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Sustainable Coagulation–Flocculation Pathways for Water and Wastewater Treatment: Advances, Mechanisms, and Environmental Implications of Natural and Tannin-Based Coagulants

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ABSTRACT: The treatment of water and wastewater remains one of the most critical environmental engineering challenges of the twenty-first century, driven by population growth, industrialization, agricultural intensification, and the increasing scarcity of clean water resources. Among the various physicochemical treatment processes, coagulation–flocculation has historically played a central role due to its effectiveness in removing turbidity, suspended solids, organic matter, nutrients, and a wide range of contaminants. However, the extensive reliance on conventional inorganic coagulants such as alum and iron salts has raised concerns related to sludge generation, residual metal toxicity, ecological impacts, and long-term sustainability. In response, there has been a growing global shift toward natural, plant-based, and tannin-derived coagulants as environmentally benign alternatives. This article provides an in-depth, theory-driven and critically elaborated analysis of natural and tannin-based coagulants for water and wastewater treatment, strictly grounded in existing scholarly literature. The discussion integrates insights from studies on plant extracts, fruit peels, seeds, chitosan, and tannin-rich biomaterials, as well as comparative evaluations against conventional chemical coagulants. Particular emphasis is placed on wastewater streams such as textile effluents, dairy wastewater, aquaculture discharges, biodiesel wastewater, vegetable oil refinery effluents, and drinking water turbidity control. Beyond performance metrics, the article deeply explores coagulation mechanisms, extraction and valorization pathways, environmental impacts, cost considerations, and emerging research trajectories. By synthesizing these dimensions, the study contributes a comprehensive academic perspective on how natural coagulants can support sustainable water management while addressing technical, environmental, and socio-economic constraints.

Keywords: Natural coagulants, Tannin-based coagulants, Wastewater treatment, Coagulation–flocculation, Sustainable water treatment, Plant-based materials

INTRODUCTION

Access to clean and safe water is universally recognized as a fundamental human right, yet it remains unevenly distributed across regions due to environmental degradation, industrial pollution, and inadequate treatment infrastructure. Rapid industrial expansion, particularly in sectors such as textiles, food processing, aquaculture, biodiesel production, and oil refining, has significantly increased the discharge of complex wastewater streams containing suspended solids, organic matter, nutrients, oils, dyes, and other pollutants. Conventional water and wastewater treatment systems have relied heavily on coagulation–flocculation as a core unit operation to address these contaminants. The process functions by destabilizing colloidal particles and facilitating their aggregation into flocs that can be removed by sedimentation or filtration.

Historically, inorganic coagulants such as aluminum sulfate and ferric chloride have been favored due to their high efficiency, predictable behavior, and relatively low upfront cost. Despite these advantages, extensive research has highlighted their limitations, including the production of chemically contaminated sludge, the risk of residual metal ions in treated water, and potential adverse impacts on aquatic ecosystems and human health. These concerns are particularly pronounced in developing regions, where sludge management infrastructure is often inadequate and water reuse is increasingly necessary.

In recent decades, sustainability considerations have reshaped the research agenda in water treatment, prompting a renewed interest in natural coagulants derived from renewable biological sources. These materials, including plant extracts, fruit peels, seeds, polysaccharides, and tannin-rich biomass, have demonstrated promising coagulation properties while offering advantages such as biodegradability, reduced toxicity, and valorization of agricultural waste. The utilization of natural coagulants aligns closely with circular economy principles, as many are sourced from by-products of food and agricultural industries.

Among natural coagulants, tannin-based materials have emerged as particularly versatile due to their polyphenolic structure, high molecular weight, and ability to interact with a wide range of contaminants. Research spanning drinking water treatment, industrial wastewater remediation, and aquaculture effluent management has documented their effectiveness in turbidity reduction, organic matter removal, and nutrient control. Concurrently, studies on citrus peels, papaya seeds, dragon fruit peels, chitosan, and blended natural coagulants have expanded the spectrum of viable bio-based options.

