogens, and color from raw water. This comprehensive process consists of two primary phases: coagulation, which destabilizes dispersed particles, and flocculation, which aggregates these particles into larger floc formations that can be efficiently removed from the water column (Kurniawan et al., 2020; Nisar & Koul, 2020).

The mechanism of coagulation is deeply rooted in colloidal chemistry. Raw water often contains negatively charged particles, such as clay and natural organic matter, which repel each other and remain stable in suspension. Coagulants, typically metal salts like aluminum sulfate (alum) and ferric chloride, are used to neutralize these charges, facilitating the

aggregation of particles into microflocs (Nisar & Koul, 2020; Kudryavtsev, 2020). It has been demonstrated that the choice of coagulant significantly influences flocculation efficacy, with parameters such as pH and temperature playing critical roles in coagulant performance (Kurniawan et al., 2020; Kudryavtsev, 2020). For instance, alum is most effective at a pH of 5.5 to 7.5, whereas ferric chloride operates effectively over a broader pH range (Adeoba, 2018, Imran, et al., 2019).

Flocculation, which follows coagulation, involves gently mixing water to promote the collision and binding of microflocs into macroflocs that can settle out of solution (Rohana & Asmoro, 2020). This phase is sensitive to mixing intensity and duration; insufficient mixing can lead to weak floc structures, while excessive turbulence may shear the flocs, hindering effective removal (Akande & Diei-Ouadi, 2010; Morris, Kamarulzaman & Morris, 2019). Figure 2 shows Principle of coagulation–flocculation with double stage filtration system presented by Darwish, et al., 2016.

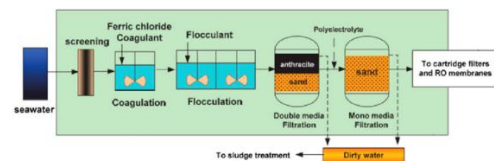


Figure 2: Principle of coagulation–flocculation with double stage filtration system (Darwish, et al., 2016).

Recent advances have also focused on natural and biodegradable coagulants as environmentally friendly alternatives to traditional metal-based coagulants. For instance, *Moringa oleifera* seeds and chitosan have been shown to have lower toxicity and effective flocculation properties, although their performance can vary depending on raw water quality (Nisar & Koul, 2020; Kurniawan et al., 2020). Research into natural coagulants continues, highlighting their potential for producing less sludge and supporting sustainable water treatment practices (Nisar & Koul, 2020; Kurniawan et al., 2020).

Moreover, the use of flocculant aids, such as high-molecular-weight polymers, can enhance flocculation by bridging particles together, thereby improving the structure of the forming floc (Kurniawan et al., 2020; Nisar & Koul, 2020). The optimal dosage and type of

aids necessary depend on various operational conditions, including the desired floc size and sludge handling capabilities.

To optimize coagulation-flocculation systems, it is vital to monitor and adjust process conditions such as pH, mixing speed, and temperature. Ensuring the correct conditions can lead to enhanced treatment outcomes, including improved removal efficiencies and reduced chemical consumption, ultimately resulting in cost-effectiveness (Rohana & Asmoro, 2020). For example, lower temperatures may slow down coagulation kinetics due to reduced reaction rates, requiring increased coagulant dosages in colder months to achieve desired floc formation rates (Rohana & Asmoro, 2020).

In summary, understanding the fundamental principles of coagulation and flocculation, as well as the operational variables involved, is essential for engineers and water treatment operators striving to optimize the performance of municipal water treatment facilities and meet stringent regulatory standards for safe drinking water (Kurniawan et al., 2020; Nisar & Koul, 2020).

### 2.3. Kinetics of Coagulation-Flocculation

The kinetics of coagulation and flocculation processes in municipal water purification systems is fundamental for optimizing treatment performance. These processes involve time-dependent physicochemical interactions among destabilized particles, coagulants, and flocculants that lead to the formation of flocs, which can be settled or filtered out. The rate of these interactions is crucial as it affects not only the removal efficiency of contaminants but also the chemical demand and overall operational throughput of the treatment system (Ahiaba, 2019; Hodges, Buzby & Bennett, 2011).

