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Enhancement of coagulation-flocculation using Opuntia ficus-indica mucilage for turbidity removal: Ain Zada dam (Algeria)

Mohammed Tiaiba*[1], Belkacem Merzouk[2]

[1]Environment and Health Laboratory, Faculty of Natural and Life Sciences and Earth and Universe Sciences, Dept. of Agricultural Sciences, Mohamed El-Bachir El-Ibrahimi University, Bordj Bou Arreridj, 34000, Algeria
[2]Laboratory of Water, Environment and Renewable Energies, Faculty of Technology, University of M'sila, Dept. of Hydraulics, University Pole, Road Bordj Bou Arreridj, M'sila 28000, Algeria

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Abstract. Surface water quality deterioration presents critical challenges for drinking water production in arid regions, where sustainable treatment solutions are essential. This study investigates Opuntia ficus-indica (OFI) mucilage as a natural coagulant aid for turbidity removal from Ain Zada dam water in northeastern Algeria. We systematically evaluated coagulation-flocculation parameters including pH (4-10), four coagulants (aluminum sulfate, aluminum chloride, ferric sulfate, ferric chloride) at 100-500 mg L^{-1}, mixing conditions, settling time, pre-chlorination, and OFI mucilage (10-150 mL). Jar tests on water with 74-201 NTU turbidity revealed mixed organic-inorganic composition (60-70% organic colloids). A key finding is coagulant-specific compatibility with OFI mucilage: aluminum-based coagulants showed significant enhancement (aluminum sulfate improved from 57.69% to 75.77%; aluminum chloride from 68.61% to 81.85% with 10 mL mucilage per liter), while iron-based coagulants exhibited reduced efficiency (ferric sulfate decreased from 76.19% to 70.59%; ferric chloride from 79.62% to 74.43%), indicating fundamentally distinct chemical interactions between metal hydroxide surface chemistry and anionic mucilage polysaccharides. Pre-chlorination enhanced treatment to 82.85% removal while enabling 75% coagulant dose reduction. This work provides mechanistic insights into cactus-derived biopolymer integration in conventional water treatment, establishing design guidelines for sustainable implementation in arid regions where Opuntia ficus-indica is abundant.

Keywords: coagulant aid; coagulation-flocculation; mucilage; Opuntia ficus indica; surface water treatment; turbidity removal

1. Introduction

Freshwater availability poses a critical global challenge, with approximately 1.2 billion people lacking access to safe drinking water and over six million children dying annually from waterborne diseases [1, 2]. In North Africa, water scarcity presents unique challenges due to arid climate conditions, increasing urbanization, and growing industrial demands. The Ain Zada dam, serving as a strategic water source for northeastern Algeria, exemplifies regional water quality challenges faced by Algerian surface water treatment facilities. Economic constraints in

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*Corresponding author, Ph.D., E-mail: mohamed.tiaiba@univ-bba.dz

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developing countries make sustainable, locally-available treatment aids particularly valuable for enhancing conventional treatment processes while reducing dependence on imported chemicals, directly connecting to national water security and sustainable development goals.

Surface water quality has significantly deteriorated due to excessive accumulation of dissolved organic and inorganic substances, living organisms, and suspended solids [3, 4]. Water intended for human consumption requires comprehensive treatment: physical and chemical pretreatment, clarification through coagulation-flocculation, sedimentation, and filtration, followed by final disinfection.

The coagulation-flocculation technique has been widely applied in surface water treatment due to its numerous advantages [5]. It efficiently removes organic matter, suspended particles, and colloidal substances that contribute to turbidity, while also demonstrating high efficacy in eliminating protozoa, bacteria, and viruses. Additionally, the process is valued for its cost-effectiveness, ease of operation, and energy efficiency [6-8]. Among the most commonly employed inorganic coagulants are iron- and aluminum-based compounds, such as ferrous sulfate, ferric sulfate, ferric chloride, aluminum sulfate, polyferric sulfate, and polyaluminum chloride [9, 10].

In response to environmental and health concerns over synthetic coagulants, green technologies have emerged focusing on sustainable adsorbents from industrial by-products, agricultural wastes, or natural resources [11-13]. Opuntia ficus-indica mucilage has been studied as an eco-friendly material for removing heavy metals, dyes, and turbidity from water [14-17]. Zhang et al. [11] demonstrated that combining cactus coagulant with aluminum chloride improved conventional coagulation-flocculation sewage treatment efficacy compared to aluminum chloride alone. OFI mucilage offers significant advantages: it is biodegradable, non-toxic, and readily available in arid and semi-arid regions, making it a sustainable and cost-effective alternative to synthetic chemicals [9, 18].

The comprehensive testing of multiple conventional coagulants alongside OFI mucilage serves critical purposes. Practical considerations include varied availability and cost of different coagulants in Algeria, requiring flexibility in treatment options, and different performance levels under varying seasonal water quality conditions. Scientific justifications include understanding how OFI mucilage interacts with different coagulation mechanisms—specifically charge neutralization versus sweep flocculation—and studying charge interactions between Al^{3+} and Fe^{3+} ions with different charge densities and hydrolysis behaviors affecting their interaction with anionic polysaccharides in OFI mucilage.

This study aimed to evaluate the performance of coagulation-flocculation treatment for turbidity removal using different coagulants (aluminum sulfate, ferric sulfate, aluminum chloride, and ferric chloride) at various dosages. The investigation examined operational parameters including pH, mixing conditions, settling time, pre-chlorination, and coagulant aid types and dosages (synthetic anionic polyelectrolyte as flocculant aid, and OFI mucilage as natural coagulant aid) to determine optimal conditions for turbidity removal from surface water.

2. Materials and methods

2.1 Plant material and mucilage extraction

OFI cladodes (thornless variety) were collected from Ouled Dahmane region (Bordj Bou

Arreridj, 36°04'N, 4°46'E, 900 m altitude) in northeastern Algeria during April 2023. The cladodes were temporarily stored at 4°C until processing to preserve mucilage quality. The extraction of mucilage was performed according to the following protocol: cladodes were thoroughly cleaned with tap water followed by distilled water to remove impurities. Black spots were carefully removed, and the superficial cuticle was eliminated according to Adjeroud et al. [18], as this layer acts as a barrier to biomolecule extraction. The cleaned cladodes were air-dried at ambient temperature (22 ± 2°C) for 30 minutes, then cut into small pieces (approximately 2 × 2 cm). The diced plant tissues were homogenized for 45-50 seconds using a domestic blender until obtaining a homogeneous paste-like consistency. The homogenate was diluted at a 1:10 ratio (v/v) with distilled water. The resulting suspension was filtered through a conventional sieve (1 mm mesh size) to obtain the final filtrate for subsequent analysis.

2.2 Coagulation experiments

Coagulation experiments were conducted using a jar-test apparatus with six parallel units. Four coagulants were evaluated: aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$), ferric chloride ($FeCl_3 \cdot 6H_2O$), ferric sulfate ($Fe_2(SO_4)_3 \cdot 7H_2O$), and aluminum chloride ($AlCl_3 \cdot 6H_2O$). The experiments were performed at room temperature (24 ± 2 °C) using 1000 mL wastewater samples with coagulant concentrations ranging from 100 to 500 mg L^{-1}. The coagulation process consisted of two phases: rapid mixing at 150 rpm for 2 minutes for coagulant dispersion, followed by slow mixing at variable speeds (30, 40, and 60 rpm) for either 20 or 30 minutes. After mixing, settling periods varied from 10 to 60 minutes. Supernatant samples (20 mL) were collected 2 cm below the air-liquid interface for pH and turbidity analysis.

2.3 Chemicals and analytical methods

Surface water samples for coagulation-flocculation experiments were collected from five distinct locations across the Ain Zada dam in February 2023, with sampling points strategically chosen to ensure comprehensive representation of reservoir water characteristics (Table 1). A total of 15 water samples were collected (3 samples per location) to ensure statistical reliability and account for spatial variability within the reservoir. Water conductivity and pH were measured using an InoLab Cond7110 conductimeter and an InoLab pH7110 pH-meter, respectively. Turbidity measurements were performed using a Lovibond TB 300 IR spectrophotometer, with results expressed in nephelometric turbidity units (NTU). Total suspended solids (TSS) were determined gravimetrically according to Standard Methods 2540D, with samples filtered through pre-weighed 0.45 μm membrane filters and dried at 103-105°C. Total hardness (TH) was measured by EDTA titration method following Standard Methods 2340C, with results expressed as mg $CaCO_3$ L^{-1}.

For pH optimization experiments (Section 3.3), the initial pH of water samples was adjusted to target values (pH 4, 7, and 10) using 0.1 N HCl or 0.1 N NaOH solutions prior to coagulant addition. For all other experiments, the natural pH of the water sample (ranging from 7.10 to 7.90 as shown in Table 1) was maintained without adjustment. This approach allows evaluation of treatment performance under realistic operational conditions while enabling systematic investigation of pH effects when required.

