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REVIEW

A Review of Biomass-Based Natural Coagulants for Water Pollution Remediation: Impact of Properties and Coagulation Operational Parameters

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ABSTRACT

The rapid growth of cities, industries, and population has made tackling water scarcity increasingly challenging as the global demand for clean drinking water continues to rise. Consequently, extensive research in water and wastewater treatment, specifically focusing on the coagulation process, has ensued. Coagulation plays a critical role in water treatment, and its effectiveness depends on the type of coagulant used. However, the widespread use of chemical coagulants raises concerns for the environment and public health. Consequently, there has been growing interest in exploring natural alternatives derived from plants and animals. This review examines how the properties of natural coagulants, as well as coagulation process parameters, impact their ability to remove pollutants. Factors such as surface morphology, surface charge, molecular weight, and functional groups of the coagulant, as well as coagulation parameters like pH and dosage, significantly influence the removal of turbidity, color, and organic matter from water. Effective natural coagulants typically possess rough and porous structures that help trap particles, have a higher molecular weight for better performance, exhibit a higher zeta potential for improved charge neutralization, and contain reactive functional groups. Coagulation activity is greatly affected by the pH of the water being treated and the amount of natural coagulant used. By optimizing these properties and conditions, natural coagulants derived from plants offer environmentally friendly and cost-effective alternatives to chemical coagulants in large-scale water treatment. This review distinguishes itself by providing a comparative analysis of both plant-based and animal-based natural coagulants, especially in terms of the influence of coagulant properties, addressing a gap in recent literature that predominantly focuses on coagulation operational parameters.

Keywords: Biomass-based coagulants, Water pollution remediation, Natural coagulants, Coagulation parameters, Sustainable water treatment

1. Introduction

Water is a vital natural resource essential for our daily lives, supporting ecosystems and human existence [1]. However, many developing countries face challenges in accessing clean water due to factors like rapid urbanization and population growth [2]. This scarcity leads to health issues for over 1.6 million people, emphasizing the need for water and wastewater treatment research. Coagulation and flocculation are crucial processes in water treatment, where suspended particles contribute to turbidity. Coagulants are added to destabilize these particles and form flocs for easier removal. Chemical coagulants like alum and ferric salts are commonly used, but natural alternatives derived from plants and animals, such

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as isinglass and chitosan, offer potential substitutes [3]. Plant-based coagulants like Moringa seed powder have been traditionally used in rural areas for water treatment [4]. Exploring the properties and effectiveness of natural coagulants can help address water scarcity challenges. This review focuses on evaluating various natural coagulants derived from plants and animals for pollutant removal. It examines their efficacy, analyzes their efficiency under different conditions, and presents relevant data on coagulant properties significant for their effectiveness. While several researchers have explored the potential of natural coagulants in various studies, a review paper that consolidates the analysis of the properties of these coagulants from the literature search has not been comprehensively undertaken previously.

2. Coagulation and flocculation for water purification

Coagulation and flocculation technology have long been used as primary treatments for wastewater [5]. However, the use of chemical coagulants such as alum and ferric chloride presents several drawbacks. They can be highly toxic, posing risks to human health and the environment [6, 7]. Chemical coagulants have been associated with diseases like Alzheimer's and neurotoxicity, and some compounds have carcinogenic effects [6]. Additionally, chemical coagulants are expensive, particularly for developing countries, and require coagulant aids to treat highly turbid water, further increasing costs [1, 8]. Chemical coagulants also generate large volumes of non-biodegradable sludge, leading to high disposal and operating costs [7, 8].

Electrocoagulation, while environmentally beneficial, has its limitations. Factors such as electrode passivation and thickness can raise material and energy costs [9]. The process requires costly and labor-intensive regular cleaning and maintenance of electrodes, with sacrificial electrodes needing frequent replacement due to oxidation in wastewater streams [10]. Additionally, the outcomes of electrocoagulation can be unpredictable and influenced by various factors, posing challenges in predicting treatment results [11].

