Eco-Friendly Multistage Treatment of Dairy Wastewater Using Natural Coagulants: Mechanisms, Performance Evaluation, and Future Perspectives-A Review

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ABSTRACT

The dairy industry is one of the major agro-based sectors contributing significantly to global wastewater generation. Dairy effluent is characterized by high concentrations of organic matter, suspended solids, fats, and nutrients, resulting in elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Conventional treatment methods using chemical coagulants such as alum and ferric salts are widely employed; however, these methods are associated with drawbacks including high sludge production, residual toxicity, and increased operational costs. In recent years, natural coagulants derived from plant-based materials, biopolymers, and agro-wastes have emerged as sustainable alternatives due to their biodegradability, low toxicity, and economic feasibility. This review critically examines the characteristics of dairy wastewater, mechanisms of coagulation, and the performance of various natural coagulants. Furthermore, their integration into multistage treatment systems and future prospects for large-scale applications are discussed, highlighting their potential for sustainable wastewater management.

Keywords: Dairy wastewater, natural coagulants, sustainable treatment, coagulation-flocculation, eco-friendly wastewater management.

INTRODUCTION

The rapid growth of the dairy industry has resulted in increased water consumption and wastewater generation. Dairy processing units utilize large volumes of water for operations such as equipment cleaning, pasteurization, homogenization, and product processing. Consequently, the generated wastewater contains substantial amounts of biodegradable organic matter, including lactose, proteins, and lipids (Demirel *et al.*, 2018; Verma *et al.*, 2018; Ahmad *et al.,* 2021). In addition to organic pollutants, dairy effluents also contain detergents, sanitizers, and inorganic salts, which contribute to fluctuating physicochemical characteristics (Kushwaha *et al.,* 2020; Rinaudo, 2019).

The seasonal variation in milk production and processing further influences wastewater composition, making treatment more complex (Demirel *et al*., 2018; Kushwaha *et al*., 2020).Moreover, stringent environmental regulations necessitate the implementation of efficient and sustainable treatment strategies (Chen, 2004; Ali *et al.,* 2021).The discharge of untreated dairy wastewater into natural water bodies leads to severe environmental issues such as oxygen depletion, eutrophication, and ecological imbalance (Kushwaha *et al*., 2020; Muthuraman and Sasikala, 2018; Rinaudo, 2019; Abidin *et al*., 2020).Coagulation–flocculation is a widely used primary treatment method (Verma *et al.,* 2018; Yin, 2018; Bhatia *et al*., 2018). However, chemical coagulants raise concerns regarding sludge toxicity and cost (Verma *et al*., 2018; Yin, 2018; Chen *et al*., 2021).

Natural coagulants have gained attention due to their eco-friendly nature (Teh *et al*., 2016; Choy *et al.,* 2017; Zaman *et al*., 2020; Zhou *et al.,* 2022).

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REVIEW METHODOLOGY

This review was conducted using a systematic and structured approach to ensure scientific rigor and transparency. Relevant literature was collected from major academic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar.

The literature search was performed using specific keywords such as *"dairy wastewater treatment," "natural coagulants," "coagulation–flocculation,"* and *"eco-friendly wastewater management."* Boolean operators (AND, OR) were applied to refine the search and improve relevance.

The inclusion criteria were:

- Peer-reviewed journal articles published between 2004 and 2024
- Studies focusing on dairy wastewater or similar high-strength organic effluents
- Research evaluating natural coagulants or comparative analysis with chemical coagulants
- Studies reporting quantitative performance data such as COD, BOD, and turbidity removal

The exclusion criteria included:

- Non-peer-reviewed articles, reports, and conference abstracts
- Studies lacking experimental or quantitative data
- Research unrelated to coagulation–flocculation or dairy wastewater treatment

After screening and eligibility assessment, relevant studies were selected and critically analyzed to compare treatment efficiency, mechanisms, operational parameters, and limitations. The collected data were synthesized to provide a comprehensive evaluation of natural coagulants and their applicability in multistage wastewater treatment systems.

Characteristics of Dairy Wastewater

Dairy wastewater is a complex and highly variable effluent, the composition of which depends on processing operations, product type, and cleaning practices. It is typically rich in biodegradable organic matter, including lactose, proteins, fats, and oils, along with suspended solids and essential nutrients such as nitrogen and phosphorus (Ahmad *et al*., 2019; Kushwaha *et al.,* 2020; Ahmad *et al*., 2021). The presence of detergents, sanitizers, and residual chemicals further contributes to fluctuations in physicochemical properties, making the wastewater composition dynamic and difficult to standardize.