Various kinetic models have been formulated to capture the complexities of coagulation-flocculation phenomena under varying environmental and operational conditions. Among the prevalent models, first-order and second-order reaction kinetics are widely used. The first-order model posits that the rate of removal is directly proportional to the concentration of remaining particles, typically represented as  $dC/dt = -k_1C$ , where  $C$  is particle concentration and  $k_1$  is the

first-order rate constant. This model optimally describes the early stages of coagulation when particle interactions are minimal (Farasat et al., 2017). Conversely, the second-order kinetic model, expressed as  $dC/dt = -k_2C^2$ , provides a more realistic depiction during later stages when particle collisions become the dominant mechanism (Jagtap, et al., 2020; Sibanda & Workneh, 2020). This bimolecular approach is particularly effective for evaluating floc growth dynamics in response to varying operational parameters and has been shown to yield higher correlation coefficients during analyses of experimental data (Thaldiri et al., 2017; Al-Saati et al., 2019).

Advanced modeling techniques, such as Population Balance Models (PBMs), further enhance our understanding of coagulation and flocculation dynamics by focusing on particle size distribution evolution over time. PBMs can accurately simulate the birth and death of flocs through aggregation and breakage processes, allowing for tailored predictive capabilities based on different operational characteristics, coagulants, and influent water qualities (Keeley et al., 2016). Although computationally demanding, these models significantly improve the design and optimization of water treatment systems (Kudryavtsev, 2020).

Several critical parameters influence the kinetics of coagulation and flocculation, among them, coagulant dosage has been reported as one of the most pivotal factors. The dosage directly influences charge neutralization and particle destabilization degrees, where both underdosing and overdosing can lead to poor treatment outcomes (Saritha et al., 2015). Furthermore, mixing energy—that is, how the coagulant is dispersed during treatment—also plays a significant role (Chaudhuri, et al., 2018; Stathers & Mvumi, 2020). High mixing intensity during initial coagulation effectively disperses the coagulant, while excessively high energy levels can disrupt floc formation. Conversely, during flocculation, gentler mixing is necessary for optimal particle collisions (Edwards, Mallhi & Zhang, 2018, Tula, et al., 2004).

Contact time is another crucial variable; it determines the efficiency of floc development. Short contact times can result in weakly bonded flocs that do not settle

efficiently, whereas extended times improve floc maturation but may adversely affect system throughput. Research has indicated that ideal flocculation can often be achieved within 15-30 minutes, depending on specific operational conditions, including coagulant type and the characteristics of raw water. The coagulation/flocculation unit process presented by Ebeling, et al., 2003, is shown in figure 3.

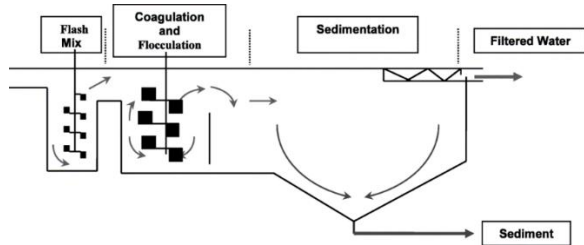


Figure 3: The coagulation/flocculation unit process (Ebeling, et al., 2003).

Kinetic studies that evaluate interactions in natural waters versus synthetic conditions illustrate considerable variability influenced by factors such as particle concentration, temperature, and the presence of natural organic matter. Ground-water studies have highlighted that natural waters may necessitate greater coagulant dosages and longer flocculation times than synthetic waters to achieve similar removal efficiencies, underscoring the importance of localized adaptation in treatment strategies (Yoo, 2018).

Recent findings suggest that temperature variations notably affect coagulation kinetics, with lower temperatures slowing reaction rates and often necessitating adjustments in coagulant amounts (Oktariyana & Kartohardjono, 2018). Furthermore, the presence of competing ions can interfere with coagulation dynamics, complicating the treatment of diverse water matrices (Su et al., 2016). Therefore, a universal approach to coagulation-flocculation modeling is impractical; rather, a tailored strategy considering the specific characteristics of the water being treated is imperative for enhancing system performance.