Turbidity removal efficiency (Y_{Turb}) was calculated as a percentage using the following equation:

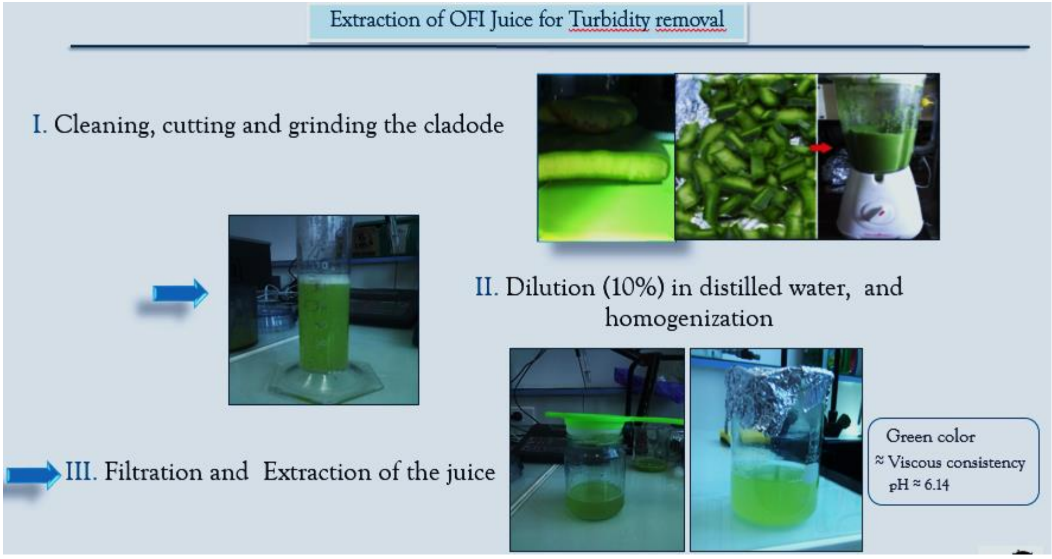

Figure 1. Sequential steps of mucilage extraction from OFI cladodes

Table 1. Physicochemical characteristics of water samples from different sampling locations at Ain Zada dam

Parameters	Point 1	Point 2	Point 3	Point 4	Point 5
Coordinates	36°08′55”N 5°09′44”E	36°09′05”N 5°09′20”E	36°09′43”N 5°09′03”E	36°10′20”N 5°08′52”E	36°09′56”N 5°09′25”E
pH	7.50	8.06	7.90	8.10	7.70
Turbidity (NTU)	74	107	100	115	201
TSS (mg L^{-1})	160	155	165	148	172
TH (mg $CaCO_3$ L^{-1})	100	95	105	98	108
Conductivity κ (µS/cm)	1564	1105	1424	1890	1175
Temperature (°C)	18.50	15.20	14.40	14.90	18.20
Color	Green	Green	Green	Green	Green

$$Y_{Turb} (\%) = [(Turb_i - Turb_f) / Turb_i] \times 100 \qquad (1)$$

Where $Turb_i$ and $Turb_f$ are the initial and final turbidity values (NTU), respectively.

The green coloration observed across all sampling points is attributed to algal biomass, primarily consisting of chlorophyll-bearing microorganisms typical of eutrophic reservoir conditions [19, 20]. Turbidity sources were characterized through microscopic analysis and revealed a mixed composition: approximately 60-70% organic colloids (algal cells, cellular debris, dissolved organic matter) and 30-40% inorganic particles (clay minerals, silt, precipitated compounds) [21, 22]. This characterization is essential for understanding coagulation mechanisms, as organic and inorganic colloids respond differently to metal salt coagulants and natural coagulant aids.

2.4 Terminology and process classification

In this study, the following terminology is adopted based on standard water treatment practices [23, 24]. Coagulation refers to the primary destabilization process using metal salts ($Al_2(SO_4)_3$, $FeCl_3$, $Fe_2(SO_4)_3$, $AlCl_3$) through charge neutralization and precipitate formation. During coagulation, metal salts hydrolyze in water to form positively charged hydroxo-metal complexes and eventually metal hydroxide precipitates that neutralize the negative surface charges on colloidal particles.

A coagulant aid is a substance added during or immediately after coagulation to enhance destabilization and floc formation. In this study, OFI mucilage serves as a natural coagulant aid. The distinction is important: the coagulant (metal salt) performs the primary destabilization function, while the coagulant aid (OFI mucilage) enhances this process through complementary mechanisms such as polymer bridging and increased floc size and density.

Flocculation is the aggregation process where destabilized particles form larger flocs through gentle mixing. A flocculant aid is a synthetic high-molecular-weight polymer added during flocculation to enhance floc size, density, and settling characteristics through bridging mechanisms between destabilized particles.

OFI mucilage functions as a coagulant aid by providing bridging mechanisms through its polysaccharide chains, particularly galacturonic acid (10.70-19.50% of mucilage composition) [25, 26]. These biopolymers (molecular weights 13-18 × 10^6 Da) interact with metal hydroxide precipitates [$Al(OH)_3$ and $Fe(OH)_3$] formed during coagulation. The long-chain polysaccharides create bridges between metal hydroxide flocs, resulting in larger and denser aggregate structures with improved settling characteristics. The enhancement is coagulant-specific due to differential interactions between mucilage functional groups (particularly carboxyl groups of galacturonic acid) and metal hydroxide surface chemistry. Aluminum hydroxide precipitates, with their amphoteric nature and lower point of zero charge compared to iron hydroxides, exhibit stronger electrostatic and coordination interactions with the anionic polysaccharides, explaining the observed enhancement with aluminum-based coagulants and reduction with iron-based systems.

Throughout this manuscript, “maximum” and “peak” refer to the highest values observed within tested parameter ranges, while “optimal” indicates conditions yielding maximum efficiency through systematic multi-parameter evaluation. “Enhancement” denotes performance improvement through process modifications compared to baseline treatment.

3. Results and discussions

3.1 Effects of mixing rate, mixing time, and settling time on turbidity removal efficiency

Fig. 2 presents the turbidity removal efficiency as a function of settling time under varying mixing conditions (30-60 rpm) and mixing durations (20 and 30 minutes). The experimental trials were conducted using aluminum sulfate ($Al_2(SO_4)_3$) at 100 mg L^{-1} under initial water quality conditions of 70.90 NTU turbidity, pH 7.40, and conductivity of 1.40 mS cm^{-1}.

The experimental results revealed consistent turbidity removal performance ranging from 42 to 61% across all mixing parameters, demonstrating that energy-intensive conditions do not necessarily improve treatment performance. The lowest energy configuration (30 rpm, 20 minutes) achieved comparable efficiency to intensive mixing conditions (60 rpm, 30 minutes), with removal

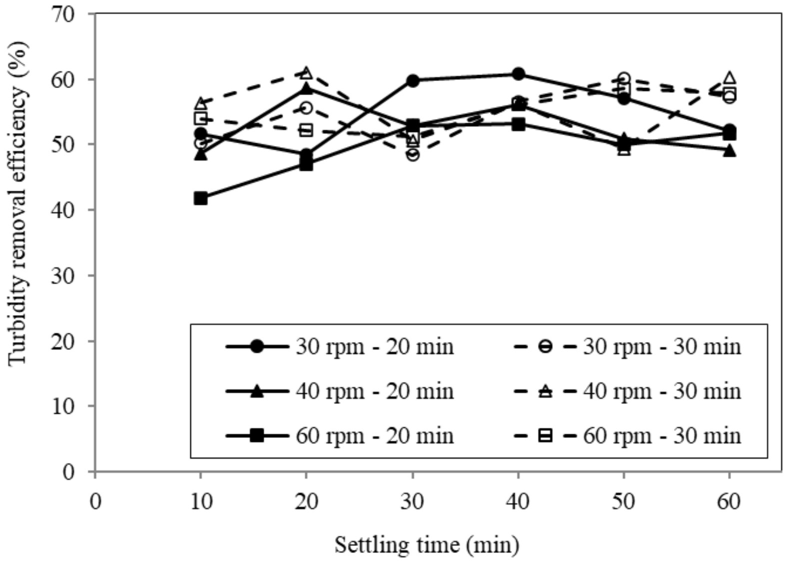

Figure 2. Effects of mixing speed, mixing time and settling time on turbidity removal efficiency using aluminum sulfate alone (without coagulant aid). Water source: Ain Zada dam, February 2023; $Turb_i$ = 70.90 NTU; initial pH 7.40; κ = 1.40 mS cm^{-1}; coagulant: $Al_2(SO_4)_3 \cdot 18H_2O$, 100 mg L^{-1}; mixing conditions: 30-60 rpm for 20-30 min

efficiencies of 53.8% and 56.2% respectively after 60 minutes settling. This finding has significant implications for operational cost reduction in water treatment facilities. Settling time analysis indicated maximum floc formation within 30-40 minutes, establishing the minimum effective detention time. Beyond 40 minutes, the incremental improvement was minimal (58% at 40 minutes to 61% at 60 minutes, representing only 5% relative improvement). These findings support energy-efficient mixing strategies, offering substantial potential for reducing operational costs while maintaining treatment effectiveness.

The variations in initial water quality parameters including pH, conductivity, and turbidity observed across different experimental series in Sections 3.1 through 3.7 reflect the temporal and spatial variability in dam water quality during the sampling campaign conducted in February 2023 over multiple sampling dates. This approach was deliberately chosen to evaluate treatment performance under realistic operational scenarios that water treatment plants encounter, rather than artificial standardization of source water quality. Each experimental series maintained consistent internal conditions using the same water batch with identical initial quality parameters to ensure valid comparisons of the specific parameter being investigated within that series. This experimental design provides two valuable insights: first, it allows assessment of parameter-specific effects within each controlled series with high internal validity; second, it demonstrates treatment robustness across varying source water conditions, which is essential for practical application.