One of the defining features of dairy effluent is its high organic load. Biochemical oxygen demand (BOD) values generally range between 800 and 3000 mg/L, while chemical oxygen demand (COD) can exceed 5000 mg/L, indicating a substantial concentration of biodegradable pollutants (Demirel *et al*., 2018; Kushwaha *et al*., 2020; Ahmad *et al.,* 2021). This elevated organic content promotes rapid microbial activity, which can significantly deplete dissolved oxygen in receiving water bodies if discharged untreated.

In addition, fats and oils present in the wastewater tend to form stable emulsions and surface films, which hinder oxygen transfer and reduce the efficiency of biological treatment processes (Muthuraman and Sasikala, 2018; Rinaudo, 2019). Proteins such as casein and whey contribute to the colloidal nature of the effluent, making solid–liquid separation challenging without adequate pre-treatment. Furthermore, dissolved solids, including chlorides, sulfates, and residual cleaning agents, may interfere with downstream biological processes and affect overall treatment performance (Ahmad *et al*., 2021; Ali *et al*., 2021).

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Another critical aspect is the variability in wastewater characteristics due to seasonal production changes and fluctuations in water usage. Hydraulic and shock load variations in dairy industries can significantly impact treatment system stability and efficiency. These factors necessitate the adoption of robust and adaptable treatment strategies, particularly effective pre-treatment methods such as coagulation–flocculation, to destabilize colloidal particles and enhance pollutant removal.

Table 1. Typical Characteristics of Dairy Wastewater

S.NO	PARAMETER	RANGE
1.	pH	4.5-8.5
2.	BOD (mg/L)	800-3000
3.	COD(mg/L)	1500-5000
4.	TSS(mg/L)	200-1000
5.	Oil & Grease (mg/L)	50-500

Environmental Impact of Dairy Wastewater

The discharge of untreated dairy wastewater poses significant environmental challenges due to its high organic and nutrient content. Elevated levels of biodegradable organic matter stimulate rapid microbial growth, leading to the depletion of dissolved oxygen in receiving water bodies. This results in hypoxic or anaerobic conditions that are detrimental to aquatic organisms (Kushwaha *et al*., 2020; Rinaudo, 2019; Ahmad *et al.,* 2021).

In addition to oxygen depletion, the presence of nutrients such as nitrogen and phosphorus contributes to eutrophication, promoting excessive algal growth and subsequent ecosystem imbalance (Rinaudo, 2019; Crini *et al*., 2018). The decay of organic matter further generates unpleasant odors and releases greenhouse gases, including methane and carbon dioxide, thereby contributing to climate-related impacts (Chen, 2004; Mohd Salleh *et al*., 2019).

Another critical concern is the potential contamination of soil and groundwater resulting from improper disposal practices. The infiltration of untreated effluent can degrade water quality and pose risks to human health. Furthermore, the presence of residual detergents and cleaning agents may introduce toxic effects on aquatic and terrestrial ecosystems.

These environmental implications highlight the necessity for efficient and sustainable treatment strategies, particularly those that minimize ecological impact while maintaining high treatment efficiency (Ali *et al*., 2021).

Conventional Chemical Coagulants: Performance and Limitations

Chemical coagulants such as alum and ferric salts are widely employed in wastewater treatment due to their high efficiency in removing turbidity, suspended solids, and colloidal particles. These coagulants function primarily through charge neutralization and sweep flocculation mechanisms, facilitating the aggregation and subsequent settling of suspended particles (Verma *et al*., 2018; Yin, 2018). Their effectiveness, reliability, and ease of application have made them the preferred choice in many industrial treatment systems.

Despite these advantages, several limitations restrict their long-term sustainability. One of the major concerns is the generation of large volumes of sludge, which often contains residual metal ions and requires careful handling and disposal. This not only increases operational costs but also raises environmental concerns. Additionally, the performance of chemical coagulants is highly sensitive to pH and dosage conditions, necessitating continuous monitoring and process optimization.

Another significant drawback is the potential health risk associated with residual metal content in treated water if not adequately controlled. Furthermore, the reliance on chemical inputs contributes to increased treatment costs and environmental burden. These limitations have driven growing interest in alternative approaches, particularly the use of natural coagulants, which offer a more sustainable and eco-friendly solution.

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Natural Coagulants: Mechanisms and Performance

Natural coagulants are derived from plant materials, animal sources, and microorganisms.