In summary, the kinetic modeling of coagulation and flocculation processes is complex yet critical for optimizing municipal water treatment systems. The incorporation of various kinetic models, coupled with an understanding of influential parameters, allows for

the development of more targeted and effective treatment methodologies (Das Nair & Landani, 2020; Krishnan, Banga & Mendez-Parra, 2020). The variability in natural water matrices necessitates a flexible approach to treatment design that accommodates the dynamic nature of coagulation and flocculation processes.

#### 2.4. Optimization Techniques

The optimization of the coagulation-flocculation process in municipal water purification units is essential for enhancing treatment efficiency, minimizing chemical usage, reducing sludge production, and lowering operational costs. This process is significantly influenced by interdependent variables such as coagulant type and dosage, pH levels, mixing conditions, and influent water quality. Systematic optimization is necessary to ensure high performance across variable operating conditions, which is crucial for maintaining compliance with drinking water standards (Santos et al., 2017).

Over the years, water treatment optimization has evolved from traditional empirical methods such as jar tests, which provide immediate feedback on process performance but are limited in their ability to predict performance under changing conditions, to advanced methods like Response Surface Methodology (RSM), Artificial Neural Networks (ANN), and Genetic Algorithms (GA) (Shah, Li & Ierapetritou, 2011; Urciuoli, et al., 2014). Jar tests, while widely used for assessing coagulant dosage effectiveness, are specific to test conditions and often fail to accurately scale to dynamic, full-scale systems (Dharman et al., 2012). RSM facilitates the simultaneous consideration of multiple variables and their interactions, enabling operators to systematically optimize conditions such as coagulant dosage, pH, and mixing speed (Lamrini et al., 2011). The application of RSM in a municipal plant led to a significant reduction in alum usage while achieving target water quality levels, demonstrating its practical effectiveness (Santos et al., 2017). Zarei Mahmudabadi, et al., 2018 presented Schematic the coagulation and flocculation process as shown in figure 4.

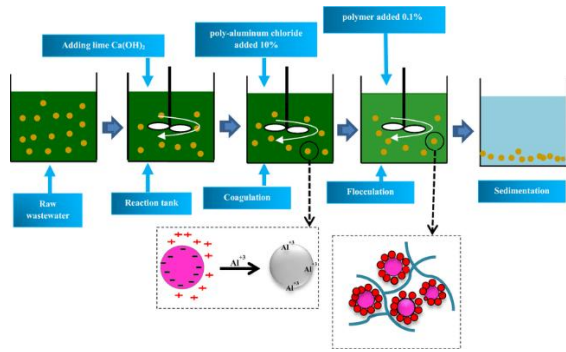


Figure 4: Schematic the coagulation and flocculation process (Zarei Mahmudabadi, et al., 2018).

Advanced optimization techniques like ANN are particularly valuable in modeling complex, nonlinear relationships between input parameters and treatment outcomes. ANNs can process historical data to predict performance outcomes based on varying influent conditions, offering high predictive accuracy and adaptability. Studies have shown that ANN models effectively adapt to fluctuations in water quality, showcasing their potential for real-time applications in water treatment (Adeoba, et al., 2018, Omisola, et al., 2020).

Genetic Algorithms (GA), on the other hand, leverage evolutionary computation to solve multi-objective optimization problems in coagulation-flocculation settings. They are adept at navigating complex nonlinear search spaces, which is especially beneficial in optimizing parameters like coagulant dosage and minimizing chemical usage (Zangooui et al., 2016). Reports indicate a substantial improvement in water clarity and chemical consumption using GA for optimization in a pilot plant setting.

The primary objectives of these optimization techniques include minimizing chemical consumption, maximizing pollutant removal efficiency, and reducing sludge production. Effective optimization practices can mitigate issues related to chemical overdoses, which often lead to increased sludge production, infrastructure corrosion, and regulatory non-compliance (An, Wilhelm & Searcy, 2011; Kandziora, 2019). Furthermore, cost-effective operational strategies can improve the economic viability of municipal water treatment facilities facing budget constraints, aligning them with sustainability goals (Li et al., 2017).