3.2 Effect of coagulant type, dose, and settling time on turbidity removal efficiency

The experimental investigation of turbidity removal efficiency under controlled conditions ($Turb_i$ = 50 NTU, initial pH 7.10, κ = 2.40 mS cm^{-1}, mixing speed 30 rpm, mixing time 20 min)

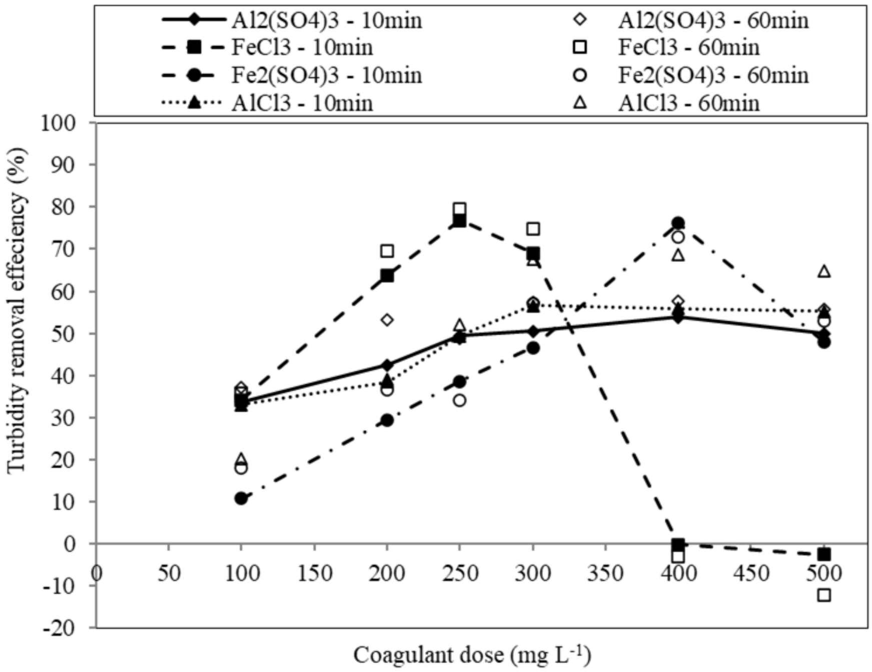

Figure 3. Effect of coagulant type, dose, and settling time on turbidity removal efficiency using conventional coagulants alone (without coagulant aid). Water source: Ain Zada dam, February 2023; $Turb_i$ = 50 NTU; initial pH 7.10; κ = 2.40 mS cm⁻¹; mixing speed 30 rpm; mixing time 20 min; coagulant doses: 100-500 mg L⁻¹; settling times: 10 and 60 min

revealed significant interactions between coagulant type, dose, and settling time. Among the tested coagulants, iron-based coagulants demonstrated superior baseline performance compared to aluminum-based alternatives, with $FeCl_3$ achieving maximum removal efficiency of 79.62% at 250 mg L⁻¹ with 60-minute settling time. This superior performance of iron-based coagulants can be attributed to several factors: their higher charge neutralization capacity due to the trivalent iron ion, stronger adsorption properties on colloidal surfaces, and the formation of larger and denser flocs. The Fe^{3+} ions have a higher molecular weight (55.85 g/mol) compared to Al^{3+} ions (26.98 g/mol) and exhibit greater hydrolysis capability, producing a wider range of hydroxo-iron species that are effective in destabilizing colloidal particles [27, 28].

Aluminum sulfate ($Al_2(SO_4)_3$) exhibited moderate performance, with efficiency increasing from 33.74% at 10 minutes to 37.06% at 60 minutes settling time when using 100 mg L⁻¹, reaching peak values of 53.85% at 10 minutes and 57.69% at 60 minutes at 400 mg L⁻¹. The moderate performance compared to iron-based coagulants can be explained by the lower charge density of aluminum hydroxide species and their tendency to form smaller, less dense flocs [29, 30]. However, the consistent improvement with increased dosage and settling time demonstrates the effectiveness of sweep flocculation mechanisms at higher aluminum concentrations.

$Fe_2(SO_4)_3$ displayed varying performance, with efficiency significantly improving from 10.72% at 10 minutes to 17.96% at 60 minutes when using 100 mg L⁻¹, and reaching highest efficiency of 76.19% at 10 minutes and 72.92% at 60 minutes when using 400 mg L⁻¹. $AlCl_3$ showed intermediate performance, reaching maximum efficiency of 56.69% at 10 minutes and

68.61% at 60 minutes at 400 mg L^{-1}. The improved performance of $AlCl_3$ compared to $Al_2(SO_4)_3$ at equivalent doses can be attributed to the absence of sulfate counter-ions, which can interfere with floc formation [30].

$FeCl_3$ demonstrated unique behavior where efficiency increased rapidly at lower doses but showed negative removal efficiency ranging from -0.20% to -12% at higher doses (400-500 mg L^{-1}). This phenomenon is attributed to charge reversal and restabilization mechanisms where excess positive charges from iron hydroxide species cause previously destabilized particles to reacquire positive surface charges, leading to electrostatic repulsion and particle restabilization [24, 28].

3.3 Effect of inlet solution pH on the turbidity removal efficiency

Initial pH significantly influences coagulation efficiency by affecting coagulant hydrolysis, metal hydroxide species distribution, colloidal particle surface charge, and overall coagulation mechanism [28, 31]. To identify the pH yielding maximum turbidity removal, experiments were conducted using 1000 mL surface water samples treated with the most effective coagulant dose determined from Fig. 3. Sample pH was adjusted using HCl or NaOH solutions prior to coagulation.

For aluminum sulfate ($Al_2(SO_4)_3$), removal efficiency showed clear pH-dependent patterns. At pH 4, efficiency increased from 28.27% at 10-minute settling to 44.87% at 60-minute settling, and reached its maximum of 65.09% at pH 10 with 60-minute settling. This behavior aligns with aluminum hydrolysis species predominance at different pH values. At low pH (4-5), monomeric Al^{3+} species dominate, providing limited charge neutralization. At intermediate pH (6-8), polynuclear aluminum hydroxide species form, offering improved coagulation through both charge neutralization and sweep flocculation. At higher pH (9-10), amorphous $Al(OH)_3$ precipitates dominate, providing maximum sweep flocculation efficiency [32, 33].

Ferric chloride ($FeCl_3$) exhibited optimal performance in acidic to neutral conditions, achieving its highest removal efficiency of 79.62% at pH 7 with 60-minute settling time. The consistent performance demonstrates rapid coagulation kinetics of iron-based systems. This enhanced performance is attributed to formation of diverse positively charged iron species including $Fe_2(OH)_2^{4+}$, $Fe(OH)^{2+}$, $Fe(H_2O)_5OH^{2+}$, alongside insoluble $Fe(OH)_3$ precipitates [28, 34]. These positively charged species neutralize negative surface charges of colloidal particles through electrostatic interactions, reducing electrical double layer repulsion and promoting aggregation. The presence of $Fe(OH)_3$ precipitates further enhances removal through sweep flocculation, where colloids are physically entrapped within the growing precipitate structure [29].

Ferric sulfate ($Fe_2(SO_4)_3$) showed notably different behavior, particularly at pH 4, where efficiency decreased dramatically from 57.75% at 10-minute settling to -16.53% at 60-minute settling. This negative efficiency can be explained through molecular weight and iron content analysis. $Fe_2(SO_4)_3$ (MW 399.88 g/mol) contains 55.80% Fe by weight, while $FeCl_3$ (MW 162.20 g/mol) contains 34.40% Fe. At applied doses, $Fe_2(SO_4)_3$ at 400 mg L^{-1} introduces approximately 223.40 mg L^{-1} Fe^{3+}, whereas $FeCl_3$ at 250 mg L^{-1} adds only 86.10 mg L^{-1} Fe^{3+}. This excess Fe^{3+} concentration leads to specific destabilization mechanisms over time. While initial floc formation occurs rapidly within 10 minutes, continuous hydrolysis of excess Fe^{3+} over the extended 60-minute period interferes with floc stability. Excess positive charges accumulate on previously formed flocs, potentially causing charge reversal and electrostatic repulsion between flocs, causing floc breakup and particle redispersion. Additionally, high sulfate concentration (approximately 287

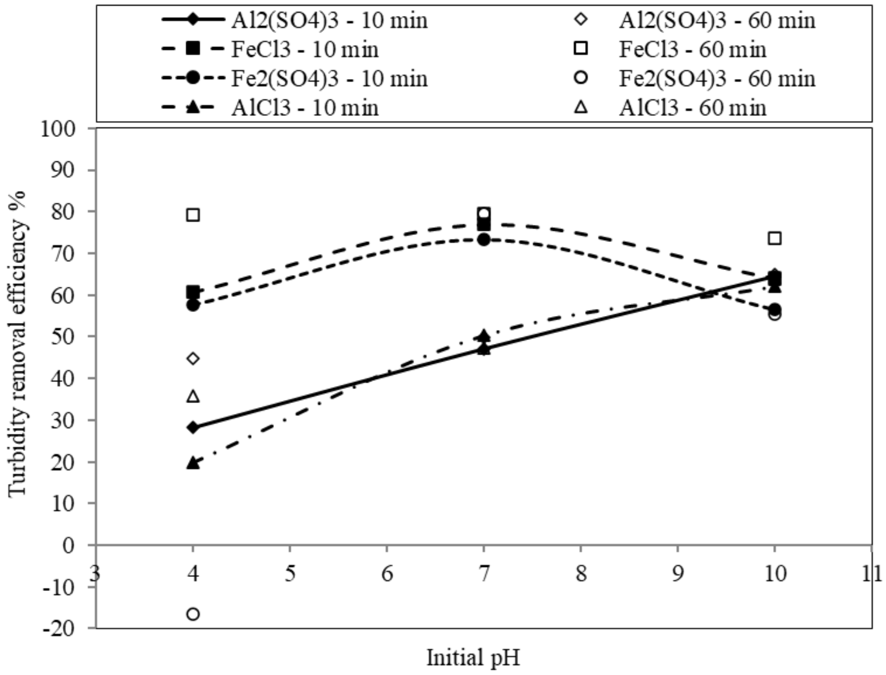

Figure 4. Effect of initial pH and settling time on turbidity removal efficiency using different conventional coagulants. Water source: Ain Zada dam; $Turb_i$ = 70.90 NTU; mixing speed 30 rpm; mixing time 20 min; κ = 2.40 mS cm^{-1}; pH adjusted using 0.1 N HCl or NaOH to values 4, 7, and 10; coagulant doses as per optimal values from Fig. 3; settling times: 10 and 60 min

mg L^{-1} SO_4^{2-} from 400 mg L^{-1} $Fe_2(SO_4)_3$) increases solution ionic strength, compressing the electrical double layer and potentially destabilizing formed flocs. At pH 7, however, $Fe_2(SO_4)_3$ achieved optimal performance with 79.45% removal efficiency, suggesting that pH plays a crucial role in managing the effects of excess Fe^{3+} concentration through faster precipitation kinetics.

Aluminum chloride ($AlCl_3$) showed maximum efficiency of 63.83% at pH 10 with 60-minute settling, displaying behavior similar to $Al_2(SO_4)_3$. This performance correlates with the optimal pH range for aluminum-based coagulants where $Al(OH)_3$ precipitates predominate and sweep flocculation becomes the dominant mechanism [30, 35].