Natural coagulants offer various advantages over chemical and electrochemical methods. They are eco-friendly, biodegradable, cost-effective, and generate less sludge, making disposal easier. Nevertheless, challenges include variability in coagulant quality, slower coagulation times, and potential limitations in treating highly contaminated water. Recent studies have showcased the effectiveness of natural coagulants in eliminating diverse pollutants from wastewater, including turbidity, heavy metals, and organic matter [12–16].

2.1. Coagulation/Destabilizing mechanism

Coagulation processes are crucial for purifying water and eliminating suspended particles. These processes involve different methods, including double-layer compression, electrostatic coagulation, charge neutralization, adsorptive coagulation, and precipitation/sweep coagulation. By employing these techniques, colloidal particles can be effectively destabilized and removed, resulting in enhanced water quality. Understanding and implementing these coagulation methods are vital for efficient water treatment, ensuring access to clean and safe drinking water. Coagulation involves balancing colloidal particle charges with a chemical reagent or by conditioning suspended solids, creating larger, settleable particles [17]. Cationic coagulants neutralize negative charges, causing particles to stick together and form larger flocs that are easily removed by filtration [18]. In wastewater treatment, flocculation triggers particle agglomeration to form larger flocs, achieved by stirring the sample to merge smaller particles into larger masses for easier separation [17, 19]. A summary of these mechanisms can be found in Table 1, providing valuable insights into their respective roles in water purification. Biomass-based coagulation mechanisms involve adsorption, charge neutralization, and bridging. Natural coagulants contain active functional groups that interact with pollutants [20]. For example, *Moringa oleifera* seeds contain cationic proteins that neutralize negatively charged particles, facilitating agglomeration and subsequent removal as proposed by Saini [21] in Fig. 1.

2.2. Natural coagulants

In water treatment, the utilization of natural coagulants has gained increased interest as a sustainable alternative to chemical coagulants [32]. The application of natural coagulants has been explored for over 2,000 years and offers several benefits like lower cost, reduced sludge, and better biodegradability [33]. They are obtained from plant and animal sources [3]. As natural coagulants are eco-friendly and can effectively treat turbid waters, they show promise for the future of water treatment. Biomass-based coagulants are renewable as they are derived from sustainable sources such as plants and animal by-products. Studies have shown their renewability

Table 1. Types of coagulation mechanism.

Coagulation mechanism	Description	Advantage	Disadvantage	References
Double-Layer Compression	Uses ions with a counter charge of colloids to penetrate the double layer, reduces electrostatic repulsion, increases van der Waals forces, and binds destabilized colloids.	Larger flocs due to a higher aggregation rate	Low sedimentation due to friction between large flocs, strength depends on ionic charge	[3, 22–25]
Sweep Flocculation	Colloids in a net-like structure of amorphous metal hydroxide through hydrolysis; smaller flocs with good settling ability, slower formation, and high fractal dimension.	Good settling ability; complex flocs with high fractal dimension	Flocs prone to breakage due to repulsion forces	[25–27]
Charge Neutralization	Adsorbs oppositely charged coagulants to colloid surfaces, reduces repulsive forces, increases van der Waals forces, and forms stronger and more compact flocs.	Stronger, more compact flocs, high fractal dimension, resistant to shear force	Relies on physical bonds, making flocs weaker than those formed by interparticle bridging	[27–31]
Interparticle Bridging	Uses polymeric chains to form colloid-polymer-colloid structures, flocs are flaky, strong, and not easily broken due to chemical bonds formed by a polymeric chain.	Very strong flocs, natural coagulants enhance floc growth significantly more than chemical coagulants	Lowest fractal dimension indicates less complexity compared to other mechanisms	[25, 27, 30, 31]

and lifecycle benefits, supporting their use in sustainable water treatment practices [12, 13].

Using biodegradable natural coagulants, which could reduce the amount of sludge and at the same time do not contribute to the toxicity of the sludge, might appeal to water utilities [34]. The organic sludge produced by natural coagulants could enhance environmental sustainability through reuse in various sectors, including civil engineering (e.g., cement, concrete, and mortar), agriculture, land-based applications, and wastewater treatment [35]. The quantity of sludge generated from okra and passion fruit seeds is notably lower compared to the amount produced when treating dairy effluent with chemical coagulants like $FeSO_4$ and $KAl(SO_4)_2 \cdot 12H_2O$ [36]. Prabhakaran et al. [37] noted that employing a natural coagulant derived from *Eichhornia crassipes* decreased the sludge volume generated during the treatment of textile effluents in contrast to chemical coagulants. Furthermore, the sludge from the natural coagulant is environmentally friendly, biodegradable, and suitable for use as organic plant fertilizer.

