ISSN: 0973-4929, Vol. 20, No. (1) 2025, Pg. 06-18

Current World Environment

www.cwejournal.org

Unlocking the Water Purification Potential of Fruit Waste: A Review

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Abstract

Current studies are increasingly directed toward extracting beneficial bioactive compounds from fruit waste, offering both environmental and health-related advantages. This strategy not only reduces organic waste but also meets the growing interest in phenolic compounds known for their protective role against chronic diseases. This review investigates the operational principles of bio-coagulants in water purification processes. Typically, water treatment comprises several steps, beginning with coagulation and flocculation, followed by sedimentation and then filtration. Coagulation-flocculation plays a vital role as the first stage, where agents are added to promote the clustering of suspended particles. Traditional chemical coagulants-like aluminum sulfate, polyaluminum chloride (PAC), and iron-based salts are effective but come with drawbacks, including high costs and potential health concerns. These chemicals may alter water's pH balance and result in waste that is not easily biodegradable. In contrast, plant-based coagulants have shown promise in effectively treating water, offering a more environmentally friendly and safer alternative to conventional methods. Among these, the seeds of *Mangifera indica* have been identified as particularly effective. Additionally, the peels of *Musa paradisiaca* also demonstrate coagulation potential. This review aims to identify accessible, cost-effective, and sustainable natural alternatives for producing potable water, especially in developing countries. It evaluates plant-based alternatives to chemical coagulants, focusing on their mechanisms, extraction, and effectiveness. The paper identifies promising sources like *Mangifera indica* and highlights research gaps to guide future eco-friendly water treatment innovations. At the end of this review, readers will have a comprehensive understanding of the process associated with the choice, extraction, cleaning and stability of coagulation, depending on the plants used in water treatment.

Article History

Received: 12 March 2025

Accepted: 19 April 2025

Keywords

Biodegradable sludge;
Bio-coagulants;
Flocculation;
Sedimentation;
Turbidity;
Water treatment.

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Doi: https://dx.doi.org/10.12944/CWE.20.1.2

Introduction

Access to clean water is essential for life, yet pollution from industrialization and urbanization threatens water quality, especially in rural areas reliant on untreated sources. Water constitutes approximately 75% of the human body weight.[1] The rise in industrialization and urbanization has escalated water contamination, making pollution a critical global issue. Approaching pure and safe drinking water is essential for all forms of livelihoods, but is an important issue in rural areas. Many rural communities rely on rivers and wells for their daily water supply; however, these sources often do not meet the necessary quality standards.[2] Water is necessary for personal consumption, hygiene, and food preparation.[3] One of the primary objectives of water treatment is to eliminate suspended particles. While disinfection is often viewed as equally or more crucial, effective clarification is essential for ensuring reliable disinfection, as particles can protect microorganisms in the water. The clarification process typically includes coagulation, flocculation, settling, and filtration.[4] Coagulation and flocculation are key physicochemical processes in the treatment of surface water and these processes effectively decrease algae, bacteria, turbidity, colour, organic matter, and mud particles.[5] Various chemical coagulants and disinfectants are employed in water treatment. However, there are signs that certain waterborne pathogens are developing resistance to treatments involving chlorine, alum, and lime. Additionally, chlorine and halogen compounds used for water disinfection have been associated with cancer risks due to the formation of tetrahalomethane compounds, which can act as hormone mimics.[1] Additionally, synthetic polymers and their associated undesirable substances may interact with other materials during treatment, resulting in by-products whose health effects are not well understood.[6] Recently, several effective coagulants derived from plants have been discovered. In the last few years, *Mangifera indica*[7-10] and *Musa paradisiaca*[11-15] are the most widely used plant materials as effective natural coagulants for water treatment, especially in village areas. Certain plants can act as coagulants due to their ability to neutralize the colloidal particle charge and facilitate coagulation process via polymer-bridging mechanism.[16] Natural coagulants generate sludge that is more biodegradable and less voluminous, typically comprising only 20-30% of the sludge produced by alum treatment.[17] Additionally, these coagulants should be safe for human health and the environment. Although natural coagulants have gained attention, studies evaluating the efficiency of fruit waste-derived biocoagulants are still scarce.