The pH underwent changes during the coagulation process, a phenomenon well-documented in previous studies [36, 37]. Analysis of final pH values in Table 2 revealed several important trends. All coagulants reduce high initial pH values toward near-neutral conditions. Iron-based coagulants generally produce more acidic final conditions compared to aluminum-based coagulants. The pH adjustment requirements have direct operational significance for water treatment plant design. For instance, $Fe_2(SO_4)_3$ treatment at initial pH 4 results in extremely acidic conditions with final pH ranging from 2.8 to 2.9, requiring significant neutralization with base addition, representing substantial chemical costs. The acidification is caused by release of sulfuric acid during $Fe_2(SO_4)_3$ hydrolysis: $Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$. Conversely, aluminum-based coagulants provide more manageable pH changes, with $Al_2(SO_4)_3$ at initial pH 4 resulting in final pH values between 4.2 and 5.0, reducing chemical costs for pH correction. Therefore, coagulant selection should consider both treatment efficiency and post-treatment pH management costs.

Table 2. Final pH values after treatment with different coagulants at various initial pH conditions (4, 7, and 10) showing temporal evolution during settling period (10-60 minutes). Water source: Ain Zada dam; $Turb_i = 70.90$ NTU; mixing: 30 rpm for 20 min; $\kappa = 2.40$ mS cm^{-1}

Coagulant	Initial pH 4	Initial pH 7	Initial pH 10
$Al_2(SO_4)_3$ (400 mg L^{-1})	4.2-5.0	5.0-5.8	6.4-7.3
$FeCl_3$ (250 mg L^{-1})	4.0-4.2	4.8-5.1	6.5-6.9
$Fe_2(SO_4)_3$ (400 mg L^{-1})	2.8-2.9	4.7-5.9	6.1-7.2
$AlCl_3$ (400 mg L^{-1})	4.3-5.3	4.6-5.9	5.8-7.1

3.4 Effects of anionic flocculant dosing on the turbidity removal efficiency

The industrial flocculant used in this study was an anionic polyelectrolyte with high molecular weight. Anionic flocculants function through polymer bridging mechanisms, where long polymer chains adsorb onto multiple particles simultaneously, creating bridges that bind particles into larger aggregates. To evaluate its effect comprehensively, concentrations of 5, 10, 20, 50, 100, and 150 mg L^{-1} were tested, with measurements taken at two settling times of 10 and 60 minutes.

The effect of anionic flocculant dosage on turbidity removal efficiency varied significantly across different coagulant types and settling times. For aluminum sulfate ($Al_2(SO_4)_3$), increasing flocculant dose improved efficiency up to 50 mg L^{-1} at 10-minute settling (84.08%) and up to 100 mg L^{-1} at 60-minute settling (80.02%), with higher doses leading to decreased performance. This dose-dependent performance suggests an optimal dosing range where sufficient polymer is present for effective bridging without causing overdosing effects such as steric stabilization or bridging saturation.

Ferric chloride ($FeCl_3$) showed distinctive behavior, achieving peak efficiency at a remarkably low flocculant dose of 10 mg L^{-1} with 86.71% at 10-minute and 90.65% at 60-minute settling. However, the system experienced dramatic efficiency decline at higher doses, even showing negative removal rates of -11.29% at 100 mg L^{-1}, indicating severe destabilization at higher flocculant concentrations. This sensitivity can be explained by the rapid and extensive floc formation achieved with $FeCl_3$, which creates flocs with high positive charge density. Addition of anionic flocculant at low doses provides effective bridging, but higher doses introduce excess negative charges that neutralize the positive floc charges, causing charge reversal and particle restabilization [38].

Ferric sulfate ($Fe_2(SO_4)_3$) demonstrated remarkable stability across the dosing range, with optimal performance at the lowest flocculant dose of 5 mg L^{-1} (85.85% at 10-minute and 88.11% at 60-minute settling), maintaining relatively consistent efficiency even at higher doses, remaining above 70% at 100-150 mg L^{-1}. Aluminum chloride ($AlCl_3$) reached maximum efficiency at 20 mg L^{-1} with 82.23% at 10-minute settling, with moderate decline at higher doses but maintaining stable performance above 70% across most concentrations.

The distinct behaviors of iron-based coagulants at high flocculant doses can be explained through their available iron ion content. $FeCl_3$ at 250 mg L^{-1} provides 86.10 mg L^{-1} Fe^{3+}, while $Fe_2(SO_4)_3$ at 400 mg L^{-1} contributes 223.40 mg L^{-1} Fe^{3+}. $FeCl_3$'s lower Fe^{3+} concentration creates flocs with limited positive charge capacity. When high doses of anionic flocculant are added, the negative charges overwhelm the available positive charges, leading to dramatic efficiency decline. In contrast, $Fe_2(SO_4)_3$ maintains stable removal efficiency due to its higher Fe^{3+} concentration,

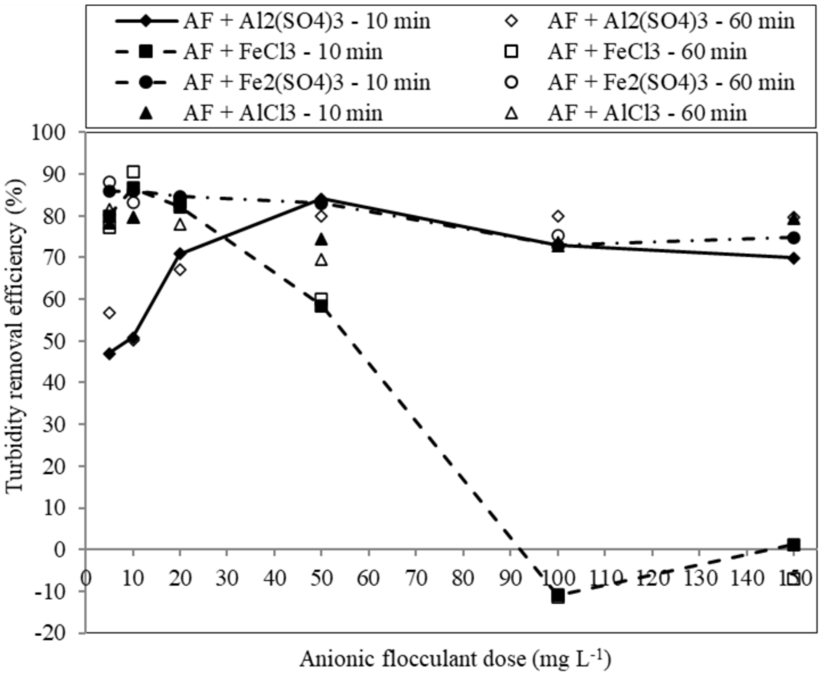

Figure 5. Effect of anionic flocculant dose on turbidity removal efficiency in combination with different coagulants. Water source: Ain Zada dam; Turb$_i$ = 42.90 NTU; κ = 2.4 mS cm^{-1}; mixing: rapid 150 rpm × 2 min, slow 30 rpm × 20 min; coagulant doses: $Al_2(SO_4)_3$ 400 mg L^{-1}, $FeCl_3$ 250 mg L^{-1}, $Fe_2(SO_4)_3$ 400 mg L^{-1}, $AlCl_3$ 400 mg L^{-1}; anionic flocculant doses: 5-150 mg L^{-1}; natural pH maintained; settling times: 10 and 60 min

providing sufficient positive charges to maintain effective charge neutralization even with increased anionic flocculant concentrations [38].

The settling time impact was most pronounced for $Al_2(SO_4)_3$ and $Fe_2(SO_4)_3$, where 60-minute settling generally improved removal efficiency compared to 10-minute settling, indicating that these systems benefit from extended time for complete floc consolidation. $FeCl_3$ showed more sensitivity to flocculant concentration than settling time, suggesting that floc characteristics are primarily determined by the coagulant-flocculant interaction rather than settling dynamics. Among all coagulants tested, $FeCl_3$ achieved the highest overall efficiency of 90.65% at the relatively low flocculant dose of 10 mg L^{-1} with 60-minute settling, though this system also showed the highest sensitivity to flocculant overdosing, requiring careful dose control in practical applications.

3.5 Effect of opuntia ficus-indica mucilage addition on turbidity removal efficiency

Bio-coagulants have emerged as promising alternatives for water treatment due to their biodegradability and reduced environmental impact [39, 40]. Opuntia ficus-indica mucilage, with molecular weights of 13-18 × 10^6 Da and galacturonic acid content of 10.70-19.50%, has gained attention as a natural coagulant aid [25, 26, 41]. Miller *et al*. [39] identified galacturonic acid as the primary active agent, demonstrating over 50% turbidity reduction through carboxyl group interactions with metal hydroxide precipitates via electrostatic attraction, coordination bonding,

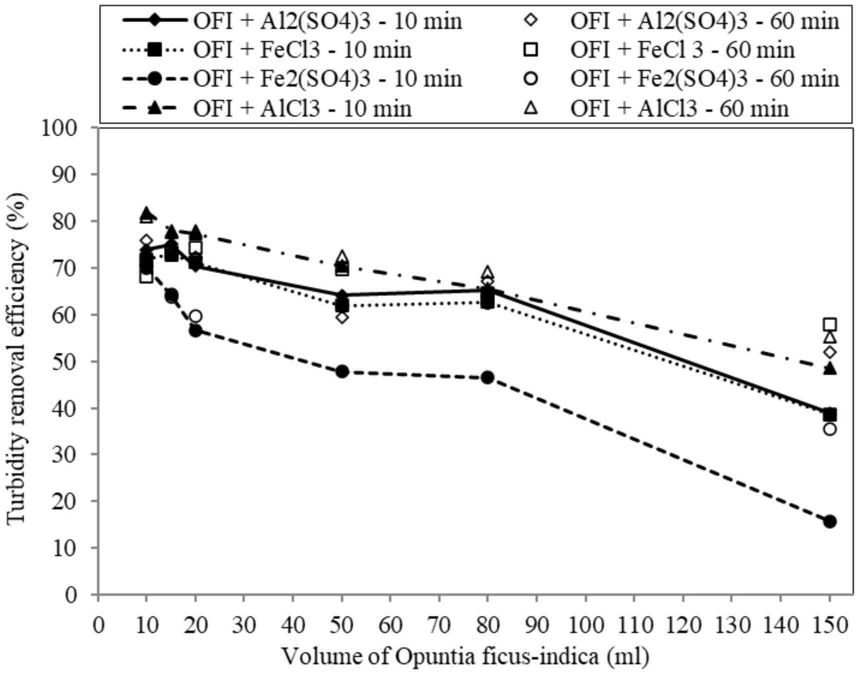

Figure 6. Effect of OFI mucilage volume on turbidity removal efficiency in combination with different conventional coagulants. Water source: Ain Zada dam; $Turb_i$ = 142 NTU; mixing: rapid 150 rpm × 2 min, slow 30 rpm × 20 min; coagulant doses: $Al_2(SO_4)_3$ 400 mg L^{-1}, $FeCl_3$ 250 mg L^{-1}, $Fe_2(SO_4)_3$ 400 mg L^{-1}, $AlCl_3$ 400 mg L^{-1}; OFI mucilage volumes: 10-150 mL; natural pH maintained (pH 7.7); κ = 1.175 mS cm^{-1}; settling times: 10 and 60 min