2.2.1. Types of natural coagulants

2.2.1.1. Animal-based coagulants. These types of coagulants are typically derived from extracts of shellfish exoskeletons, animal bones, shell extracts, and chitosan (Table 2). Chitosan is a linear copolymer formed when chitin is deacetylated [38]. Due to its natural origins, the polysaccharide is hydrophilic, biodegrades easily, poses no harm to the environment, and is capable of effectively absorbing various metal ions due to amino groups in the polymeric chain [39].

Chitosan is commonly derived from arthropods or marine invertebrates, insects, yeasts, and certain fungi. It has a cellulose-like structure at the molecular level, exhibiting long polymeric chains similar to cellulose, and offers many benefits over conventional chemicals [40]. Chitosan exhibits cost-effectiveness, non-toxicity, biodegradability, biocompatibility, solubility in weak acids, and pH sensitivity, making it a versatile material [41, 42]. Additionally, it demonstrates versatile properties, including enhancing biosorption, preventing secondary pollution, enabling sludge reuse as a biofertilizer [43], and exhibiting high effectiveness in reducing chemical oxygen demand (COD) and removing water turbidity [44]. While most studies on chitosan-based coagulants focus on those derived from crab or shrimp shells, other studies explore the use of alternative sources such as snail shells, krill, insects, and fungi (Fig. 2) [45]. According to Oladoja and Aliu [46], the snail shell acts as an effective coagulant aid by increasing the concentration of the dye's solid phase and promoting the sweeping coagulation of dye molecules by the coagulant. Animal-based coagulants show high removal efficiencies, with research gaps in scalability, economic feasibility, and limited study quantity signaling a need for further investigation.