Natural coagulants have emerged as promising alternatives to conventional chemical coagulants due to their biodegradability, low toxicity, and sustainable origin. These coagulants are typically derived from plant materials, animal sources, and microbial products, and they contain bioactive compounds such as proteins and polysaccharides that facilitate the coagulation process (Teh *et al.,* 2016; Choy *et al*., 2017; Zaman *et al.,* 2020; Mehta *et al*., 2021).

Protein-based coagulants, such as those obtained from *Moringa oleifera*, function primarily through charge neutralization. The positively charged proteins interact with negatively charged colloidal particles, reducing repulsive forces and promoting aggregation. In contrast, polysaccharide-based coagulants such as chitosan and plant-derived mucilage operate mainly through polymer bridging, where long-chain molecules link suspended particles to form larger flocs that can be easily separated.

In addition to charge neutralization and polymer bridging, adsorption also plays a significant role in the coagulation process, particularly for agro-waste-derived materials. These mechanisms often act simultaneously, enhancing the overall efficiency of natural coagulants in removing turbidity, suspended solids, and organic matter.

Several studies have reported that natural coagulants can achieve turbidity removal efficiencies of up to 90%, along with substantial reductions in COD and BOD levels. For instance, *Moringa oleifera* and chitosan have demonstrated effective pollutant removal under optimized conditions. However, the efficiency of these coagulants is influenced by multiple factors, including pH, dosage, mixing conditions, and the characteristics of the wastewater being treated.

Table 2 A: Protein-Based Natural Coagulants

S.NO	Coagulant	Source	Component	Efficiency	Reference
1.	*Moringa oleifera*	Seeds	Cationic proteins	High turbidity removal	Rinaudo (2019); Abidin *et al.* (2020)
2.	*Cicer arietinum*	Chickpea	Proteins	Moderate	Zaman *et al.* (2020)
3.	*Vigna unguiculata*	Cowpea	Proteins	Moderate	Mehta *et al.* (2021)
4.	*Glycine max*	Soybean	Proteins	High	Das *et al*. (2023)
5.	*Phaseolus vulgaris*	Bean	Proteins	Moderate	[Zaman *et al.* (2020)
6.	*Pisum sativum*	Pea	Proteins	Moderate	Mehta *et al.* (2021)
7.	*Dolichos lablab*	Hyacinth bean	Proteins	Moderate	Zhou *et al*. (2022)
8.	Tamarind seed kernel	Tamarind	Proteins	High	Mehta *et al.* (2021)
9.	Fenugreek seeds	Trigonella frenum-graecum	Proteins	Moderate	Li *et al*. (2020)
10.	Groundnut cake	Peanut	Proteins	Moderate	Wang *et al. (*2022)

Table 2B: Polysaccharide-Based Natural Coagulants

S.NO	Coagulant	Source	Component	Efficiency	Reference
1.	Chitosan	Shellfish	Polysaccharide	High COD removal	Garcia-Fayos *et al.* (2021); Bratby (2016)
2.	Cactus	Plant	Mucilage	Moderate	Ong *et al*. (2020)
3.	Banana peel	Agro-waste	Cellulose	Moderate	Ahmad *et al.* (2018); Garcia-Fayos *et al*. (2021)
4.	Potato starch	Potato	Starch	Moderate	Zaman *et al.* (2020)
5.	Corn starch	Maize	Starch	Moderate	Mehta *et al.* (2021)

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6.	Rice husk	Agro-waste	Cellulose	Moderate	Zhou *et al.* (2022)
7.	Okra mucilage	*Abelmoschus esculentus*	Polysaccharide	High	Mehta *et al. (*2021)
8.	Aloe vera	Plant	Gel polysaccharides	Moderate	Wang *et al.* (2022)
9.	Guar gum	*Cyamopsis tetragonoloba*	Galactomannan	High	Li *et al.* (2020)
10.	Xanthan gum	Microbial	Polysaccharide	High	[Mehta *et al.* (2021)

They contain bioactive compounds such as proteins and polysaccharides that facilitate coagulation (Teh, *et al.*, (2016), Saleem, *et al.*, (2019), Zaman, *et al.*, (2020), Mehta, *et al.*, (2021)). These materials are renewable, biodegradable, and environmentally friendly, making them suitable alternatives to chemical coagulants (Choy, *et al.*, (2017), Zhou, *et al.*, (2022), Das, *et al.*, (2023)).

Natural coagulants operate through multiple mechanisms including charge neutralization, polymer bridging, and adsorption (Choy, *et al.*, (2017), Ghernaout, (2020), Bhatia, *et al.*, (2018)).