This study examines the viability of utilizing fruit waste as an eco-friendly coagulant for water treatment, the advantages and challenges of utilizing biocoagulants, identify existing knowledge gaps and propose future strategies to enhance the use of fruit waste in water purification. The objective is to enhance understanding of sustainable and eco-friendly water treatment technologies, meeting the rising demand for clean drinking water while reducing environmental harm. This review does not dismiss the potential of other plant parts in water treatment; rather, it aims to clarify the focus of this review and highlight areas of interest. This review explores the potential of fruit waste-derived biocoagulants, highlighting their mechanisms, benefits, challenges, and knowledge gaps, with the aim of advancing sustainable, safe, and accessible water purification solutions for underserved communities.

A Comprehensive Insight into Water Purification Method

Natural surface water sources require treatment to eliminate haziness, colour, harmful bacteria and poisonous dissolved gas. Coagulation (agglomeration), followed by flocculation (aggregation), plays a crucial role in this process by converting fine particles responsible for turbidity, colour, and harmful bacterial into bigger floc aggregates. These aggregates may either settle as precipitates or remain suspended in the water. These flocs are then conditioned for easy removal in the next stages of the treatment process. Conventional chemical coagulants used in water treatment pose health and environmental risks, including toxic by-products and pathogen resistance.[18] Coagulation specifically targets the removal of colloidal particles by modifying them so they can interact and bond together, forming larger floc particles. The treatment of drinking water generally consists of two main stages: particle aggregation and microbial elimination (Fig. 1).

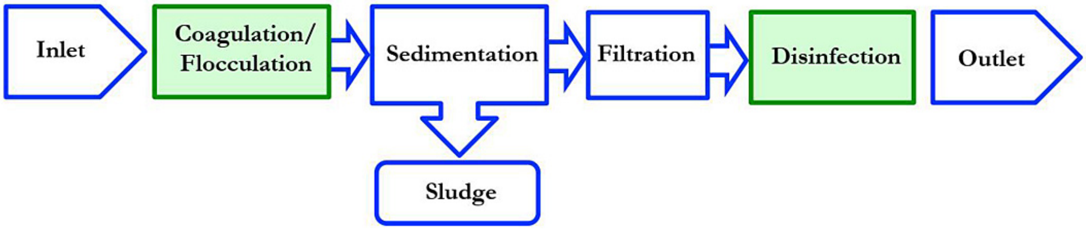

Fig. 1: Standard Methods for Water Purification.[18]

The treatment begins as raw water flows into the system through the entry point. The following processes are carried out in a water treatment plant.[18]

Coagulation/Flocculation

Initially, natural or synthetic coagulants are introduced to destabilize suspended materials like dust, organic substances, and microbes. These particles clump together to form larger masses called flocs, which can be more easily separated.[18]

Sedimentation

Once floc formation is complete, the water proceeds to the sedimentation tank. Gravity helps the heavier flocs settle at the bottom, producing a layer of sludge. This sludge is later extracted and handled separately.[18]

Filtration

Next, the water undergoes filtration, which targets smaller particles left behind after sedimentation. This stage typically uses media like sand, gravel, or activated carbon to trap and remove remaining contaminants.[5]

Disinfection

The nearly purified water is then disinfected to destroy any surviving pathogens, such as bacteria and viruses. Methods such as chlorination, ozonation, or UV exposure are commonly used to ensure microbiological safety.[18]

Outlet

Finally, the clean water exits through the outlet and is distributed for public use, including household and community supply.

Each step in this process plays a vital role in removing physical, chemical, and biological contaminants. This multi-stage approach ensures the water meets safety standards, making it suitable for human consumption, especially in regions where water quality is compromised by pollution.[18]

Water cloudiness is caused by Floating particles and organic contaminants. Since colloidal materials do not settle easily, they remain dispersed in the water and cannot be efficiently removed by Screening or settling alone. Essentially, the solid matter classified as colloids are too small to settle quickly and too tiny to be captured by filter pores. Additionally, most colloids are stable due to their negative charge, which prevents them from aggregating with other colloidal particles.[18]

Coagulants work by neutralizing the negative charges on particles, leading to their destabilization. Flocculation involves the aggregation of these destabilized particles into larger clusters called flocs, which then settle out of the water due to gravity, a process known as sedimentation. When water has high cloudiness, a supplementary flocculant may be needed along with the coagulant to enhance clarity. The level of turbidity is usually measured with a turbidimeter, and the readings are given in Nephelometric Turbidity Units (NTU).