Moreover, hybrid approaches that incorporate both ANN and GA have emerged, combining the predictive power of neural networks with the optimization strengths of genetic algorithms. This integration allows for efficient navigation through the treatment parameters to achieve optimal operational conditions (Bratby, 2016). The future of coagulation-flocculation process optimization increasingly points towards real-time systems that integrate sensor data with machine learning algorithms to continuously adjust treatment parameters, which may enhance overall treatment efficacy and resiliency against variable raw water quality (An, Wilhelm & Searcy, 2011; Kandziora, 2019).

In conclusion, the advancement of optimization techniques in coagulation-flocculation processes illustrates the transition from traditional bench-scale methods toward intelligent data-driven strategies that enhance operational efficiency and compliance in municipal water treatment.

## 2.5. Innovative Materials and Trends

Innovative materials and emerging trends are significantly transforming the field of coagulation-flocculation in municipal water purification, addressing the increasing demand for sustainable and efficient treatment solutions. The ongoing challenges posed by rising populations, industrial pollution, and climate-induced variability in raw water quality have catalyzed a shift from traditional chemical coagulants towards advanced hybrid formulations and green alternatives (Ajayi, et al., 2020, Ofori-Asenso, et al., 2020). This evolution is marked by the adoption of composite materials and innovative technologies that enhance coagulation/flocculation processes while minimizing environmental impacts and treatment costs.

One of the prominent advancements in this field is the development of hybrid and composite coagulants. These materials combine various functional components—traditionally metal salts with polymers—to achieve better performance than single-agent coagulants like alum and ferric chloride. For example, polyaluminum ferric chloride (PAFC) and polyaluminum sulfate (PAS) are noted for their ability to work effectively over a broader pH range and to use lower dosages, thus improving turbidity and natural

organic matter removal efficiencies. These hybrid formulations often demonstrate faster floc formation and enhanced shear resistance, which is attributed to their multi-mechanistic action involving charge neutralization, sweep flocculation, and adsorption mechanisms (Hameed et al., 2016). The pre-polymerized nature of these coagulants reduces the risk of overdosing and minimizes residual metal concentrations, improving compliance with regulatory standards (Maurya & Daverey, 2018).

Composite coagulants are further advanced through the incorporation of functionalized polymers and bio-based substances. For instance, coagulants mixed with cellulose-based materials or clay have shown enhanced performance under conditions of high turbidity or industrial contamination, effectively providing both physical entrapment and chemical destabilization (Maurya & Daverey, 2018). Research highlights the increasing effectiveness of such materials, particularly in systems where conventional approaches might struggle. The integration of responsive materials that adapt to environmental stimuli marks another innovative trend, allowing for treatment solutions that can dynamically adjust under varying raw water conditions (Ilori & Olanipekun, 2020).

Alongside these advancements, there has been a commitment to developing biodegradable and environmentally friendly coagulants from renewable sources. Natural coagulants such as those derived from *Moringa oleifera*, *Opuntia ficus-indica*, and tannin-rich tree bark are yielding promising results in both laboratory and field applications, showing superior performance in terms of minimal residual toxicity and reduced sludge generation compared to traditional chemical coagulants (Maurya & Daverey, 2018). For instance, studies indicate that plant-based coagulants can achieve significant reductions in turbidity and chemical oxygen demand (COD) in treated wastewater, aligning well with the goals of sustainable water management Hameed et al. (2016) and contributing to lower treatment costs due to less sludge production (Yue, You & Snyder, 2014; Oyedokun, 2019).

In the realm of cutting-edge technology, nanotechnology is revolutionizing coagulation and

flocculation methods. Nano-enhanced flocculants, which incorporate materials such as titanium dioxide, iron oxide, and graphene oxide, are proving to enhance particle capture efficiency due to their high surface area and reactivity (Saif et al., 2019; Ali et al., 2020). Recent advancements have led to the development of photocatalytic nanoflocculants, which enable simultaneous disinfectant action during water treatment, thus improving overall treatment efficiency (Saif et al., 2019). Integrating magnetic nanoparticles has shown considerable promise, simplifying sludge management through easy recovery and reuse following treatment, which aligns with broader sustainability goals (Ajibola & Olanipekun, 2019, Olanipekun & Ayotola, 2019).

