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Plant-Based Natural Coagulants in Sustainable Water and Wastewater Treatment: Mechanisms, Performance, and Emerging Applications

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Abstract: The increasing pressure on global water resources, driven by population growth, industrial expansion, and pharmaceutical and chemical contamination, has intensified the demand for sustainable and environmentally benign water and wastewater treatment technologies. Conventional coagulation–flocculation processes, largely dependent on inorganic coagulants such as alum and ferric salts, are effective but raise concerns related to sludge toxicity, residual metal content, secondary pollution, and long-term ecological and health impacts. In response, plant-based natural coagulants have emerged as promising alternatives, attracting significant academic and practical attention over the past two decades. This article provides an extensive, theory-driven and evidence-based examination of natural coagulants derived from plant seeds, leaves, gums, and agricultural by-products, with a particular emphasis on their application in turbidity reduction, pharmaceutical removal, and industrial wastewater treatment. Drawing strictly on the provided literature, the study elaborates on coagulation mechanisms, material characteristics, process optimization, comparative performance with alum, and sustainability implications. The methodology adopted is a comprehensive qualitative synthesis of experimental, modeling, and review-based studies, enabling a deep interpretation of trends, consistencies, and contradictions within existing research. Results discussed indicate that natural coagulants, such as Moringa oleifera, okra gum, rosehip seeds, papaya seeds, and various local plant leaves, demonstrate high removal efficiencies under optimized conditions, often approaching or matching conventional coagulants while offering superior environmental compatibility. The discussion critically evaluates limitations related to dosage variability, organic load addition, storage stability, and scalability, while also exploring future research directions including composite coagulants, hybrid systems, and circular economy integration. The article concludes that plant-based natural coagulants represent a viable and strategically important pathway toward sustainable water and wastewater management, particularly in developing and resource-constrained regions.

Keywords: natural coagulants, water treatment, wastewater management, plant-based materials, turbidity removal, sustainable treatment

INTRODUCTION

Water is universally recognized as a fundamental resource for human survival, economic development, and ecological balance. Despite its abundance at the planetary scale, accessible and safe freshwater constitutes only a small fraction of total water resources. Rapid urbanization, industrialization, agricultural intensification, and the proliferation of synthetic chemicals and pharmaceuticals have severely compromised water quality worldwide. Among the various treatment processes developed to address these challenges, coagulation and flocculation remain central to conventional water and wastewater treatment systems due to their effectiveness in removing suspended solids, colloids, organic matter, and certain dissolved contaminants (Do et al., n.d.)

Traditionally, coagulation processes rely on inorganic chemical coagulants such as aluminum sulfate (alum) and ferric chloride. While these agents are effective and widely used, their application is increasingly scrutinized due to associated drawbacks. These

include the generation of large volumes of chemically contaminated sludge, potential links between residual aluminum and neurological disorders, increased treatment costs, and environmental concerns related to mining, processing, and disposal (Ang & Mohammad, 2020). Such limitations have stimulated interest in alternative coagulants that align more closely with the principles of sustainability, environmental protection, and circular resource use.

Natural coagulants, particularly those derived from plants, have gained prominence as viable substitutes or supplements to conventional coagulants. Early traditional practices in various cultures employed plant extracts for water clarification, long before the advent of modern chemical treatment systems. Scientific investigation into these practices has intensified, resulting in a growing body of literature documenting the coagulation efficiency, mechanisms, and practical potential of diverse natural materials (BINAYKE & Jadhav, 2013).

Recent reviews and experimental studies highlight the versatility of natural coagulants in treating a wide range of water types, including surface water, municipal wastewater, industrial effluents, and aquaculture discharges. Alazaiza et al. (2022) emphasize their emerging role in pharmaceutical removal, a critical challenge given the persistence and bioactivity of pharmaceutical compounds in aquatic environments. Similarly, Mohd-Salleh et al. (2019) and Ang and Mohammad (2020) underline the sustainability advantages of natural coagulants, including biodegradability, low toxicity, and reduced sludge hazards.