Coagulants Characteristics

The stability of colloids is preserved because of the electrical charges present on their surfaces. To disrupt the stability of these particles, their charge must be counteracted, which can be done by adding oppositely charged ions. Since most colloids in water carry a negative charge, adding positively charged ions can help reduce this charge. Schulze and Hardy's research revealed that a single mole of a triply charged ion can drastically reduce the charge, having the same impact as 30 to 50 moles of a doubly charged ion or 1,500 to 2,500 moles of a singly charged ion. The purpose of coagulation is to alter colloidal particles, enabling them to clump and form larger aggregates. This process involves adding a positive ion to the water, which reduces the surface charge enough to prevent the colloids from repelling one another. A coagulant refers to the chemical substance added to facilitate this process. There are three essential properties of a coagulant:

1. In natural waters, dispersed particles typically carry a negative charge, necessitating the use of a cation to neutralize this charge, with trivalent cations being the most effective.
2. To ensure water safety, coagulants must be non-toxic.
3. The coagulant introduced should precipitate from the solution, meaning it should be insoluble at neutral pH levels, preventing the accumulation of high ion concentrations in the water. This precipitation significantly aids in the removal of colloids.

Flocculation is the process where dispersed particles come together to form larger masses called flocs (Fig. 2), which gradually sink under the influence of gravitational force in a process known as sedimentation.[19]

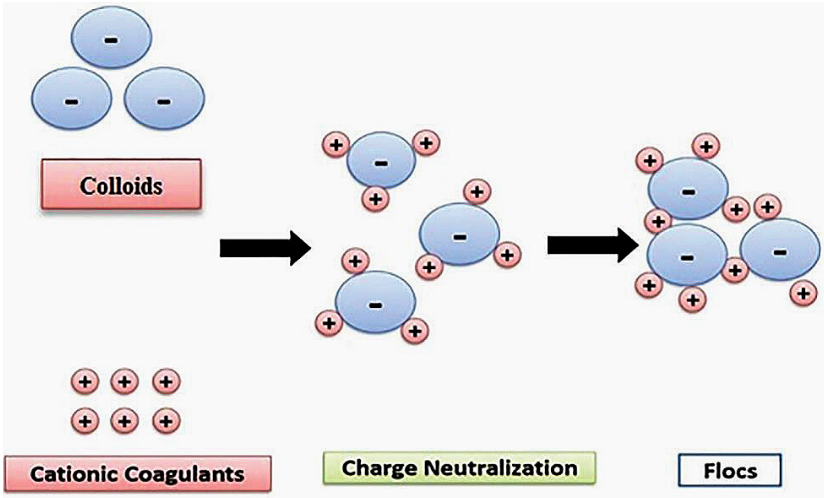

Fig. 2: Adsorption and charge neutralization.

Flocculation, in contrast, refers to the process where destabilized particles (with reduced electrical surface charge) aggregate, forming larger particles called flocs, as a result of adding coagulants. It is commonly considered a part of the coagulation process, and together, these steps are known as coagulation-flocculation. The phase of this process is depicted in Fig. 1. It is also crucial to recognize that excessive use of coagulants can reverse the charge of the colloids, leading to a redistribution of charge and transforming them into positively charged colloids, which results in re-stabilization.[20]

Suspended particles in surface water are typically negatively charged. When particles share the same charge, the repulsive forces between them help maintain their stability. To destabilize these particles, coagulants, such as simple electrolytes or metal salts that carry positively charged ions, are introduced into the water. These positive ions penetrate the electrical double layer around the particles, reducing the repulsive forces. This process, combined with the micro- and macro-flocculation steps in the flocculation process, leads to the destabilization of particles by compressing the double layer. The interaction between the negatively charged particles and the positive ions, often referred to as counter ions.[21] Fig. 3 illustrates the interaction between the negatively charged particles and the positive ions, often referred to as counter ions.[21]