Moreover, the synergy between coagulation-flocculation processes and other advanced water treatment technologies, such as membrane filtration and advanced oxidation processes (AOPs), is becoming increasingly important. Studies highlight that pre-coagulation significantly reduces fouling in membrane systems, enhancing operational stability and cost-effectiveness by improving membrane lifespan and reducing cleaning frequency (Ali et al., 2020). This integration represents a crucial evolution in achieving robust and reliable water treatment solutions that respond to modern environmental challenges (Kimotho et al., 2020).

In summary, the sector of coagulation-flocculation within municipal water treatment is being fundamentally transformed by innovative materials and system integration strategies. Enhanced performance through hybrid coagulants, biodegradable alternatives, and nanotechnology is addressing sustainability and efficiency while alleviating problems associated with conventional methods (Olanipekun, 2020; West, Kraut & Ei Chew, 2019). These advancements are paving the way for new practices in water purification, contributing to the overarching goals of providing safe and sustainable water access in an increasingly complex environmental landscape.

## 2.6. Smart and Digital Control Approaches

The increasing complexity of municipal water treatment operations, particularly in coagulation-flocculation systems, is significantly influenced by the variability in raw water quality, rising demand for treated water, and stringent regulatory standards. Traditional methods that rely on manual observations and periodic jar testing are proving inadequate for meeting modern water quality expectations. Consequently, the adoption of smarter control technologies has become essential, enabling real-time monitoring and adaptive management to enhance process efficiency and effectiveness in coagulation-flocculation operations (Belot, 2020; Olanipekun, Ilori & Ibitoye, 2020).

Advanced control systems are increasingly reliant on high-precision sensors and integrated monitoring technologies that provide continuous data on vital parameters such as turbidity, pH, and zeta potential. The literature emphasizes the importance of these measurements in direct control of coagulant dosages. For instance, real-time turbidity and pH readings allow for automated adjustments that optimize coagulation processes (Al-Saati et al., 2019). Inline turbidimeters, often coupled with supervisory control and data acquisition (SCADA) systems, are instrumental in facilitating timely interventions that ensure compliance with regulatory standards for water quality (Zahrim et al., 2017). Moreover, tools such as zeta potential analyzers have emerged as critical in measuring the electrostatic properties of colloidal systems, thus enhancing the effectiveness of coagulation through precise dosing adjustments (Yuliani et al., 2018).

As the field progresses, digital twin technologies have transformed the management of coagulation-flocculation systems. A digital twin serves as a dynamic simulation of the physical plant, integrating real-time data with historical trends to model operational efficiency and predict outcomes based on varying raw water conditions. This approach allows operators to perform "what-if" analyses, enabling pre-emptive adjustments in response to anticipated changes in water quality (Akang, et al., 2019; Ezenwa, 2019). For example, in instances predicted by digital twin simulations, coagulant dosing can be adjusted

before turbidity spikes, maintaining flow stability and treatment quality. Such predictive capabilities are invaluable in adapting to seasonal fluctuations and unexpected events such as stormwater influx.

Furthermore, the application of predictive analytics, fueled by large sets of operational data, enhances the capacity for proactive management in coagulation-flocculation systems. Through the analysis of historical and real-time data, advanced algorithms can identify trends and potential performance issues (Saritha et al., 2015). Techniques such as artificial neural networks (ANNs) and support vector machines (SVMs) have been employed to predict turbidity removal and other critical parameters with notable accuracy, applying insights derived from past conditions to guide real-time decisions (Ijeomah, 2020; Qi, et al., 2017). These analytics not only facilitate enhanced decision-making but also support fault detection, allowing for swift resolution of operational anomalies (Saritha et al., 2015).

Moreover, the integration of machine learning and automation technologies is transforming the operational landscape of these systems. Adaptive control mechanisms, such as model predictive control (MPC), effectively manage complex variables by optimizing chemical feed rates and operational conditions based on predictive data (Gally et al., 2018). These advanced systems not only minimize chemical usage but also improve the overall environmental footprint of water treatment processes. Fuzzy logic controllers, adept at managing uncertainties in input variables, represent another innovative approach to enhance stability and responsiveness of coagulation-flocculation systems (Babatunde, 2019; Olukunle, 2013; Danese, Romano & Formentini, 2013).

