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A Comparative Study of Natural and Chemical Coagulants for Turbidity Removal from Synthesized Turbid Surface Water

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ABSTRACT

Effective removal of suspended solids, colloidal turbidity, and organic fractions from surface water matrices is a foundational requirement for potable water production. Conventional water treatment schemes heavily rely on sedimentation processes augmented by synthetic chemical coagulants, predominantly Aluminum Sulfate (Alum), due to its established efficiency in large-scale utilities. However, escalating concerns regarding the environmental footprint of chemical sludge, the economic burden of sludge disposal, and potential neurotoxic health risks associated with residual aluminum have catalyzed research into sustainable biopolymer alternatives. This study systematically evaluates the coagulation performance of four plant-based extracts—Banana Peel (*Musa acuminata*), Okra (*Abelmoschus esculentus*), Orange Peel (*Citrus sinensis*), and Neem Leaves (*Azadirachta indica*)—and contrasts their efficacy against commercial Alum. Utilizing standard Jar Test apparatus, controlled experiments were conducted on synthetic turbid water stabilized at an initial turbidity of 24 NTU.

The empirical results demonstrated that among the natural alternatives, *Azadirachta indica* (Neem) leaves achieved the highest clarification efficiency at 62.50% (residual turbidity of 9 NTU), followed closely by *Abelmoschus esculentus* (Okra) at 58.33% (10 NTU). Conversely, *Musa acuminata* and *Citrus sinensis* extracts exhibited moderate and identical efficiencies of 45.84% (13 NTU). While commercial Alum maintained superior performance by achieving a 95.83% turbidity reduction down to a baseline of 1 NTU, the findings validate that natural coagulants hold significant promise as eco-friendly, non-toxic, and economically viable alternatives for decentralized, small-scale, and rural water purification systems.

Keywords: Natural coagulants, turbidity removal, Aluminum Sulfate, Jar test, water treatment, sustainable biopolymers, surface water clarification.

INTRODUCTION

Securing universal access to safe and potable drinking water remains a critical global challenge, particularly in developing jurisdictions where untreated surface water serves as the primary domestic supply. Surface water bodies are inherently vulnerable to runoff, which introduces a complex matrix of suspended solids, colloidal matter, microscopic organic debris, and pathogenic microorganisms. The presence of these constituents is macroscopically manifested as turbidity. High turbidity not only compromises the aesthetic acceptability of water but also shields pathogenic vector organisms from downstream disinfection protocols, necessitating highly efficient particle-separation technologies.

The conventional paradigm of water clarification centers on the coagulation–flocculation process. This step is engineered to destabilize stable, negatively charged colloidal suspensions, promoting their aggregation into macro-flocs that readily undergo gravity sedimentation. Globally, aluminum- and iron-based salts, such as Aluminum Sulfate $(Al_2SO_4)_3.18H_2O$ dominate this domain due to their rapid reaction kinetics and cost-effectiveness at scale. Nevertheless, the continuous deployment of chemical coagulants introduces severe operational and environmental liabilities. Chief among these are the generation of high-volume, nonbiodegradable hazardous sludge, the high cost of imported chemical matrices, and the potential long-term public health implications linked to residual aluminum ions in treated water, such as Alzheimer's disease and related neuropathology.

To mitigate these drawbacks, recent environmental research has shifted toward green chemistry, focusing on plant-derived natural coagulants as sustainable substitutes. Biopolymers extracted from agricultural by-products and indigenous flora—such as banana peels, okra pods, orange peels, and neem leaves—are rich in highly functional macromolecular components, including polysaccharides, proteins, tannins, and flavonoids. These natural agents contain active polymer chains and ionized functional groups capable of neutralizing colloidal charges or initiating particle bridging. While historical data suggests that biopolymers generally exhibit lower turbidity-removal efficiencies compared to trivalent chemical salts, their absolute biodegradability, low toxicity, near-zero cost, and local availability present a compelling case for their integration. They are especially suited for decentralized, rural, or emergency-response water treatment frameworks where access to commercial chemicals is restricted.

MATERIALS AND METHODS

Sample Collection and Synthetic Water Preparation

To ensure experimental uniformity and eliminate the transient fluctuations inherent in raw surface water, synthetic turbid water was formulated for this study. Base surface water was harvested from a local campus pond to preserve ambient ionic background characteristics. Stock colloidal suspensions were prepared by dispersing a calibrated mass of fine clay particles into the pond water, which was subsequently diluted to achieve a consistent initial turbidity of 24 Nephelometric Turbidity Units (NTU). The baseline physicochemical parameters of the sample were analyzed, revealing an average initial pH of 7.94.