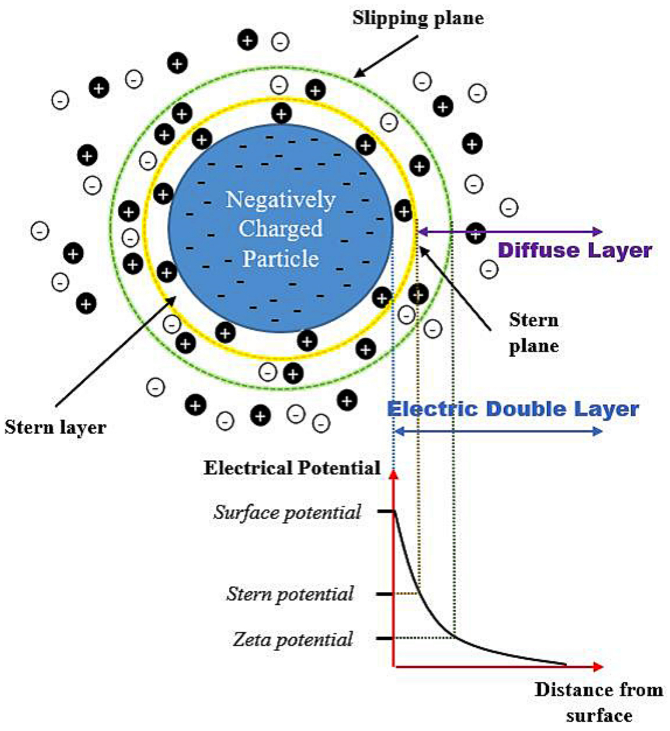

Fig. 3: Structure of electrical double layer.[21]

The zeta potential quantifies the electrical charge of particles that are dispersed in a liquid. As the ionic concentration increases, the compression of the double layer also intensifies, weakening the repulsive forces between particles and facilitating coagulation through van der Waals forces. However, enhancing ionic strength to reduce the double layer's thickness is not a practical method for destabilizing particles in water, as the required ionic strength would exceed levels deemed safe for drinking water. Consequently, coagulating agents are necessary to effectively destabilize the particles. Efficient coagulation occurs when the zeta potential is carefully adjusted toward neutrality (around 0 mV). When zeta potential values are too high in either the negative or positive direction, coagulation becomes significantly less effective.[22]

A widely used approach for assessing coagulation efficiency is the jar test. This test is carried out using specialized equipment, as illustrated in Fig. 4. The jar test aims to identify the optimal coagulant dosage needed to decrease the sample's turbidity.[22]

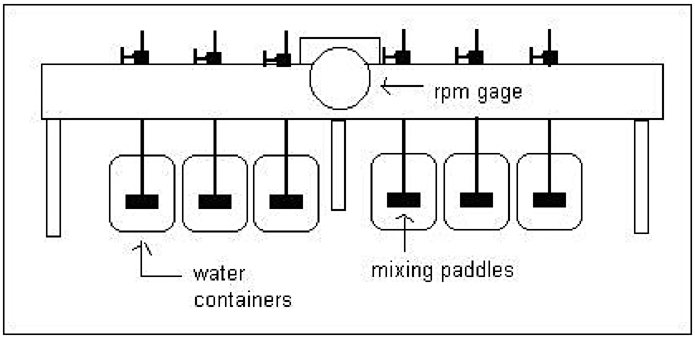

Fig. 4: Jar Test Apparatus

Several factors influence The success rate of the particle aggregation process. These incorporate: (i) the specific coagulant selection, (ii) applied coagulant amount, (iii) the characteristics of the water, such as its colour and turbidity, (iv) the pH level, (v) The time allocated for blending and floc formation, (vi) temperature, and (vii) the strength of mixing forces. The choice of coagulating agents is selected based on their ability to improve the treatment process and meet water quality standards. For effective coagulation, it is essential to eliminate (i) cloudiness in water, (ii) natural and synthetic substances, (iii) colour, (iv) dangerous microbes and disease-causing organisms, (v) Aquatic plant-like organisms, and (vi) substances that contribute to taste and odour. It is important to note that while coagulation helps in removing many impurities, microorganisms are primarily eliminated through disinfection processes.[23]