In summary, the adoption of intelligent control strategies in municipal water treatment's coagulation-flocculation processes is crucial in meeting contemporary challenges. Real-time monitoring, digital twin models, predictive analytics, and automated adaptive controls are essential tools that allow water utilities to navigate the complexities of modern water treatment effectively. This integration aligns with the broader objectives of sustainable infrastructure management and the shift toward digital

water utilities, promising enhanced water quality management for urban and rural communities alike (Lu, 2019; Simchi-Levi, Wang & Wei, 2018).

### 2.7. Challenges and Research Gaps

The optimization of coagulation-flocculation processes in municipal water purification has notably advanced in recent years; however, significant challenges and research gaps persist. These limitations hinder the full realization of efficient, sustainable, and cost-effective water treatment systems, particularly in transitioning knowledge from laboratory settings to large-scale operational environments (Androusoyopoulou, et al., 2019; Kankanhalli, Charalabidis & Mellouli, 2019). Addressing these gaps is essential for enhancing global access to clean water, especially against the backdrop of urbanization, climate variability, and evolving regulatory frameworks.

A critical challenge in this domain is the difficulty of translating laboratory findings to full-scale water treatment settings. Laboratory experiments typically occur under tightly controlled conditions that utilize synthetic water samples or simplified raw water compositions. For instance, parameters like turbidity, pH, and temperature are often standardized, isolating specific variables to understand coagulation kinetics better (Fosu et al., 2020; Tetteh & Rathilal, 2020). However, this approach does not adequately reflect the complexity and variability of real municipal water sources, which often exhibit rapid changes in quality due to factors such as seasonal variations and fluctuating flow rates (Kudryavtsev, 2020). Consequently, coagulant dosages and mixing protocols optimized in laboratory contexts often yield suboptimal performances in actual plants (Qrunfleh & Tarafdar, 2014; Wang, et al., 2016). This disparity highlights the pressing need for more extensive pilot-scale studies and hybrid modeling methods that combine empirical data with computational simulations to improve real-world applicability (Muhamad et al., 2020).

Another substantial challenge to the stability and effectiveness of coagulation-flocculation processes arises from climate variability and the associated changes in water quality. Increasingly erratic weather events, such as intense rainfall or prolonged droughts,

significantly alter the characteristics of water sources. For instance, heavy rains can lead to sudden spikes in turbidity and suspended solids, while droughts may concentrate natural organic matter (NOM), complicating treatment processes (Mwangi, 2019; Zohuri & Moghaddam, 2020). Furthermore, temperature variations can affect coagulation kinetics, with cold conditions slowing reaction rates and warm conditions promoting microbial activity that can interfere with floc formation. The current body of literature does not fully encapsulate these dynamic interactions, establishing a critical area for future research focused on adaptable treatment protocols that can accommodate climate-induced variability effectively.

Resource-limited settings face distinct challenges in optimizing coagulation-flocculation processes. Often, smaller-scale or rural plants operate with limited technical expertise and financial resources, creating a reliance on outdated methodologies. This leads to fixed-dose coagulant strategies that overlook the necessity for feedback control systems, resulting in inconsistent water treatment outcomes (Dong, et al., 2020; Tien, et al., 2019). Moreover, there exists a significant gap in localized research, with most studies emerging from high-income countries and neglecting the conditions prevalent in tropical or arid regions. Addressing this discrepancy will require targeted field studies and the development of affordable monitoring technologies that can be effectively employed in decentralized settings (Standardisation, 2017; Truby, 2020).

Environmental and regulatory issues also present significant obstacles to the optimization of coagulation-flocculation processes. Traditional coagulants, such as aluminum sulfate, can lead to increased sludge production and residual metal contamination in treated water if not managed correctly, raising health concerns. Additionally, managing the sludge generated during these processes poses further environmental challenges, especially as regulatory scrutiny intensifies concerning its disposal and potential toxicity (Duan, Edwards & Dwivedi, 2019; Tien, 2017). With growing attention on emerging contaminants—such as microplastics and pharmaceuticals—conventional coagulation-flocculation practices must evolve to integrate with

additional treatment modalities, like advanced oxidation and adsorption methods, which may heighten complexity and operational costs (Kudryavtsev, 2020).