Despite the growing body of literature, significant gaps remain in the holistic understanding of natural and tannin-based coagulants. Many studies focus on isolated case experiments without deeply engaging with underlying mechanisms, long-term environmental implications, or scalability challenges. Furthermore, comparative assessments often emphasize removal efficiency while underexploring sludge characteristics, life-cycle impacts, and integration into existing treatment systems. Addressing these gaps requires an extensive theoretical elaboration that situates experimental findings within broader environmental, economic, and technological contexts.

This article responds to that need by presenting a comprehensive, publication-ready synthesis of natural and tannin-based coagulation–flocculation research. Drawing strictly from the provided references, it develops a nuanced academic narrative that examines the evolution of coagulation science, the mechanisms governing natural coagulant performance, methodological approaches used in optimization studies, and the implications for sustainable water and wastewater treatment.

METHODOLOGY

The methodological foundation of this research article is rooted in an extensive qualitative synthesis of peer-reviewed studies focused on natural and tannin-based coagulants for water and wastewater treatment. Rather than generating new experimental data, the approach emphasizes theoretical integration and critical interpretation of existing research findings. This strategy is particularly appropriate given the objective of maximizing conceptual depth and explanatory rigor while adhering strictly to the provided reference corpus.

The reviewed studies employ a diverse range of experimental methodologies, reflecting the heterogeneity of wastewater types and natural coagulant sources. Commonly, jar test experiments serve as the primary evaluation tool for coagulation–flocculation performance. These tests involve controlled mixing stages, including rapid mixing to disperse the coagulant and slow mixing to promote floc formation, followed by settling periods. Removal efficiencies for turbidity, chemical oxygen demand, color, suspended solids, and nutrients are typically assessed through standard analytical procedures, as reported across multiple studies (Dotto et al., 2019; Justina et al., 2018).

Optimization techniques play a central role in refining the performance of natural coagulants. Response surface methodology, for instance, has been widely applied to identify optimal operating conditions such as coagulant dosage, pH, and mixing intensity, particularly in complex wastewater streams like biodiesel wastewater (Daud et al., 2018). These statistical approaches allow for the exploration of interaction effects between variables, offering insights into the sensitivity and robustness of natural coagulation systems.

Extraction and preparation methods for natural coagulants constitute another critical methodological dimension. Studies on tannin-based coagulants emphasize the importance of extraction parameters, solvent selection, and purification techniques in determining coagulant efficacy (Hoyos-Martínez et al., 2019). Similarly, research on fruit peels and seeds highlights preprocessing steps such as drying, grinding, and aqueous extraction as determinants of active compound availability (Dollah et al., 2019; Ismail et al., 2018).

Comparative methodologies are also prominent, with several studies directly evaluating natural coagulants against conventional chemical coagulants under identical conditions. Such comparisons provide valuable benchmarks for assessing not only removal efficiency but also sludge volume, settling behavior, and operational practicality (Madala et al., 2025; Justina et al., 2018).

In aquaculture and marine systems, methodological adaptations are evident due to the sensitivity of aquatic organisms and the salinity of effluents. Studies in this domain incorporate ecological considerations and focus on suspended solids and nutrient removal while minimizing toxicity risks (Letelier-Gordo and Fernandes, 2021; Gibson et al., 2020).

Overall, the methodological landscape reflected in the literature underscores a convergence toward integrative evaluation frameworks that combine performance metrics, optimization analysis, and environmental considerations. This article synthesizes these methodological insights to support a deeper theoretical understanding of natural coagulation processes.

RESULTS

The collective findings across the reviewed literature consistently demonstrate that natural and tannin-based coagulants are capable of achieving substantial improvements in water and wastewater quality. Turbidity removal emerges as one of the most robust and widely reported outcomes, with plant-based coagulants derived from citrus peels, papaya seeds, dragon fruit peels, and tannin extracts showing high effectiveness across diverse water matrices (Dollah et al., 2019; Dollah et al., 2021; Ismail et al., 2018).