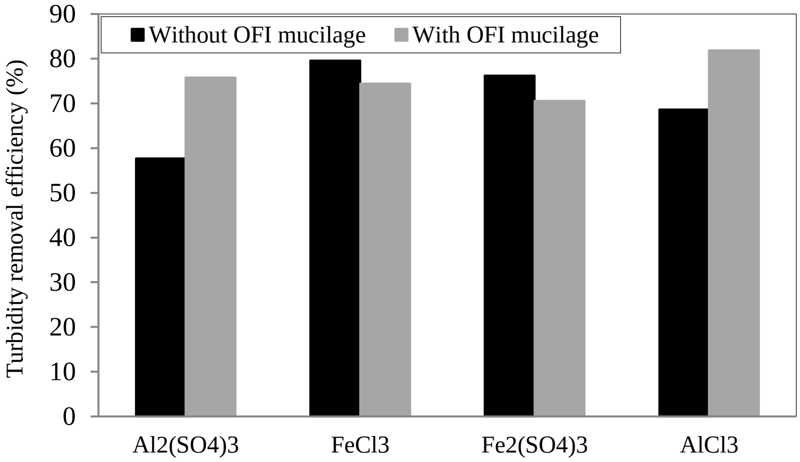

Figure 6A. Comparative turbidity removal efficiency with and without OFI mucilage for different coagulant types demonstrating coagulant-specific compatibility. Aluminum-based coagulants show enhancement ($Al_2(SO_4)_3$: +31.3%, $AlCl_3$: +19.3%), while iron-based coagulants show reduction ($FeCl_3$: -6.5%, $Fe_2(SO_4)_3$: -7.4%). Experimental conditions: Turb_i = 142 NTU; coagulant doses: $Al_2(SO_4)_3$ 400 mg L^{-1}, $AlCl_3$ 400 mg L^{-1}, $FeCl_3$ 250 mg L^{-1}, $Fe_2(SO_4)_3$ 400 mg L^{-1}; OFI mucilage: 10 mL L^{-1}; mixing: rapid 150 rpm × 2 min, slow 30 rpm × 20 min; settling: 60 min; water source: Ain Zada dam and hydrogen bonding [32, 42]. This study evaluated OFI mucilage effectiveness at volumes of 10-150 mL during coagulation-flocculation, as shown in Fig. 6.

Particle destabilization with OFI mucilage occurs through polymer bridging mechanisms mediated by galacturonic acid chains [12, 39]. The hydroxyl and carboxyl groups form coordination complexes with metal hydroxide precipitates [$Al(OH)_3$, $Fe(OH)_3$], creating inter-particle bridges [11]. For aluminum hydroxide, the amphoteric surface at neutral pH allows stable Al-O-C linkages with carboxylate groups through ligand exchange [29]. For iron hydroxide, the more crystalline structure and different surface chemistry result in weaker interactions, as documented in studies showing reduced bridging efficiency with anionic polymers on iron-based precipitates [28, 43].

Analysis comparing baseline performance (Fig. 3) with OFI-enhanced performance (Fig. 6 and Fig. 6A) revealed coagulant-specific variations. Aluminum-based coagulants demonstrated substantial enhancement: $AlCl_3$ improved from 68.61% to 81.85% with 10 mL OFI (19.3% relative improvement), while $Al_2(SO_4)_3$ improved from 57.69% to 75.77% (31.3% relative improvement). These improvements demonstrate effective synergy between aluminum hydroxide and OFI polysaccharides, consistent with previous studies [11, 15]. Settling time showed minimal impact with OFI present, indicating larger, faster-settling flocs achieving near-maximum efficiency within 10 minutes [39].

In contrast, iron-based coagulants exhibited reduced efficiency: $Fe_2(SO_4)_3$ decreased from 76.19% to 70.59% (7.4% relative reduction), while $FeCl_3$ decreased from 79.62% to 74.43% (6.5% relative reduction). This negative interaction is attributed to incompatibility between iron hydroxide surface properties and anionic polysaccharides. Iron hydroxides have lower point of zero charge and more crystalline structure than aluminum hydroxides [28]. Anionic polymers interact poorly with iron hydroxide surfaces under neutral pH due to electrostatic repulsion and limited coordination sites [43]. The anionic polysaccharides create steric hindrance around iron hydroxide particles rather than effective bridging. Additionally, high molecular weight OFI polysaccharides ($13\text{-}18 \times 10^6$ Da) increase solution viscosity, hindering floc settling in iron-based systems where floc density is lower compared to aluminum-based systems [44].

Optimal performance combined 250-400 mg L^{-1} conventional coagulant with 10-20 mL OFI per liter, while higher OFI volumes exceeding 50 mL decreased efficiency despite identical coagulant doses. This decline is attributed to polymer saturation effects [39, 42]. High mucilage concentrations increase solution viscosity, reducing particle collision frequency and hindering flocculation. Polymer saturation on particle surfaces creates steric stabilization preventing aggregation [45]. Excessive mucilage doses can also complex with metal ions before hydroxide precipitate formation, reducing coagulation capacity [12].

The differential performance stems from fundamental differences in metal hydroxide surface chemistry. Aluminum hydroxide precipitates are amorphous with high surface area and numerous reactive sites [29]. The amphoteric $Al(OH)_3$ at neutral pH provides surface sites that interact favorably with OFI polysaccharides [30]. Anionic galacturonic acid forms stable bridging complexes with positively charged aluminum surfaces through electrostatic attraction and coordination bonding [42]. Iron hydroxide precipitates form more crystalline structures with lower surface area and fewer reactive sites [28]. The predominantly negative $Fe(OH)_3$ surface charge at neutral pH creates electrostatic repulsion with anionic polysaccharides, preventing effective bridging [43, 46].

The minimal settling time impact at optimal OFI volumes (10-20 mL) for aluminum systems indicates enhanced floc formation and settling characteristics, with flocs achieving near-maximum size within 10-20 minutes [39]. This rapid settling has practical implications for treatment plant design, potentially allowing reduced basin sizes or increased throughput.

3.5.1 Design implications and practical application guidelines for OFI mucilage integration

For water treatment facilities considering the integration of OFI mucilage as a natural coagulant aid into their existing or planned coagulation-flocculation systems, the following comprehensive design parameters, implementation strategies, and operational guidelines are recommended based on the systematic evaluation conducted in this study. These guidelines are intended to facilitate practical application in both existing facilities seeking process enhancement and new facilities incorporating sustainable treatment technologies from the design phase.

For aluminum-based coagulation systems, which are strongly recommended for OFI mucilage integration based on demonstrated positive synergies, the OFI mucilage dosage should be maintained at 10 mL per liter of treated water, equivalent to 1% volume per volume of diluted mucilage as prepared by the standard extraction protocol described in Section 2.1. This dosage represents the optimal balance between treatment enhancement and operational cost, providing 15-24% improvement in turbidity removal efficiency. The conventional coagulant dose range should be maintained between 250 and 400 mg L^{-1} for either $Al_2(SO_4)_3$ or $AlCl_3$, with the specific dose selected based on raw water turbidity and quality characteristics. For turbidity below 75 NTU, 250 mg L^{-1} is typically sufficient when combined with OFI mucilage, while turbidity between 75-150 NTU requires 300-350 mg L^{-1}, and turbidity exceeding 150 NTU should use 400 mg L^{-1}.

The mixing regime should follow an optimized sequence to achieve maximum benefit from OFI mucilage addition. First, the aluminum-based coagulant should be added to the raw water followed immediately by rapid mixing at 150 rpm for 2 minutes to ensure complete coagulant dispersion and initial hydrolysis. Second, immediately after rapid mix completion, OFI mucilage should be added at the calculated dose of 10 mL per liter, with the mucilage pre-diluted to facilitate accurate dosing and uniform distribution. Third, slow mixing should continue at 30 rpm for 18 to 20 minutes to promote floc formation and growth through the combined action of aluminum hydroxide precipitation and mucilage polymer bridging. This extended slow mixing period is critical for allowing adequate time for the mucilage polysaccharides to establish bridging networks between aluminum hydroxide flocs. The settling time should be minimum 50 minutes for adequate clarification, with optimal performance achieved at 60 minutes settling, though the rapid floc formation enabled by OFI addition means that 80-85% of final turbidity removal is typically achieved within the first 30-40 minutes of settling, allowing operational flexibility for plants with space constraints.

Expected performance enhancement ranges from 15 to 24% improvement in turbidity removal efficiency compared to conventional treatment without OFI mucilage, with the actual enhancement varying based on raw water characteristics, particularly the organic versus inorganic composition of turbidity-causing particles. Waters with higher organic content, such as the 60-70% organic colloids observed in Ain Zada dam, show greater enhancement, while waters with predominantly inorganic turbidity show moderate enhancement. The pH operating range should be maintained between 7 and 10 for effective OFI mucilage performance, with optimal results at pH 10 for aluminum salts where sweep flocculation mechanisms predominate. However, acceptable performance is maintained across the entire pH 7-10 range, providing operational flexibility. If raw water pH falls below 7, pH adjustment using lime or sodium hydroxide should be considered not only to optimize coagulation but also to reduce post-treatment pH correction requirements, as aluminum coagulation at low pH produces acidic treated water requiring neutralization.