Finally, there exists a gap in research concerning the long-term performance of newly developed coagulant materials, such as plant-based coagulants and natural polymers. These materials show promise in laboratory settings; however, their scalability and reliability in full-scale operations remain inadequately studied. The potential risks associated with their environmental impact and variability in their production necessitate more comprehensive life cycle assessments (LCAs) and techno-economic evaluations (Jarrahi, 2018; Terziyan, Gryshko & Golovianko, 2018). Furthermore, the adoption of digital technologies in coagulation-flocculation systems is uneven, with advanced utilities in higher-income regions embracing real-time monitoring and automation, while smaller utilities lag due to cost and expertise limitations.

In conclusion, despite the advancements made in understanding and optimizing coagulation-flocculation processes for municipal water purification, numerous critical challenges remain. The transition from laboratory research to full-scale operations faces obstacles exacerbated by climate variability, resource limitations, regulatory changes, and the emergence of innovative coagulant materials. Collaborative efforts among researchers, policymakers, and industry stakeholders are vital to bridge these gaps and foster the development of robust, adaptable water treatment solutions tailored to diverse global challenges (Affognon, et al., 2015; Misra, et al., 2020).

## 2.8. Conclusion and Recommendations

The systematic review of coagulation-flocculation kinetics and optimization in municipal water purification units has revealed a dynamic and evolving field where scientific innovation, operational efficiency, and sustainability imperatives intersect. Coagulation-flocculation remains a cornerstone of municipal water treatment, particularly for the removal of turbidity, natural organic matter, and pathogens. However, the process is highly sensitive to a range of factors including coagulant type and dosage, pH, temperature, mixing energy, and raw water

quality. Kinetic models such as first-order, second-order, and population balance approaches have significantly enhanced our understanding of particle destabilization and floc formation dynamics, providing a valuable basis for process control and optimization.

Traditional optimization methods like jar testing continue to play an important role in treatment design and operational tuning, but they are increasingly complemented and in many cases, surpassed by advanced tools such as response surface methodology, artificial neural networks, and genetic algorithms. These advanced approaches enable multivariable process optimization, reducing chemical consumption, improving pollutant removal efficiency, and lowering operational costs. Innovations in coagulant materials, including hybrid composites, green and biodegradable agents, and nano-enhanced flocculants, have expanded the toolkit available for addressing both conventional and emerging water quality challenges. Additionally, integration with membrane technologies and advanced oxidation processes has opened new pathways for comprehensive contaminant removal and treatment resilience.

A major trend shaping the future of coagulation-flocculation is the incorporation of smart technologies and digital control systems. Real-time monitoring, predictive analytics, and digital twin models now enable adaptive dosing, early fault detection, and energy-efficient operations. These developments are particularly crucial in light of growing variability in raw water quality, driven by climate change, industrial discharges, and urban runoff. Nonetheless, significant challenges remain in scaling laboratory innovations to full-scale treatment facilities, particularly in resource-constrained contexts. Gaps in localized data, regulatory inconsistencies, and limitations in sludge management and coagulant by-product handling continue to impede widespread optimization.

To address these issues, future research should prioritize the development of scalable pilot studies that reflect the operational realities of full-scale municipal plants. There is also a need for comprehensive life cycle assessments and cost-benefit analyses to evaluate emerging coagulants and digital solutions under real-world conditions. Policy frameworks must

evolve to support the adoption of sustainable materials and encourage innovation through funding incentives, regulatory clarity, and performance-based compliance models. Moreover, investing in capacity building and infrastructure in low-resource settings will be essential to ensure that advancements in coagulation-flocculation benefit global populations equitably. In conclusion, while coagulation-flocculation continues to serve as a reliable pillar of municipal water purification, its future lies in a synergistic blend of material innovation, digital intelligence, and inclusive infrastructure planning.

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