Synthetic Coagulants

Currently, many large water treatment facilities, particularly those operating on a pilot scale, utilize various coagulants. Common synthetic coagulants include Alum, aluminum-based coagulants, iron(III) chloride, advanced ferric coagulants, derivatives of polyacrylamide and branched-chain polyamines.[24] Although These chemical binding agents can be expensive and may have negative health implications, they are still widely used due to the limited availability of alternatives.

Drawbacks of Synthetic Coagulants

Chemical coagulants are commonly utilized for reducing turbidity in both water and wastewater treatment, but their use can lead to serious health concerns. Alum (aluminum sulfate) is particularly prevalent in water treatment facilities. However, its application has been linked to various health, economic, and environmental issues, including neurological disorders such as percentile dementia and a potential link to Alzheimer's disease.[6,25,26] Additionally, alum can hinder bone mineralization.[27] The sludge generated during treatment is often large in volume and non-biodegradable, resulting in increased treatment costs. Furthermore, the expense associated with importing these chemicals can lead to a reduction in international currency reserves for countries. The effect of aluminum-based coagulants on pH levels of processed water necessitates the addition of lime to mitigate these effects, which adds further costs.[28] To address these drawbacks, it is essential to seek alternatives. Natural coagulants present a viable alternative to synthetic coagulating agents. This discussion focuses exclusively on botanical-derived aggregation agents.

Eco-friendly Coagulants

Due to cost considerations and environmental concerns associated with synthetic organic polymers and inorganic chemicals, there is increasing interest in using natural materials. A practical approach is to substitute conventional chemicals in eco-conscious purification methods alternatives which have a reduced environmental impact Regarding manufacturing aspects, usage, as well as disposal practices. Several scholarly evaluations have demonstrated the performance of botanical-derived coagulants in diverse water purification methods applications.[5, 29-31] Various eco-friendly coagulating agents, including *Mangifera indica* seeds and peels of *Musa paradisiaca*, show significant potential for water coagulation.

Extraction of Active Components

The green extract can originate from various sources, but the extraction methods are generally similar. Various solvents can be utilized to isolate seeds, including water, organic compounds, or salt solutions. Among these, due to its high polarity, easy availability, and affordability, water is the preferred solvent. However, salt is the next most commonly used medium for extracting proteins. The key compounds are processed as demonstrated in Figure 5. In certain cases, Liquid extracts and fine particulates might contain additional Botanical substances that are Abundant in mineral compounds, potentially increasing the organic load in water, necessitating further purification. This additional processing is typically achieved through methods such as precipitation, lyophilization, ion exchange, or dialysis.[32]

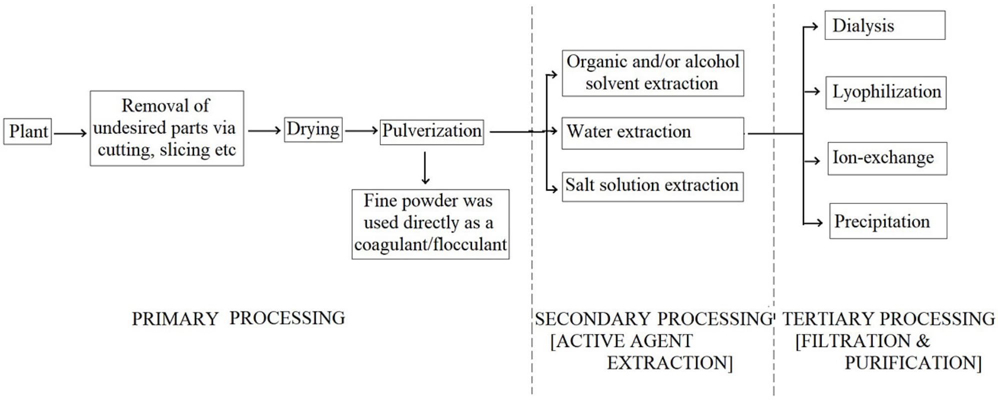

Fig. 5: Overview of the processing steps for preparing plant-based coagulants.[18]