Extraction and Preparation of Coagulant Matrix

The plant materials evaluated in this study—comprising banana peels (*Musa acuminata*), okra (*Abelmoschus esculentus*), orange peels (*Citrus sinensis*), and neem leaves (*Azadirachta indica*)—were sourced locally. The raw materials were thoroughly rinsed with deionized water to remove surface impurities and dust. Subsequently, the biomass was sliced and dehydrated in a forced-convection laboratory oven at 60°C until a constant dry weight was reached, preventing thermal degradation of the active biopolymers. The dried samples were mechanically pulverized using a kitchen mixer and sieved through a standard mesh to obtain fine, homogenous powders. Commercial grade Aluminum Sulfate $(Al_2SO_4)_3.18H_2O$ was similarly ground into a fine powder to serve as the control benchmarking standard.

Stock solutions for each coagulant were prepared within a concentration range of 5 to 20 g/L. The respective powders were dissolved in distilled water and subjected to magnetic stirring at 150 rpm for 30 minutes to facilitate the extraction of active coagulating agents (such as water-soluble proteins and polysaccharides). The resulting crude extracts were filtered through Whatman No. 1 filter papers to remove insoluble cellulosic matter, and the clear filtrates were preserved under refrigeration at 4°C for immediate experimental use.

Jar Test Experimental Design

Coagulation-flocculation trials were carried out using a standard digital multi-position Jar Test apparatus. Each experimental run utilized a 900 mL volume of the prepared synthetic turbid water, introduced into identical glass beakers. The samples were dosed with sequentially varied volumes of the respective natural and chemical coagulant stock solutions. The optimization protocol was executed through a standardized three-phase hydrodynamic sequence:

- **Rapid Mixing (Destabilization Phase):** Accelerated agitation at 120 rpm for duration of 2 minutes to ensure homogeneous coagulant dispersion and maximize particle-coagulant collision frequency.

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- **Slow Mixing (Flocculation Phase):** Gentle agitation at 30 rpm for 20 minutes to encourage the physical growth of micro-flocs into heavy macro-flocs via inter-particle bridging while preventing shear-induced floc breakage.

- **Sedimentation Phase:** Quiescent settling for a period of 30 minutes under zero-shear conditions to allow gravity settling of the formed flocs.

Following the settling period, clarified supernatant samples were carefully aspirated from a fixed depth of 2 cm below the liquid surface. The residual turbidity of the treated water was quantitatively determined using a pre-calibrated laboratory Nephelometric turbidity meter. The percentage turbidity removal efficiency was computed utilizing the fundamental mass-balance relation:

$$\% \text{ Efficiency } (\eta) = \{(T_0 - T_f)/T_0\} \times 100\%$$

Where T_0 represents the initial water turbidity (24 NTU) and T_f denotes the residual turbidity obtained post-treatment.

RESULTS AND DISCUSSION

Evaluation of Baseline Water Matrix

The experimental water matrix demonstrated stable baseline properties prior to coagulant introduction, characterized by a moderately alkaline pH of 7.94 and a medium-range turbidity profile of 24 NTU. This alkaline pH is highly favourable for assessing the performance of natural biopolymers as it influences the ionization state of the coagulant groups as well as the solubility of Alum.

Performance Dynamics of Plant-Based Natural Coagulants

The experimental results indicated that the plant-derived coagulants possessed distinctly varying capabilities for reducing turbidity, governed by their unique biochemical constituents. The operational performance parameters compiled at optimal dosages are detailed in Table 1.

Table 1: Clarification Efficacy and Residual Turbidity of Natural Coagulant Substrates

Botanical Source	Systematic Botanical Nomenclature	Optimal Residual Turbidity (NTU)	Net Turbidity Removal Efficiency (η)
Neem Leaves	Azadirachta indica	9.00	62.50%
Okra Pods	Abelmoschus esculentus	10.00	58.33%
Banana Peel	Musa acuminata	13.00	45.84%
Orange Peel	Citrus sinensis	13.00	45.84%

Among the natural candidates, *Azadirachta indica* (Neem) leaf extract yielded the most pronounced clarification performance, registering an efficiency of 62.50% and depressing the initial turbidity to 9 NTU. This enhanced activity is principally ascribed to the presence of water-soluble, positively charged protein fractions within neem leaves. These proteins act as natural positively charged polyelectrolytes that destabilize the negatively charged particle fractions. Furthermore, antimicrobial compounds present in Neem may also aid in the coagulation of organic bioparticles.