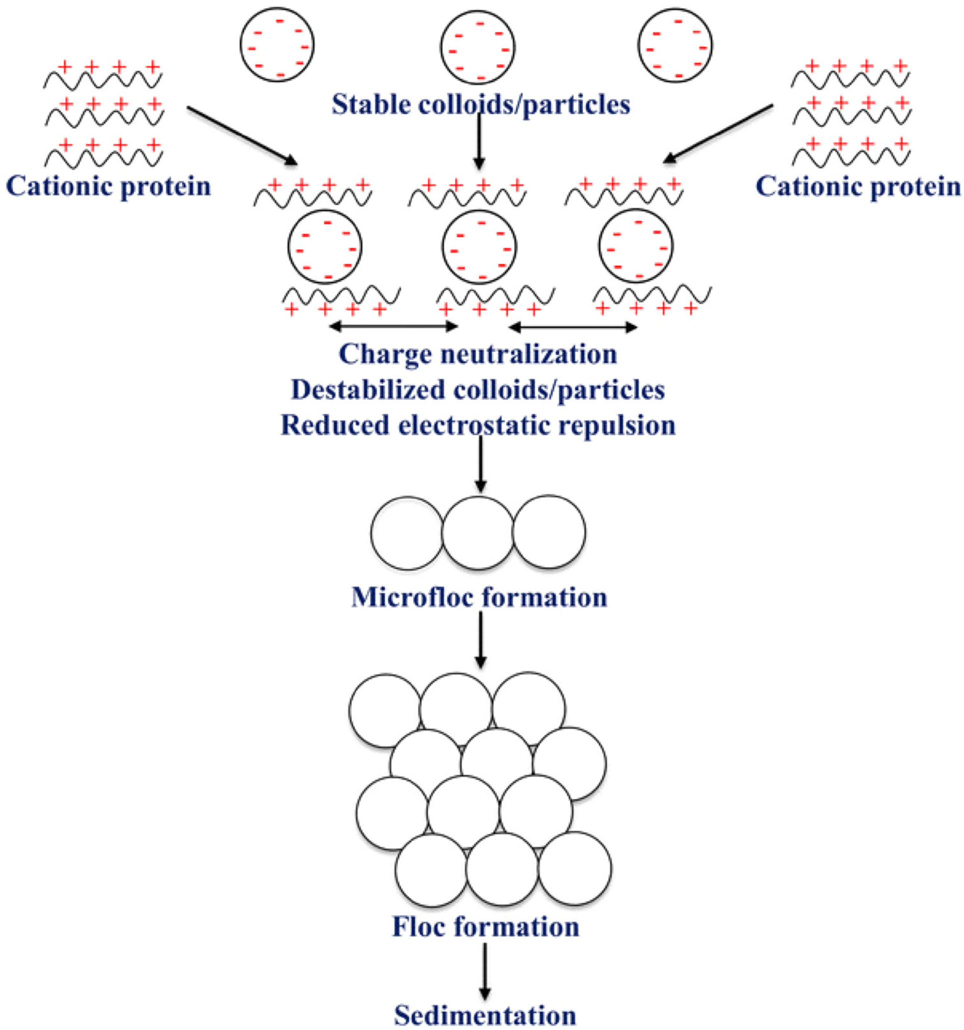

Fig. 1. Mechanism of water coagulation and sedimentation using *Moringa oleifera* cationic proteins [21].

Table 2. Examples of animal-based natural coagulants.

Type	Study findings	References
Crab shell	97% removal of turbidity (coagulant aid)	[47]
	98.2% removal of turbidity (coagulant aid)	[48]
Achatinoidea shell	99.22% removal of TDS	[49]
Shrimp shell	96% reduction of oil	[50]
Periwinkle shell	83.57% removal of particles	[51]
Snail shell	60% reduction in dye concentration	[46]
Eggshell	98.52% reduction in TSS 98.88% reduction in Color	[52]
Devilfish	79% reduction in COD 94% reduction in TSS	[53]
Chitosan	90% reduction in solids concentration 95% reduction in residual oil concentration	[54]
Chitosan	99% reduction in TSS 98.4% reduction in turbidity 68.3% reduction in COD 95.6% reduction in NH_4-N 96% reduction in color 94.9% reduction in oil and grease	[55]

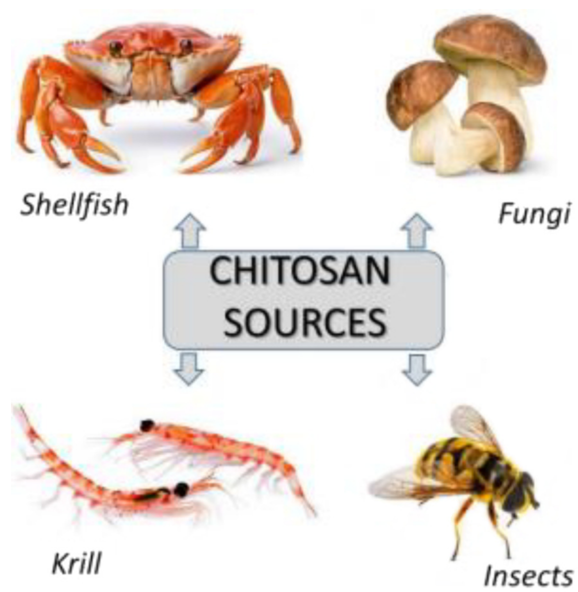

Fig. 2. Sources of chitosan [45].

Table 3. Examples of plant-based natural coagulants.

Type	Study findings	References
Aloe vera	28.23% reduction in turbidity	[70]
Moringa oleifera	99% reduction in turbidity	[71]
	85% reduction in chlorophyll	[65]
	84% reduction in turbidity	[72]
	88% reduction in *E. coli* removal	[73]
Orange peel	97% reduction in turbidity	[74]
Roselle seeds	93% reduction in turbidity	[67]
Banana pith	80% reduction in turbidity	[75]
Phaseolus vulgaris	95% reduction in turbidity	[76]
Corn starch	98% reduction in *E. coli* and *S. aureus*	[77]
Rice starch	80% reduction in microalgae	[78]
	50%–78% reduction in kaolin	[79]
Cactus-banana peels composite	82.15% reduction in TSS	[80]
	84.02% reduction in *E. coli*	
Avocado seed	94.34% reduction in methylene blue	[81]
powder	95.28% reduction in crystal violet	
	99.64% reduction in turbidity	
Oat extract	99% reduction in turbidity	[82]