Mechanism of Plant-Based Coagulating Agents

Coagulation operates through four main mechanisms: compression of the electrical double layer, polymer-induced bridging, charge destabilization, and enmeshment coagulation. For coagulants derived from plants, only the mechanisms of polymer-induced bridging and electrostatic charge neutralization are applicable.[33,34] When high-molecular-weight polymers are introduced in minimal quantities into a dispersed particle solution, they adhere to the particles in a manner allowing one strand to link multiple suspended particles, effectively Linking them as a unified structure (Fig. 6). The clusters generated by the polymer bridging process tend to be significantly stronger than those created by charge neutralization.[35,36]

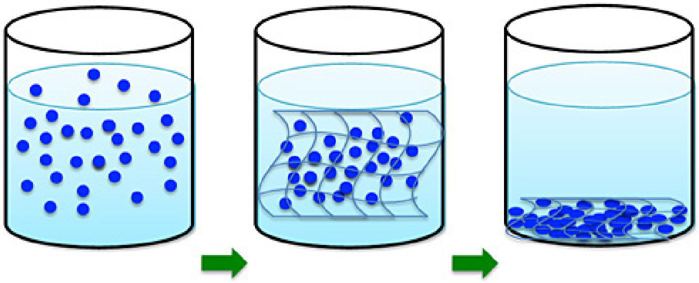

Fig. 6: Coagulation/Flocculation mechanism.[18]

Managing Turbidity with Natural Coagulants

The effectiveness of various natural coagulants in coagulation can be evaluated through the Jar test. This effectiveness varies based on the properties of the plant materials employed. Table 1 illustrates the percentage of turbidity reduction achieved by these natural coagulants.

The percentage of turbidity reduction is determined using the following equation.

Turbidity removal efficiency = (Ti - Tf) / Ti × 100%

In this formula, T_i represents the clarity of the water sample prior to treatment, while T_f denotes the clarity of the water sample after treatment.

An Examination of Natural Coagulants for Turbid Water

Studies on natural coagulants derived from plants, including Moringa oleifera, cactus extracts, and legume seeds, have shown significant effectiveness in reducing turbidity and eliminating contaminants from water. Despite growing interest in natural coagulants, the use of fruit waste for water purification remains inadequately studied. Previous research indicates that fruit waste contains bioactive components like polysaccharides, proteins, and phenolic compounds, which play a crucial role in coagulation and flocculation. Although certain studies have explored the use of fruit peels and seeds in wastewater treatment, there is still a need for an in-depth analysis of their coagulation mechanisms, effectiveness in contaminant removal, and feasibility for large-scale implementation. The plants examined in this review are mango seeds and banana peels belong to distinct botanical families. Each plant appears to have unique capabilities in the remediation of freshwater and wastewater, with the various parts of these plants being utilized as coagulants or flocculants. The percentage of Table 1 shows the reduction of turbidity using natural coagulants.

Table 1: A comparison of different natural coagulants and their efficiency in removing turbidity.

Name of the species	Plant Part	Efficiency in removing turbidity	References
Mangifera indica	Seed	98.6%	7
		92.0%	8
		90.0%	9
		85.4%	10
Musa paradisiaca	Peels	98.8%	11
		97.0%	12
		96.0%	13
		89.9%	14
		88.0%	15

Seeds of *Mangifera Indica*

Mangifera indica is a tall evergreen tree Capable of growing up to 15-30 meters tall, featuring a dark green, and umbrella-like canopy. The trunk can measure over 3.7 meters in circumference. The leaves are simple in structure, glossy, and dark green in colour.[37]

The seed's dry weight comprises approximately 6 to 7.76% protein. Despite their low protein content, the nuclei contain essential amino acids-leucine, isoleucine, methionine, phenylalanine, lysine, threonine, tyrosine, and valine-suggesting high-quality protein.[38]