In textile wastewater treatment, natural coagulants such as chitosan and tannin-based formulations have been shown to significantly reduce color and organic load, often approaching the performance of conventional inorganic coagulants (Hassan et al., 2009; Dotto et al., 2019). These results are particularly notable given the complex composition of textile effluents, which include dyes, surfactants, and high concentrations of organic matter.

Dairy wastewater studies further highlight the comparative efficiency of vegetable tannins relative to polyaluminium chloride, demonstrating effective removal of suspended solids and organic pollutants while generating more biodegradable sludge (Justina et al., 2018). Similarly, investigations into vegetable oil refinery wastewater reveal that combined natural flotation and chemical precipitation strategies can enhance overall treatment efficiency while reducing chemical dependency (Hartal et al., 2024).

In aquaculture wastewater contexts, tannin-based and plant-derived coagulants have proven effective in reducing suspended solids and nutrients, contributing to improved effluent quality and reduced environmental impact on receiving waters (Tomasi et al., 2025; Ahmad et al., 2024). Blended natural coagulants have also shown synergistic effects, achieving higher removal efficiencies than individual components alone (Karnena et al., 2022).

Optimization studies consistently report that natural coagulants exhibit strong pH-dependent behavior, with optimal performance typically observed near neutral pH ranges. This characteristic is advantageous for practical applications, as it reduces the need for extensive pH adjustment compared to some chemical coagulants (Gaikwad and Munavalli, 2019; Daud et al., 2018).

Across the literature, sludge characteristics associated with natural coagulants are described as less voluminous and more environmentally compatible than those produced by conventional chemicals. Although quantitative sludge analyses vary, the qualitative consensus supports the potential for easier handling and safer disposal or reuse.

DISCUSSION

The widespread effectiveness of natural and tannin-based coagulants observed in the literature invites a deeper theoretical examination of the mechanisms underlying their performance. Unlike inorganic salts that primarily operate through charge neutralization, natural coagulants often combine multiple mechanisms, including adsorption, polymer bridging, and complexation. The presence of functional groups such as hydroxyl, carboxyl, and phenolic moieties enables strong interactions with suspended particles and dissolved organic matter (Tomasi et al., 2022).

Tannins, in particular, exhibit high affinity for proteins, metals, and organic compounds due to their polyphenolic structure. This multifunctionality explains their consistent performance across varied wastewater types, from dairy and textile effluents to aquaculture discharges. The ability of tannins to form stable flocs also contributes to improved settling behavior and reduced residual turbidity (Das et al., 2022).

From a sustainability perspective, the valorization of agricultural and forestry residues as coagulant sources represents a significant advancement. Citrus peels, papaya seeds, chestnut shells, and dragon fruit peels are often discarded as waste, yet their transformation into functional coagulants adds economic value and reduces environmental burden (Hoyos-Martínez et al., 2019; Tomasi et al., 2025).

Nevertheless, challenges remain. Variability in raw material composition can lead to inconsistent performance, necessitating standardized extraction and quality control protocols. Additionally, large-scale implementation requires careful assessment of supply chains, storage stability, and compatibility with existing treatment infrastructure. While cost analyses suggest favorable economics in many cases, comprehensive life-cycle assessments are still limited (Igwegbe et al., 2021).

The bibliometric analysis of coagulation–flocculation research underscores a rapidly expanding global interest in natural coagulants, particularly in the context of sustainability and green engineering (Hizam et al., 2024). This trend suggests that future research will increasingly focus on hybrid systems, process integration, and policy frameworks that support the adoption of eco-friendly treatment technologies.

CONCLUSION

The body of evidence synthesized in this article unequivocally demonstrates that natural and tannin-based coagulants represent a viable and sustainable alternative to conventional chemical coagulants for water and wastewater treatment. Their effectiveness across diverse applications, coupled with environmental and socio-economic benefits, positions them as key components of future water management strategies. While technical and logistical challenges persist, ongoing research and innovation are steadily addressing these barriers. By integrating theoretical understanding with practical considerations, natural coagulants have the potential to reshape coagulation–flocculation practices in alignment with global sustainability goals.

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