Despite this growing interest, significant knowledge gaps remain. Variability in raw material composition, inconsistent performance across water matrices, and limited large-scale implementation studies continue to constrain widespread adoption. Moreover, much of the existing literature focuses on isolated experimental outcomes, with insufficient theoretical integration and comparative analysis across different plant-based coagulants and wastewater types.

The present article addresses these gaps by offering an in-depth, theoretically grounded synthesis of plant-based natural coagulants in water and wastewater treatment. By strictly adhering to the provided references, the study seeks to integrate mechanistic understanding, experimental findings, optimization strategies, and sustainability considerations into a coherent narrative. This approach not only consolidates existing knowledge but also critically examines limitations and future research trajectories essential for translating laboratory success into real-world application.

Methodology

The methodological approach adopted in this study is qualitative, integrative, and analytical, designed to produce a publication-ready research article grounded entirely in existing peer-reviewed literature and conference proceedings. Rather than generating new experimental data, the study synthesizes findings from the provided references to construct a comprehensive theoretical and interpretive framework for understanding the role of plant-based natural coagulants in water and wastewater treatment.

The primary sources include review articles, experimental studies, modeling-based investigations, and conference papers focusing on natural coagulants derived from seeds, leaves, gums, and other plant materials. Key studies addressing pharmaceutical removal, turbidity reduction, industrial wastewater treatment, and aquaculture effluents were examined in detail to ensure balanced coverage of application domains (Alazaiza et al., 2022; Ahmad et al., 2024; Madala et al., 2025).

The analysis followed a thematic synthesis strategy. First, conceptual foundations of coagulation and flocculation were examined to contextualize natural coagulant mechanisms relative to conventional chemical processes (Do et al., n.d.). Second, individual plant-based coagulants were analyzed in terms of material properties, preparation methods, and reported performance metrics. Third, optimization approaches, including response surface methodology and modeling-based assessments, were explored to understand how operational parameters influence removal efficiency (Desta & Bote, 2021; Amran et al., 2021).

Comparative analysis formed a critical component of the methodology. Studies directly comparing natural coagulants with alum or other chemical coagulants were examined to identify performance trade-offs, operational advantages, and contextual suitability (Madala et al., 2025). Sustainability dimensions, including environmental impact, sludge management, and resource availability, were integrated throughout the analysis based on interpretive insights from review studies (Ang & Mohammad, 2020; Mohd-Salleh et al., 2019).

To maintain academic rigor, all major claims and interpretations are explicitly supported by in-text citations using the author–year format. The methodology avoids quantitative synthesis or meta-analysis, as numerical data presentation is restricted. Instead, descriptive interpretation is used to articulate trends, relationships, and theoretical implications.

Results

The synthesis of the reviewed literature reveals a consistent pattern of effectiveness for plant-based natural coagulants across diverse water and wastewater treatment applications. Although performance varies depending on source material, preparation technique, and water matrix, the overall findings suggest that natural coagulants can achieve substantial reductions in turbidity, suspended solids, organic load, and specific contaminants under optimized conditions.

One of the most extensively studied natural coagulants is Moringa oleifera seed extract. Desta and Bote (2021) demonstrate that optimized dosages of Moringa seeds significantly improve wastewater clarity, with removal efficiencies enhanced through systematic parameter optimization. The coagulation activity is attributed primarily to water-soluble cationic proteins that neutralize negatively charged colloids, facilitating aggregation and sedimentation. These findings are echoed in broader reviews highlighting the versatility and accessibility of Moringa-based coagulants in developing regions (Mohd-Salleh et al., 2019).

Beyond Moringa, several other plant-derived materials show promising results. Agarwal et al. (2003) report effective treatment of tannery effluent using okra gum, emphasizing its polymeric nature and capacity to bridge particles into stable flocs. Similarly, Ahmad et al. (2022) identify local plant leaves as effective turbidity-removal agents, underscoring the potential of region-specific resources in decentralized water treatment systems.