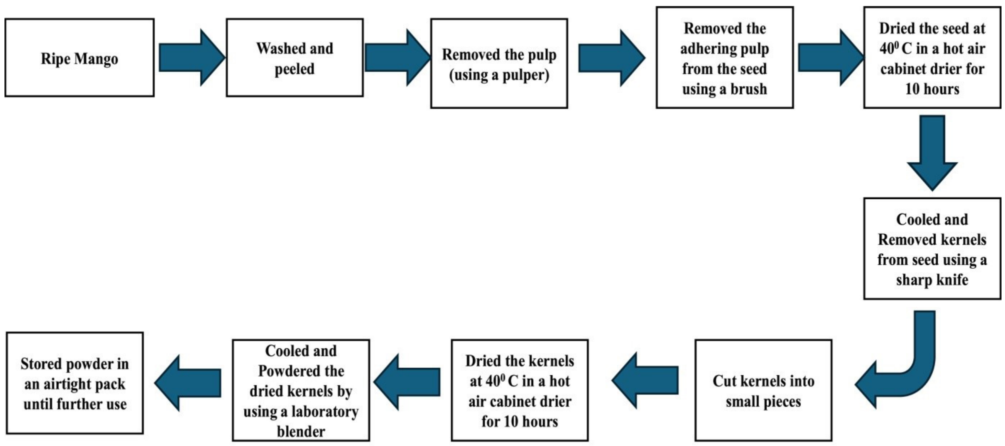

Fig. 7: Flow chart of Mango Seed Powder Preparation.[39]

The seed of the mango has gained significant scientific attention due to its classification as an organic waste rich in bioactive compounds, such as Polyphenols, carotenoids, ascorbic acid, and fiber, all of which contribute to enhancing human health.[38] It is also a rich provider of essential carbohydrates

(58-80%) and Contains 6-13% protein, along with essential amino acids and significant lipid (6-16%), particularly stearic and oleic acids.[38] Research has shown that it exhibits anticancer properties, particularly against breast and colon cancer, as well as antimicrobial effects against both Gram-positive and Gram-negative bacteria,[38] which are linked to its potent antioxidant activity.

To evaluate the coagulation-flocculation characteristics of mango fruit, the seed kernels are typically extracted, cleaned with distilled water, and sliced. The kernels are then dried at varying temperatures, such as 40°C for 10 hours[39] or 120°C for 1 hour,[7] or alternatively, they can be sun-dried for a week before being ground into a powder.[8]

These remarkable results suggest that the coagulating properties of mango should be explored in greater detail. Although earlier studies have suggested that proteins are the primary active compounds responsible for mango's coagulation ability, recent findings by Seghosime *et al.*,[8] indicate that the high carbohydrate content in mango seed kernels may also play a role in influencing its coagulating activity. Among the evaluated *Mangifera indica* genotypes-Apple mango, Kate, Kent, Bire, Doodo red, Takataka, Kagoogwa, and Tommy Atkins-the protein contents were found to be 38.02%, 30.66%, 15.94%, 22.11%, 21.50%, 16.98%, 16.36%, and 17.87%, respectively. Apple mango demonstrated the highest protein concentration, making it the most promising candidate for use as a natural coagulant.[38] Since proteins are primarily responsible for coagulating activity, this finding highlights the importance of further investigation into other plant sources with similar potential.

Peels of *Musa paradisiaca*

The *Musa paradisiaca* plant is a large, herbaceous flowering plant with a tree-like appearance. It has a false stem (pseudostem) made of leaf sheaths, and an underground stem (rhizome) that produces suckers. Banana plants can grow to be 3-30 ft tall, varies based on the type and environmental factors. Leaves of banana are broad, tender, and spirally arranged. They can grow to be 8.9 ft long and 2 ft wide. Banana plants produce reddish-purple flowers on a large spike at the top of the pseudostem. Banana plants produce clusters of green fruit that mature to yellow. Banana peel accounts for about 40% of the total weight of a fresh banana, resulting in a significant amount of waste.[40] It is rich in various active organic compounds, including polysaccharides, cellulose, pectin, and hemicellulose, as well as pigments and other low molecular weight substances.[41] Banana peels are a rich source of starch, cellulose, galacturonic acid, and pectin, with the specific proportions varying depending on the type of banana, the method of analysis, and the stage of ripeness.[42] The chemical analysis of banana peel powder revealed the following composition: fat (12.75%), ash (15.40%), protein (5.4%), and fiber (47.63%).[43]