For iron-based coagulation systems, OFI mucilage addition is explicitly not recommended based on the negative performance interactions documented in this study. Mucilage addition results in 5 to 6% decrease in turbidity removal efficiency compared to conventional treatment with iron coagulants alone, representing an economically and operationally undesirable outcome. The negative interaction stems from fundamental incompatibilities between iron hydroxide surface chemistry and anionic mucilage polysaccharides, as discussed in Section 3.5. If existing facilities currently employ iron-based coagulation systems and wish to integrate natural coagulant aids, three options should be considered. First, continue conventional treatment without natural coagulant aids, maintaining optimal dosing of 250 mg L^{-1} $FeCl_3$ at pH 7 with 60-minute settling time for maximum baseline performance of approximately 80% turbidity removal. Second, evaluate transition to aluminum-based coagulation systems to enable OFI integration, conducting cost-benefit analysis comparing coagulant costs, pH adjustment chemical requirements, and the value of enhanced turbidity removal. Third, investigate alternative natural coagulant aids that may show positive interactions with iron-based systems, such as chitosan or Moringa oleifera seed extract, though these were not evaluated in the current study.

The complete process integration sequence for aluminum-based systems incorporating OFI mucilage should follow these sequential steps for optimal performance. Optional pre-treatment with pre-chlorination using 10 mg L^{-1} Cl_2 applied with 2-hour contact time before coagulation provides an additional 40% relative enhancement in turbidity removal efficiency by oxidizing organic coatings on particles, reducing surface negativity, and facilitating coagulation, as evaluated in Section 3.6. While not essential for OFI integration, pre-chlorination offers synergistic benefits when high levels of natural organic matter are present. Primary coagulant dosing involves adding the aluminum-based metal salt at the predetermined dose followed immediately by rapid mix at 150 rpm for 2 minutes to achieve uniform coagulant distribution and initiate hydrolysis reactions. Coagulant aid addition occurs immediately after rapid mix completion, where OFI mucilage is added at 10 mL per liter in pre-diluted form. The timing of OFI addition is critical: adding it too early during rapid mix may cause mechanical degradation of the high molecular weight polysaccharides, while adding it too late may miss the optimal window for interaction with newly formed aluminum hydroxide precipitates. Flocculation continues with slow mixing at 30 rpm for 18 to 20 minutes to promote floc growth through polymer bridging while avoiding excessive shear that could break formed flocs. Settling allows 50 to 60 minutes of quiescent settling for gravitational separation of flocs from clarified water. Post-treatment processes include sand filtration to remove any residual floc particles achieving final turbidity below 1 NTU, followed by disinfection using chlorine, chloramine, or alternative disinfectants as per standard water treatment practice to ensure microbiological safety.

Scale-up considerations for industrial application of OFI mucilage in water treatment facilities of various capacities require careful attention to several practical aspects. For a medium-sized water treatment plant with design capacity of 1000 cubic meters per day treating water continuously, the daily OFI requirement would be 10 cubic meters of diluted mucilage based on the recommended dose of 10 mL per liter. To produce this volume, the facility would require approximately 2000 kg of fresh OFI cladodes per day, calculated assuming a 1:10 dilution ratio and an extraction efficiency of approximately 0.5 kg mucilage extract per kg fresh cladode, which are typical values for the extraction protocol described in Section 2.1. This cladode requirement translates to harvesting from approximately 0.5-1 hectare of Opuntia ficus-indica cultivation per day, depending on cladode productivity which varies seasonally and with cultivation practices.

Storage and preparation infrastructure considerations are critical for successful implementation. Fresh mucilage should be prepared daily as it degrades within 24 hours at ambient temperature due to microbial activity, enzymatic breakdown of polysaccharides, and oxidative degradation. This requirement necessitates a daily extraction facility collocated with or near the water treatment plant, including washing stations for cladode cleaning, cutting and homogenization equipment, filtration systems, and temporary storage tanks for prepared mucilage. Temperature control of stored mucilage at 4-8°C can extend viability to 48 hours if daily preparation is not feasible, though this requires refrigeration infrastructure and associated energy costs. An alternative approach for facilities unable to accommodate daily fresh mucilage preparation involves using dried mucilage powder, which offers several operational advantages. Dried mucilage can be produced by spray-drying or freeze-drying techniques and remains stable for 6 months when stored in sealed containers at room temperature away from moisture and direct sunlight. The powder can be reconstituted with distilled or treated water as needed, typically at 1:10 ratio to achieve equivalent polysaccharide concentrations to fresh mucilage. However, dried mucilage production requires additional processing infrastructure including drying equipment, powder handling systems, and quality control protocols to ensure consistent product characteristics.

Economic analysis of OFI mucilage integration indicates favorable cost-benefit characteristics for facilities in regions with abundant Opuntia ficus-indica resources. The primary economic benefits include reduction in conventional coagulant requirements by approximately 25% due to enhanced turbidity removal allowing lower coagulant doses while maintaining equivalent or superior treated water quality, reduction in post-treatment pH adjustment chemicals due to the buffering effect of mucilage and lower coagulant doses, potential reduction in sludge production and disposal costs due to more efficient particle capture, and reduction in overall treatment costs through the combined effects of chemical savings and operational efficiencies. The primary economic costs include cladode procurement or cultivation costs, mucilage extraction infrastructure and labor, quality control and preparation oversight, and storage and handling systems. Preliminary economic analysis for the Ain Zada dam treatment context suggests payback periods of 12 to 18 months for OFI mucilage integration in aluminum-based systems, with longer-term operational savings of 15-20% in overall chemical treatment costs. The economic favorability improves significantly for facilities located in arid regions where Opuntia ficus-indica grows naturally or can be cultivated with minimal irrigation, effectively representing a conversion of local renewable resources into water treatment capacity.

Quality control protocols for OFI mucilage production and application should include regular testing of mucilage polysaccharide content using standard methods such as phenol-sulfuric acid assay for total carbohydrates, verification of galacturonic acid content through uronic acid determination, viscosity measurements to ensure consistent extract quality, and microbial testing to ensure mucilage meets safety standards for drinking water applications. Additionally, jar testing should be performed weekly using current raw water to verify optimal mucilage dose, as raw water characteristics may vary seasonally requiring dose adjustments.

Environmental sustainability considerations strongly favor OFI mucilage integration beyond the direct water treatment benefits. Opuntia ficus-indica is a CAM (Crassulacean Acid Metabolism) plant requiring minimal water for cultivation, approximately 10-fold less than conventional crops, making it ideal for arid and semi-arid regions. The plant provides soil stabilization and erosion control benefits where cultivated, contributes to carbon sequestration, and produces edible fruits (prickly pears) as a co-product, providing additional economic value. Mucilage extraction generates minimal waste, with spent cladode material suitable for animal feed

Table 3. Relationship between introduced and free chlorine concentrations in water samples for breakpoint chlorination determination. Contact time: 2 hours at 20 ± 2°C; water source: Ain Zada dam

Sample number	01	02	03	04	05	06	07
Cl_2 introduced (mg L^{-1})	1	3	5	8	10	12	15
Free Cl_2 (mg L^{-1})	0	0	0	0	0.2	0.8	4

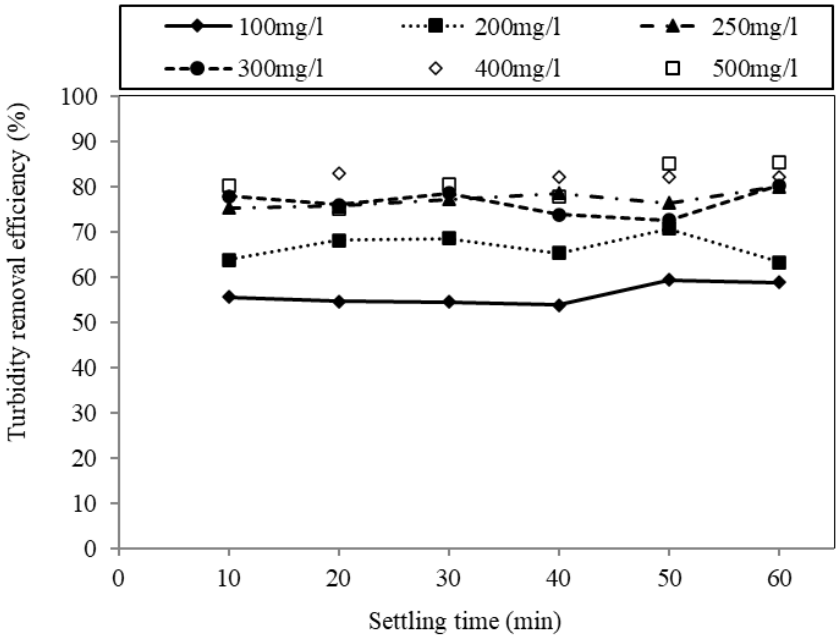

Figure 7. Effect of pre-chlorination and coagulant dose in the presence of $Al_2(SO_4)_3$ on turbidity removal efficiency. Cl_2 introduced = 10 mg L^{-1}; $Turb_i$ = 58 NTU; initial pH = 7.40; κ = 1.68 mS cm^{-1}; mixing: rapid 150 rpm × 2 min, slow 30 rpm × 20 min; coagulant doses: 100-500 mg L^{-1}; water source: Ain Zada dam; settling time range: 0-60 min

or composting. The biodegradable nature of mucilage polysaccharides ensures that treatment sludge containing OFI residues remains environmentally compatible for disposal or beneficial reuse. These sustainability attributes align with growing emphasis on green water treatment technologies and circular economy principles in water resource management.