Industrial wastewater applications represent a particularly challenging domain due to high contaminant loads and complex chemical compositions. Studies focusing on steel and iron industry effluents reveal that plant-based coagulants such as rosehip seed powder can achieve meaningful reductions in turbidity and associated pollutants (Abujazar et al., 2022; Amr et al., 2023). These results are significant, as industrial wastewater often requires intensive chemical treatment, and the demonstrated effectiveness of natural coagulants suggests opportunities for partial or full substitution of conventional agents.

Comparative studies provide further insight into performance dynamics. Madala et al. (2025) compare natural coagulants with alum for turbidity removal, finding that while alum often achieves rapid clarification at lower dosages, natural coagulants can reach comparable efficiency with optimized dosing and mixing conditions. Importantly, natural coagulants produce sludge with lower toxicity and improved biodegradability, offering downstream environmental benefits.

Emerging applications, such as pharmaceutical and antibiotic removal, highlight the expanding relevance of natural coagulants. Alazaiza et al. (2022) review evidence indicating that plant-based coagulants contribute to the removal of pharmaceutical residues, either directly through adsorption and charge interactions or indirectly by enhancing floc formation and sedimentation of contaminant-laden particles.

Overall, the results synthesized from the literature indicate that plant-based natural coagulants are not merely experimental curiosities but functionally robust materials with broad applicability. Their effectiveness is context-dependent but consistently improved through careful optimization and system-specific adaptation.

Discussion

The findings discussed above invite a deeper examination of the theoretical, practical, and strategic implications of adopting plant-based natural coagulants in water and wastewater treatment. From a mechanistic perspective, natural coagulants operate through a combination of charge neutralization, adsorption, and polymer bridging, mechanisms that are conceptually similar to those of synthetic polymeric coagulants but achieved through biologically derived macromolecules (Ang & Mohammad, 2020). This similarity explains why, under appropriate conditions, natural coagulants can rival conventional chemicals in performance.

However, the variability inherent in natural materials presents both a challenge and an opportunity. Differences in plant species, growing conditions, harvesting methods, and extraction processes lead to fluctuations in active compound concentration and coagulation efficiency. While this variability

complicates standardization, it also opens avenues for localized optimization and the valorization of indigenous plant resources (Ahmad et al., 2022).

Sustainability considerations strongly favor natural coagulants. Reviews consistently emphasize reduced environmental impact, renewable sourcing, and lower sludge toxicity compared to alum and iron salts (Ang & Mohammad, 2020; Mohd-Salleh et al., 2019). In regions where access to chemical coagulants is limited or costly, locally sourced plant-based materials offer a resilient alternative that aligns with community-based water management strategies.

Nevertheless, limitations must be acknowledged. The addition of organic matter from plant extracts can increase biochemical oxygen demand if not properly managed, potentially necessitating additional treatment steps. Storage stability and shelf life of natural coagulant preparations also remain concerns, particularly in large-scale or centralized systems. Furthermore, most studies to date focus on batch or pilot-scale experiments, leaving questions regarding long-term performance, supply chain logistics, and regulatory acceptance unresolved.

Future research directions, as suggested implicitly across the reviewed literature, include the development of composite coagulants that combine natural and minimal chemical components, advanced extraction and purification techniques to enhance consistency, and integration with other treatment processes such as adsorption and membrane filtration (Mohd-Salleh et al., 2019; Ahmad et al., 2024). Modeling-based approaches, such as those employed by Amran et al. (2021), also offer valuable tools for predicting performance and guiding scale-up.

Conclusion

The comprehensive analysis presented in this article demonstrates that plant-based natural coagulants represent a scientifically sound, environmentally sustainable, and practically viable option for water and wastewater treatment. Drawing strictly from the provided literature, the study shows that natural coagulants can effectively remove turbidity, suspended solids, pharmaceuticals, and industrial pollutants across diverse water matrices when appropriately optimized.

While challenges related to variability, scalability, and organic load remain, these are not insurmountable barriers but rather focal points for future research and innovation. In an era defined by resource constraints and environmental responsibility, the strategic integration of natural coagulants into treatment systems offers a pathway toward more sustainable and resilient water management practices. Continued interdisciplinary research, supported by policy alignment and community engagement, will be essential to realize the full potential of these natural materials in addressing global water quality challenges.

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