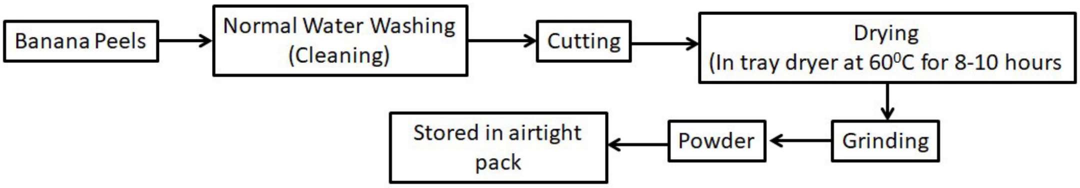

Fig. 8: Flow chart of Mango Seed Powder Preparation.

Banana peels contain proteins and polysaccharides with positive charges that bind to negatively charged suspended particles in water. This interaction results in charge neutralization and subsequent settling of the particles. Additionally, the formation of molecular bridges between particles improves the overall efficiency of their removal.[13] The coagulation process of banana peel works through charge neutralization, where opposing charges interact.

Pros and Cons of Natural Coagulants for Commercial Applications

Plant-based materials used in water treatment offer several benefits, which generally outweigh their disadvantages.[17] These benefits include.

- They are easily accessible and more cost-effective to produce.
- They are environmentally friendly, energy-

efficient, and derived from renewable resources.
- The residual sludge produced at the end of the treatment process is smaller compared to that from chemical treatments.
- They are typically non-toxic, making them safe for both human and aquatic life.
- Seed extracts serve as natural corrosion inhibitors, preventing damage to pipes.
- They do not require alkali, minimizing the need for pH adjustments.
- Low maintenance and no skilled labour are required.

Natural coagulants offer several benefits, including renewability, biodegradability, non-toxicity, and cost-effectiveness. However, their future development faces several challenges.[17]

- Their lifespan tends to be shorter due to the biodegradability of the active components, which also causes a loss in strength and stability over time.
- The commercialization of natural coagulants is hindered by factors such as funding, research and development, and market awareness.
- Another limitation is the high organic load left behind after use, which can be problematic.
- Variations in the coagulation potential of different plant species present a challenge in identifying the most effective ones.
- These coagulants can be non-specific, particularly in biosorption applications.

Directions for Future Research

Research is needed to develop methods for processing and packaging plant extract-based coagulants, making them available as commercial products while ensuring their stability for long-term storage. It is also essential to examine the sludge generated by natural coagulants to assess whether its nitrogen and phosphorus content makes it suitable for use as a soil conditioner. Furthermore, the use of seeds as natural coagulants, particularly when combined with solar disinfection, remains an underexplored opportunity. Continued research is crucial for overcoming these challenges and advancing the field.

Conclusion

Natural coagulants provide an eco-friendly and viable option for rural areas where access to standard chemical water treatment is limited. These plant-based alternatives are biodegradable, safe, and economical, making them ideal for sustainable water purification. Exploring the combination of different natural agents or their integration with chemical or synthetic treatments may further enhance performance, presenting valuable opportunities for research and innovation. Promoting the use of bio-coagulants not only contributes to environmental conservation but also showcases the nation's dedication to green technology. Such advancements can foster national pride and earn global recognition for environmental leadership.

Acknowledgement

I am thankful to the authority of Sreegopal Banerjee College, Bagati, West Bengal for providing access to computer facilities, software, and internet services.

Funding Sources

The author received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

This statement does not apply to this article.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions

The sole author was responsible for the conceptualization, data collection, writing, reviewing, editing and final approval of the manuscript.

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