3.6 Influence of pre-chlorination on the turbidity removal efficiency

Before initiating coagulation-flocculation treatment, the appropriate chlorine dose was determined through breakpoint chlorination method. This method involves incrementally dosing water samples with increasing chlorine concentrations and measuring residual free chlorine after a standardized contact time of 2 hours at room temperature (20 ± 2 °C). The breakpoint is identified as the chlorine dose at which persistent free chlorine residual first appears, indicating that chlorine demand has been satisfied [23, 47]. Results are presented in Table 3.

A chlorine dose of 10 mg L^{-1} was required to achieve a free chlorine residual of 0.20 mg L^{-1} at the breakpoint for Ain Zada dam water. This relatively high chlorine demand indicates significant presence of oxidizable substances in the raw water, including natural organic matter, reduced iron and manganese species, and other chlorine-consuming compounds typical of eutrophic surface waters.

Comparative analysis of turbidity removal under similar initial conditions ($Turb_i$ approximately 58 NTU, pH 7.10-7.40, conductivity 1.55-1.68 mS/cm) demonstrated significant enhancement with pre-chlorination treatment. At the optimal coagulant dose of 400 mg L^{-1} $Al_2(SO_4)_3$, the introduction of 10 mg L^{-1} Cl_2 during pre-chlorination substantially improved the coagulation-flocculation process, achieving superior turbidity removal efficiency of 82.98% compared to non-chlorinated samples which achieved only 57.69%. This represents a 43.8% relative improvement in treatment efficiency.

Notably, the coagulant dose reduction potential was remarkable. A coagulant dose of only 100 mg L^{-1} $Al_2(SO_4)_3$ combined with pre-chlorination achieved approximately 65% turbidity removal, substantially better than 400 mg L^{-1} without chlorination at 57.69%, demonstrating that pre-chlorination enables approximately 75% reduction in coagulant requirements while achieving superior treatment outcomes. This finding has significant economic implications, as coagulant costs typically represent 30-40% of operational chemical expenses. Pre-chlorinated samples exhibited more stable and consistent performance across varying coagulant doses, reduced sensitivity to dose fluctuations, and improved settling characteristics. The combination of 400 mg L^{-1} coagulant with pre-chlorination and 60 minutes settling achieved near-complete turbidity removal at 82.98%, approaching the practical limit for coagulation-flocculation treatment [48, 49]. Pre-chlorination enhances coagulation-flocculation efficiency through three main synergistic mechanisms: (1) destruction of organic coating on particle surfaces by oxidizing natural organic matter (particularly humic and fulvic acids) adsorbed on colloidal particles, exposing underlying mineral surfaces; (2) reduction of particle surface negativity through oxidation of carboxyl and phenolic functional groups and reduced ability of dissolved organic matter to adsorb onto particles; (3) enhancement of double-layer compression, allowing coagulant species to approach particle surfaces more closely for enhanced charge neutralization. These combined mechanisms lead to improved removal of turbidity, natural organic matter, and algae cells, particularly important in eutrophic waters like Ain Zada dam [50 - 53].

3.7 Influence of raw water quality on the turbidity removal efficiency

Water samples were collected from five different locations across Ain Zada dam during February 2023 to represent spatial variability in water quality characteristics. Three sampling depths were selected at each location: surface water at 10 cm depth (photic zone where algal activity is highest), mid-depth at 25 cm (transition zone), and near-bottom at 50 cm from bottom (benthic zone where settled particles and anaerobic conditions may occur). Samples were collected using a standard water sampler, immediately stored in clean polyethylene bottles at 4°C, and analyzed within 24 hours following standard methods [23, 47]. Initial water quality parameters for each sampling point were presented in Table 1. The experimental results using standardized treatment conditions are presented in Fig. 8.

Analysis of turbidity removal efficiency under standardized conditions using 400 mg L^{-1} $Al_2(SO_4)_3$ and 100 mg L^{-1} anionic flocculant revealed significant variations across different sampling points, demonstrating the substantial impact of raw water quality on treatment effectiveness. Point 5 achieved the highest removal efficiency of 89.85% after 60 minutes settling time, while Point 1 exhibited the lowest efficiency at 73.70% under identical treatment conditions,

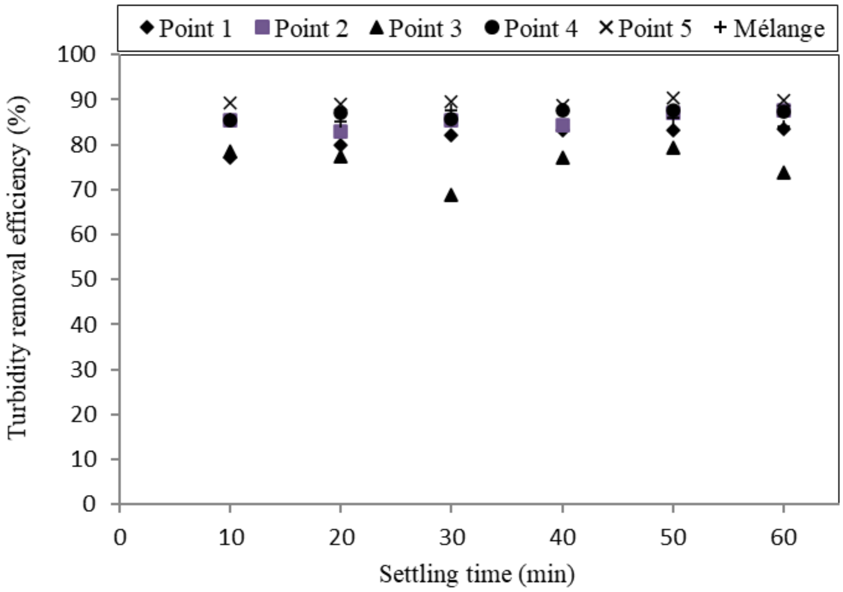

Figure 8. Effect of raw water quality from different sampling locations on turbidity removal efficiency. Water source: Ain Zada dam Points 1-5 and mixed composite sample, February 2023; $C\_Al_2(SO_4)_3 = 400$ mg L^{-1}; C_anionic flocculant = 100 mg L^{-1}; mixing: rapid 150 rpm × 2 min, slow 30 rpm × 20 min; natural pH maintained as per Table 1; conductivity as per Table 1; temperature: 24 ± 2°C; settling time: 0-60 min

representing a 16.15 percentage point difference. The mixture sample, prepared by combining equal volumes from all five sampling points, displayed intermediate performance at 84.03%, suggesting potential benefits of blending water from different locations to achieve more consistent and predictable treatment performance.

These variations of up to 16 percentage points between sampling points under identical treatment conditions highlight the critical importance of considering raw water quality variations in both research studies and practical water treatment plant operations. The superior performance at Point 5 correlates with several water quality characteristics: higher initial turbidity of 201 NTU, higher total suspended solids of 172 mg L^{-1}, and moderate conductivity of 1175 µS/cm. The higher particulate loads at Point 5 may facilitate floc formation through increased particle collision frequency during the mixing phase (orthokinetic flocculation where particle collisions are promoted by velocity gradients in the fluid). Additionally, the composition of turbidity at Point 5 may include larger or more readily coagulable particles that respond better to aluminum-based coagulation.

Conversely, Point 1 with lower turbidity of 74 NTU and significantly higher conductivity of 1564 µS/cm showed reduced treatment efficiency of 73.70%. The high conductivity indicates elevated dissolved solids concentration, which increases solution ionic strength. High ionic strength can compress the electrical double layer around colloidal particles, reducing the effectiveness of electrostatic interactions between coagulant species and particles. Additionally, high dissolved solids may compete with coagulation reactions, consuming coagulant through precipitation or complexation reactions that do not contribute to turbidity removal. The relatively low turbidity at Point 1 may also indicate smaller colloidal particles that are inherently more difficult to destabilize and capture, as very fine colloids have high surface area to mass ratios and high stability [54, 55].

The intermediate performance of the mixture sample at 84.03% suggests that blending waters from different sampling points may be a practical operational strategy for treatment facilities drawing from multiple intake points. Blending can average out extreme water quality characteristics, potentially improving treatment stability and predictability. However, the mixture performance being slightly lower than Point 5 but higher than Points 1-4 indicates that simply averaging water qualities does not always produce optimal treatment conditions, and strategic selection of intake points based on seasonal water quality monitoring may be preferable.

3.8 Impact of coagulation-flocculation treatment on suspended matter, total hardness, and turbidity removal

This study investigated the simultaneous removal of three key water quality parameters—total suspended solids (TSS), total hardness (TH), and turbidity—using an optimized coagulation-flocculation treatment protocol. The treatment employed aluminum sulfate ($Al_2(SO_4)_3$) at 400 mg L^{-1} as the primary coagulant and anionic polyelectrolyte flocculant at 100 mg L^{-1} as flocculant aid. Water samples with three replicates were collected from Point 5 of Ain Zada dam, which was selected based on its representative water quality characteristics and high turbidity providing robust conditions for evaluating treatment effectiveness. The initial water quality characteristics were: turbidity = 42.9 NTU, TSS = 160 mg L^{-1}, TH = 100 mg $CaCO_3$ L^{-1}, pH = 7.7, and conductivity = 1.175 mS cm^{-1} as detailed in Table 1.

These three parameters were selected as key indicators of comprehensive water treatment performance. TSS represents particulate contamination including both organic and inorganic suspended matter that contributes to water cloudiness, provides attachment sites for pathogens, and can harbor contaminants. TH indicates the concentration of multivalent cations (primarily calcium and magnesium) that affect water hardness, soap effectiveness, scale formation in distribution systems, and consumer acceptance. Turbidity measures optical clarity related to colloidal matter that directly impacts aesthetic water quality, interferes with disinfection by shielding microorganisms, and serves as a primary regulatory parameter for drinking water quality.

The treatment was conducted under standard operating conditions optimized through experimental series presented in previous sections: rapid mixing at 150 rpm for 2 minutes, slow mixing at 30 rpm for 20 minutes, settling for 60 minutes, and temperature maintained at 24 ± 2°C.