Table 3: Mechanisms vs Coagulant Type

S.NO	Mechanism	Description	Coagulant Example
1.	Charge Neutralization	Neutralizes particle charge	Moringa
2.	Polymer Bridging	Links particles	Chitosan
3.	Adsorption	Surface binding	Agro-waste

While natural coagulants demonstrate significant potential, their performance is not universally consistent across different studies. Variations in raw material composition, extraction methods, and wastewater characteristics can lead to fluctuations in treatment efficiency. For example, *Moringa oleifera* may achieve high turbidity removal under optimal conditions, but its effectiveness in reducing COD and BOD can vary depending on initial pollutant concentration and process parameters. Similarly, chitosan exhibits strong performance within a specific pH range but may show reduced efficiency under highly alkaline conditions.

This variability underscores a key limitation in the application of natural coagulants: their effectiveness is highly dependent on operational conditions. As a result, careful optimization and standardization are required to ensure consistent performance, particularly in large-scale applications.

Comparison Between Natural and Chemical Coagulants

Several studies have quantitatively compared the performance of natural and chemical coagulants in wastewater treatment. Chemical coagulants such as alum and ferric chloride can achieve turbidity removal efficiencies of up to 95–99%, whereas natural coagulants typically achieve removal efficiencies ranging from 80–95% depending on wastewater characteristics and dosage conditions (Chen, *et al.*, (2021), Zhou, *et al.*, (2022), Mehta, *et al.*, (2021)).

Natural coagulants such as Moringa oleifera and chitosan have demonstrated COD reduction efficiencies of 60–85% and BOD reduction efficiencies of 50–80% (Rinaudo, (2019), Abidin, *et al.*, (2020)). In contrast, chemical coagulants often provide slightly higher removal rates but generate significantly larger volumes of non-biodegradable sludge.

Additionally, sludge generated from natural coagulants is biodegradable and can be safely disposed of or reused in agricultural applications, whereas chemical sludge may contain toxic metal residues requiring specialized disposal methods. Economic analyses indicate that natural coagulants can reduce treatment costs by 20–50% due to lower chemical usage and sludge handling costs (Chen, (2004), Ali, *et al.*, (2021)).

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Table: 4 Comparison of Natural and Chemical Coagulants

S.NO	PARAMETER	NATURAL COAGULANTS	CHEMICAL COAGULANTS
1.	Source	Plant-based, biodegradable materials	Synthetic inorganic salts
2.	Cost	Low	High
3.	Efficiency	Moderate to high	High
4.	Sludge Production	Low, biodegradable	High, often hazardous
5.	Toxicity	Non-toxic	May cause toxicity
6.	Environmental Impact	Eco-friendly	Environmental concerns

Despite the generally reported performance ranges, significant variability exists in the efficiency of both natural and chemical coagulants across different studies. This variation can be attributed to differences in wastewater composition, pH, coagulant dosage, mixing conditions, and experimental scale. In the case of natural coagulants, the absence of standardized extraction and preparation methods further contributes to inconsistencies in reported results.

Moreover, most available studies are conducted under laboratory-scale conditions, which may not accurately reflect real-world industrial scenarios. Factors such as fluctuating wastewater characteristics, operational constraints, and economic considerations can influence performance at larger scales. Consequently, while natural coagulants show considerable promise, their large-scale applicability requires further validation through pilot-scale and industrial studies.

Operational Parameters Affecting Coagulation

The efficiency of coagulation depends on several factors such as pH, dosage, mixing conditions, and temperature. Optimal pH for natural coagulants is typically between 6 and 8 (Zhang, *et al.*, (2023), Bhatia, *et al.*, (2018)). Excess dosage can lead to particle restabilization, reducing efficiency (Zhang, *et al.*, (2023)). Proper mixing ensures uniform distribution and floc formation (Bhatia, *et al.*, (2018), Vijayaraghavan, *et al.*, (2020)). Temperature influences reaction kinetics and can affect coagulation efficiency (Zhang, *et al.*, (2023)). Careful optimization of these parameters is essential for achieving consistent treatment performance (Zhang, *et al.*, (2023), Bhatia, *et al.*, (2018)).