Abelmoschus esculentus (Okra) achieved a high efficiency of 58.33% (residual turbidity of 10 NTU). The coagulation pathway for okra is distinct; it is governed by its inherently high mucilage content. This long-chain molecular structure acts primarily as a powerful flocculant aide. While its charge neutralization capability is lower than that of Neem, its extensive polymer length facilitates superb inter-particle bridging, thus trapping destabilized colloids.

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Conversely, *Musa acuminata* (Banana) and *Citrus sinensis* (Orange) peels both demonstrated a moderate and identical turbidity reduction capacity of 45.84%, yielding a final turbidity of 13 NTU. The organic matrices of these agricultural products are predominantly composed of pectin, hemicellulose, and organic acids. The lower efficiency is likely due to electrostatic repulsion between the anionic groups of the pectin chains and the negatively charged surface of the colloidal substances, which limits adsorption kinetics.

Performance Dynamics of Aluminium Sulphate (Alum Control)

The chemical control framework utilizing commercial Alum achieved exceptional turbidity removal, exceeding all natural alternatives:

- **Minimum Residual Turbidity:** 1 NTU
- **Peak Clarification Efficiency:** 95.83%

This high efficiency is explained by well-established principles. When Alum is introduced into water at pH 7.94, it undergoes rapid hydrolysis to yield trivalent aluminum complexes along with highly reactive polymeric hydroxyl-aluminum cations. These positively charged species compress the electrical double layer of the suspended particles with exceptional speed. Simultaneously, the system rapidly precipitates amorphous aluminum hydroxide which forms large, dense, insoluble flocs. These flocs settle quickly via sweep flocculation, physically trapping and removing virtually all suspended colloids and achieving standard potable water limits (< 5 NTU).

Comparative Analysis and Techno-Environmental Viability

A side-by-side comparison reveals that the evaluated natural coagulants achieve approximately 45% to 65% of the primary treatment capability exhibited by commercial Alum. While raw plant extracts do not currently match the absolute clarification speeds or efficiencies of chemical salts, they present distinct operational advantages that cannot be replicated by chemical systems. The turbidity removal efficacy is graphically shown by the pie diagram represented in Figure 1.

Turbidity Removal Efficiency Comparison:

Alum………………………………95.83%

Neem………………………………62.50%

Okra……………………………….58.33%

Banana Peel...……………………..45.84%

Orange Peel……………………….45.84%

Alum treatment produces a highly acidic, metallic sludge that alters downstream pH and risks leaching aluminum ions into environments, presenting bioaccumulation hazards. In contrast, the sludge derived from plant materials is completely non-hazardous, entirely biodegradable, and can be directly diverted into composting processes. From an economic perspective, using agricultural residues like banana and orange peels or locally abundant flora like neem significantly reduces chemical import costs and operational infrastructure expenditures. This confirms that while Alum remains optimal for high-throughput centralized municipal installations, natural coagulants offer a viable, sustainable, and decentralizable alternative for treating rural, low-input water systems.

CONCLUSION

This comparative study validates that plant-based natural coagulants possess genuine technical potential for reducing turbidity in surface water applications. Among the biopolymer candidates tested under a standardized initial load of 24 NTU, *Azadirachta indica* (Neem) leaves and *Abelmoschus esculentus* (Okra) emerged as the

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most efficient variants, yielding turbidity reductions of 62.50% and 58.33% respectively. However, commercial Alum maintains its status as a more efficient single agent, achieving a final turbidity clearance of 95.83% down to 1 NTU.

The findings indicate that while natural coagulants may require optimization to meet strict municipal potable water limits on their own, they represent excellent, low-carbon, non-toxic alternatives for decentralized, rural, or small-scale treatment utilities where economic barriers or chemical supply chain disruptions prevent the use of industrial coagulants.

Future Scope

To advance the integration of green biopolymers into mainstream environmental engineering, future research efforts should target the following domains:

- **Advanced Purification and Extraction**: Investigating salt-assisted extraction (e.g., using to increase the yield of active cationic proteins from neem and okra, thereby improving their turbidity removal efficiency.
- **Dual-Coagulant Regimes**: Evaluating the performance of hybrid or dual-coagulant systems where natural polymers are coupled with reduced fractions of Alum to minimize chemical sludge without compromising water clarity.
- **Optimization of Process Kinetics**: Conducting comprehensive response-surface methodology (RSM) designs to determine the coupled impacts of shifting ambient pH, variable initial turbidity loads, and temperature on flocculation kinetics.
- **Shelf-Life and Storage Stabilization**: Developing formulation methods to extend the storage life of liquid natural extracts, protecting them from microbial degradation and ensuring long-term operational viability.

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