The results demonstrated significant and differential treatment effectiveness across all three parameters as shown in Figure 9. TSS removal achieved 50% efficiency with reduction from initial 160 mg L^{-1} to final 80 mg L^{-1}, representing removal of 80 mg L^{-1} suspended solids. This moderate efficiency is attributed to the combined action of charge neutralization by aluminum sulfate and bridging effects of the anionic flocculant. The coagulation process destabilizes suspended particles by neutralizing their surface charges through adsorption of positively charged aluminum hydroxide species, while the flocculant enhances aggregation through polymer bridging [29, 30].

TH showed 35% reduction from initial 100 mg $CaCO_3$ L^{-1} to final 65 mg $CaCO_3$ L^{-1}, representing removal of 35 mg $CaCO_3$ L^{-1} equivalent of hardness-causing ions. This reduction occurs through co-precipitation mechanisms where hardness-causing cations (Ca^{2+} and Mg^{2+}) are entrapped or adsorbed onto aluminum hydroxide [$Al(OH)_3$] flocs formed during the coagulation process. As aluminum hydroxide precipitates form, they create high surface area solids with

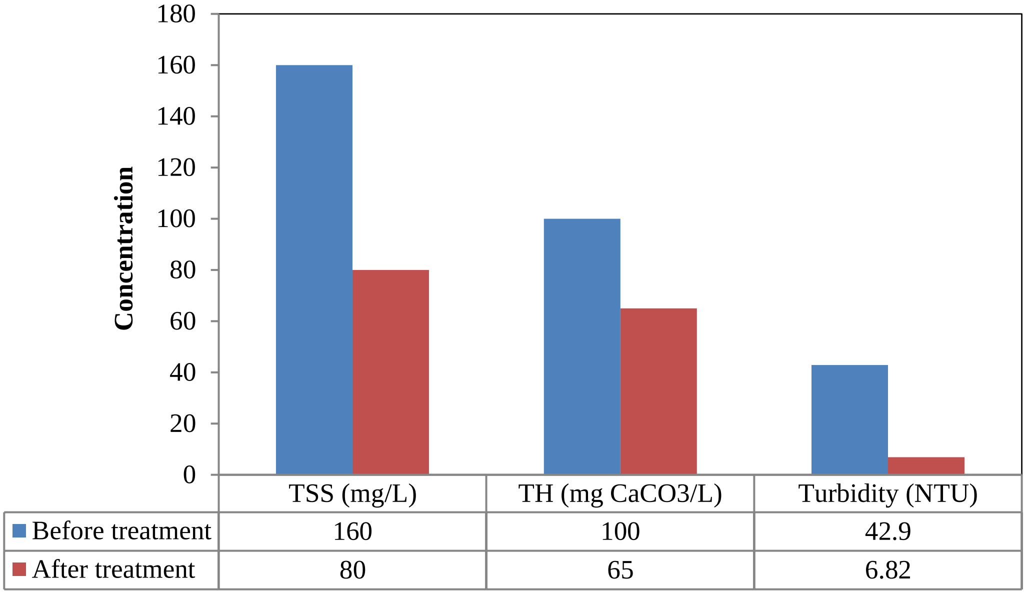

Figure 9. Effect of coagulation-flocculation treatment on suspended matter, total hardness, and turbidity removal showing initial and final concentrations. Treatment conditions: $Al_2(SO_4)_3$ = 400 mg L^{-1}; anionic flocculant = 100 mg L^{-1}; mixing: rapid 150 rpm × 2 min, slow 30 rpm × 20 min; settling: 60 min; water source: Ain Zada dam; initial conditions as per Table 1 (Turbidity = 42.9 NTU, TSS = 160 mg L^{-1}, TH = 100 mg $CaCO_3$ L^{-1})

sorption capacity for dissolved cations. Additionally, the elevated pH in the vicinity of growing aluminum hydroxide precipitates can induce localized precipitation of calcium carbonate and magnesium hydroxide that become incorporated into the floc structure. While coagulation-flocculation is not primarily designed for hardness removal, the 35% reduction represents a valuable secondary benefit that reduces scale formation potential in distribution systems and improves water softness [56].

Turbidity exhibited the highest removal efficiency at 84% with reduction from initial 42.9 NTU to final 6.82 NTU, demonstrating superior effectiveness in removing colloidal particles and fine suspended matter that contribute to light scattering and water cloudiness. The final turbidity of 6.82 NTU, while representing substantial improvement, remains above the typical drinking water standard of 1 NTU, indicating that additional polishing treatment such as sand filtration would be required to meet final regulatory requirements. The high turbidity removal efficiency demonstrates that coagulation-flocculation is particularly effective for its primary intended purpose of removing particles in the colloidal size range (0.1-10 micrometers) that cause turbidity [24].

The strong correlation between TSS removal at 50% and turbidity reduction at 84% provides important insights. This differential indicates that the coagulation-flocculation process was highly effective at removing particulate matter, with the substantially higher turbidity removal efficiency suggesting preferential removal of finer colloidal particles (0.1-10 micrometers) that contribute disproportionately to light scattering despite relatively lower mass contribution. Turbidity is caused primarily by light scattering from particles, with scattering efficiency maximized for particles near the wavelength of visible light (approximately 0.5 micrometers). The 50% TSS removal indicates that approximately half of the particle mass was captured, representing primarily the larger, denser particles that settle more readily. The differential between TSS and turbidity removal (84% versus 50%) demonstrates that turbidity-causing colloids, despite representing a smaller fraction of total particle mass, are preferentially and more effectively captured by the coagulation-flocculation process than larger suspended particles.

The 35% TH reduction, while lower than both particulate removal metrics, represents substantial mineral content reduction and demonstrates an important additional benefit beyond the primary turbidity removal function. This hardness reduction contributes to improved water quality for distribution systems by reducing scale formation potential in pipes, decreasing soap and detergent consumption in end-use applications, and improving aesthetic qualities. The moderate level of hardness removal through coagulation-flocculation suggests that facilities requiring greater hardness reduction would need to implement dedicated softening processes such as lime softening or ion exchange, but the 35% reduction achieved through conventional coagulation provides meaningful improvement at no additional cost beyond the standard treatment process.

4. Conclusions

This study systematically evaluated coagulation-flocculation processes for turbidity removal from surface water at Ain Zada dam, revealing critical insights into the application of Opuntia ficus-indica mucilage as a sustainable coagulant aid. The research demonstrated coagulant-specific compatibility with OFI mucilage through comprehensive experimental investigation: aluminum-based coagulants showed significant enhancement with $Al_2(SO_4)_3$ improving from 57.69% to 75.77% (31.3% relative improvement) and $AlCl_3$ improving from 68.61% to 81.85% (19.3% relative improvement) when using 10 mL mucilage per liter. In contrast, iron-based coagulants exhibited reduced efficiency with $Fe_2(SO_4)_3$ decreasing from 76.19% to 70.59% and $FeCl_3$ from 79.62% to 74.43%, indicating fundamentally distinct chemical interaction mechanisms between metal hydroxide surface chemistry and mucilage polysaccharides. Specifically, the anionic galacturonic acid groups in OFI mucilage form more stable bridging complexes with the amphoteric aluminum hydroxide precipitates compared to the more crystalline iron hydroxide precipitates, explaining the opposite performance trends observed with aluminum versus iron-based coagulation systems.

Iron-based coagulants achieved superior baseline performance with $FeCl_3$ reaching 79.62% turbidity removal at pH 7 without any coagulant aids, while aluminum-based coagulants reached maximum performance at pH 10 where sweep flocculation mechanisms predominate. Process enhancement through pre-chlorination at 10 mg L^{-1} Cl_2 substantially improved treatment efficiency to 82.98% and enabled approximately 75% coagulant dose reduction from 400 to 100 mg L^{-1} while maintaining equivalent turbidity removal, demonstrating significant potential for operational cost reduction. The most effective treatment configuration demonstrated energy-efficient operation using 30 rpm slow mixing for 20 minutes with extended settling time of 60 minutes being critical for maximum efficiency, achieving triple contaminant removal including 84% turbidity, 50% suspended solids, and 35% total hardness reduction in a single treatment step.

Raw water quality variations across sampling points (74-201 NTU turbidity, 1105-1890 μS/cm conductivity) produced 16 percentage point differences in treatment efficiency under identical conditions, highlighting the importance of adaptive treatment protocols responsive to source water variability. The predominantly organic turbidity composition (60-70% organic colloids from algal biomass) in Ain Zada dam influenced coagulation mechanisms and the effectiveness of natural coagulant aids.

These findings establish OFI mucilage as a viable sustainable coagulant aid specifically and exclusively for aluminum-based coagulation systems, offering promising directions for eco-friendly water treatment technologies, particularly in arid and semi-arid regions where Opuntia ficus-indica is abundant and cultivation requires minimal water resources. However, OFI mucilage is explicitly not recommended for iron-based coagulation systems due to negative performance interactions resulting in 5-6% efficiency reduction, stemming from fundamental incompatibilities between iron hydroxide surface chemistry and anionic mucilage polysaccharides. The successful implementation of OFI mucilage requires careful consideration of coagulant type compatibility, dosage optimization at 10 mL mucilage per liter treated water, appropriate process integration following the design guidelines established in Section 3.5.1, and recognition of economic and sustainability benefits including 25% coagulant reduction potential and utilization of renewable local resources.

Future research priorities should focus on: (1) mucilage preservation techniques for extended storage beyond 24 hours including evaluation of refrigeration, pasteurization, chemical preservation, and freeze-drying methods; (2) detailed molecular characterization of coagulant-mucilage interactions using advanced analytical techniques such as Fourier-transform infrared spectroscopy, nuclear magnetic resonance, and atomic force microscopy; (3) pilot-scale validation studies under varying seasonal conditions over a full annual cycle to confirm laboratory findings under realistic operational scenarios; (4) comprehensive life cycle assessment comparing OFI-enhanced treatment to conventional treatment to quantify environmental benefits including carbon footprint, energy consumption, and waste generation; (5) investigation of OFI mucilage combinations with other natural coagulant aids such as chitosan or Moringa oleifera to reveal synergistic effects and expand applicability to different water quality conditions.

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