Table 5 : Operational Parameters

S.NO	PARAMETER	OPTIMAL RANGE	EFFECT
1.	pH	6–8	Maximum efficiency
2.	Dosage	Varies	Overdose reduces efficiency
3.	Mixing Speed	Moderate	Ensures floc formation
4.	Temperature	Ambient	Affects kinetics

Multistage Treatment Approach

Multistage treatment systems integrate physical, chemical, and biological processes to achieve comprehensive removal of pollutants from dairy wastewater (Gregory, 2018; Edzwald, 2017). Typically, primary treatment involves coagulation–flocculation to remove suspended solids and colloidal matter, followed by biological processes such as activated sludge systems or anaerobic digestion for the degradation of organic pollutants (Ahmad et al., 2021). Tertiary treatment methods, including membrane filtration and advanced oxidation processes, are subsequently employed to achieve higher levels of purification (Gregory, 2018; Edzwald, 2017). The incorporation of natural coagulants into multistage systems has gained increasing attention due to their potential to reduce chemical usage and sludge toxicity (Mehta *et al.,* 2021). Several studies have demonstrated that the use of natural coagulants in the primary stage can enhance overall treatment efficiency while improving the sustainability of the process.

From a practical perspective, multistage systems offer greater flexibility in handling fluctuations in wastewater composition and hydraulic load, which are common in dairy processing industries. However, the effectiveness

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of natural coagulants in such systems is highly dependent on operational conditions, including pH, dosage, and mixing regimes.

Although promising results have been reported at laboratory scale, the transition to pilot-scale and full-scale applications remains limited. Challenges such as process optimization, consistency in coagulant quality, and integration with existing treatment infrastructure must be addressed to ensure successful implementation in industrial settings (Mohd Salleh *et al*., 2019; Ali *et al*., 2021).

Economic and Sustainability Analysis

Natural coagulants reduce chemical procurement costs and sludge disposal expenses. Their use supports circular economy principles by utilizing agricultural waste materials. Additionally, reduced environmental impact lowers compliance costs associated with wastewater discharge regulations (Chen, (2004)). These benefits make natural coagulants an economically viable and sustainable option for wastewater treatment.

Challenges and Future Perspectives

Despite the growing interest in natural coagulants, several challenges hinder their widespread application in wastewater treatment. One of the primary limitations is the variability in raw material composition, which can significantly influence coagulation performance (Choy *et al*., 2017; Zaman *et al*., 2020; Mehta *et al*., 2021). Additionally, the lack of standardized extraction and preparation methods leads to inconsistencies in efficiency across different studies.

Another important challenge is the relatively short shelf life and potential biodegradation of natural coagulants, which may affect storage and long-term usability. In many cases, higher dosages are required compared to chemical coagulants, which can impact process efficiency and operational costs (Zaman *et al*., 2020; Mehta *et al.,* 2021).

From an industrial perspective, scalability remains a critical concern. Most studies on natural coagulants have been conducted under laboratory conditions, and there is limited data on pilot-scale or full-scale implementation. Factors such as fluctuating wastewater characteristics, supply chain limitations for raw materials, and compatibility with existing treatment systems must be carefully evaluated (Zhou *et al.,* 2022; Mehta *et al*., 2021).

Future research should focus on developing standardized extraction techniques, improving the stability and storage of natural coagulants, and optimizing process parameters for large-scale applications (Li *et al*., 2020; Wang *et al*., 2022). Recent advancements in hybrid coagulant systems, combining natural and chemical coagulants, have shown promising results in balancing efficiency and sustainability (Wang *et al*., 2022; Zhou *et al*., 2022).

CONCLUSION

Natural coagulants have emerged as promising and sustainable alternatives to conventional chemical coagulants for the treatment of dairy wastewater. Their biodegradability, low toxicity, and potential cost advantages make them particularly attractive for environmentally responsible wastewater management. When integrated into multistage treatment systems, natural coagulants can contribute to effective removal of suspended solids and organic pollutants while reducing chemical dependency and sludge-related concerns.However, their performance remains variable and strongly dependent on factors such as raw material composition, extraction methods, and operational conditions. In comparison to chemical coagulants, which offer consistent and predictable efficiency, natural coagulants require careful optimization to achieve reliable results. This highlights the importance of standardization and process control for their practical application.

Furthermore, the transition from laboratory-scale studies to pilot- and industrial-scale implementation remains limited. Challenges related to scalability, storage stability, and consistent supply of raw materials must be addressed to enable widespread adoption. In this context, emerging approaches such as hybrid coagulant systems

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and nano-enhanced biopolymers offer promising pathways to improve performance and overcome existing limitations.

Overall, natural coagulants represent a viable and sustainable solution for dairy wastewater treatment. Future research should focus on large-scale validation, process optimization, and the development of standardized protocols to ensure consistent and efficient performance. With continued advancements, these materials have the potential to play a significant role in advancing sustainable wastewater treatment practices.

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