2.2.2. Plant-based coagulants

Since 2000 BC, plant extracts have been utilized for water purification, as depicted by ancient Egyptian tomb wall carvings [56]. Fruits, seeds, leaves, bark, and roots have been employed to extract various compounds for water treatment purposes [32]. Plant extracts rich in proteins, tannins, saponins, and mucilage have shown effectiveness as coagulants [39]. In developing countries, natural coagulants like beans, almonds, and *Strychnos potatorum* nuts are preferred due to their cost-effectiveness [57, 58]. Plant-based coagulants are organic, water-soluble polymers derived from different parts of plants. These polymers destabilize colloidal solutions by neutralizing particle charges, leading to the formation of flocs that aid in settling [59]. Some plant-based compounds also exhibit flocculant properties, enhancing the strength of the flocs [60, 61].

The utilization of natural plant-based coagulants represents a significant advancement in sustainable development, as noted by Choy [2]. Extensive research has been conducted on plant-based coagulants for water and wastewater treatment, with numerous studies highlighting their effectiveness [5, 62]. Coagulants from the Fabaceae family, primarily derived from leaves and seeds, have been extensively examined [63]. As depicted in Fig. 3, *Moringa oleifera*, a member of the Moringaceae family, has been widely studied and employed as a plant-based coagulant [64–66]. Other commonly investigated coagulants for reducing turbidity in water solutions include Nirmali seeds, tannins, roselle seeds, and hyacinth beans [67–69]. Plant-based coagulants offer affordability, eco-friendliness, non-toxicity, and biodegradability, making them preferable to chemical alternatives [15]. They show promise in wastewater treatment and are readily available in local communities. In conclusion, while plant-based coagulants have shown promise in laboratory and small-scale studies, further research is needed to address issues related to variability, standardization, and large-scale application. Current studies highlight their potential, but more comprehensive research is required to optimize their use and ensure consistent performance. Studies have explored coagulants from plants, as summarized in Table 3.

3. Natural coagulation

To achieve effective natural coagulation, it is important to consider three factors: the qualities of the coagulant employed, the features of the water to be treated, and the characteristics of the mixing process [83]. The coagulant properties, such as molecular weight, type of equipment and reagents used, and the chemical and physical properties of pollutants such as zeta potential, concentration of colloidal particles, presence or absence of impurities, trace elements, dissolved salt ions, and chemicals, can all impact the coagulation process [1]. In this review, we discuss the role of coagulant properties in influencing the effective removal of solids in water pollution.

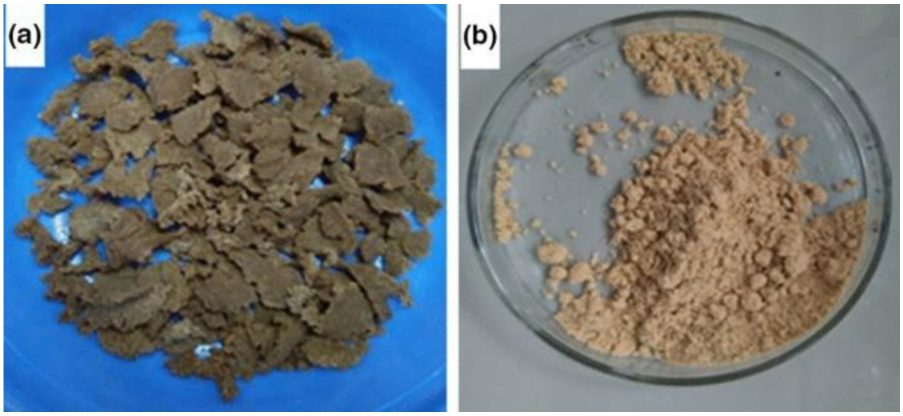

Fig. 3. *Moringa oleifera seed* (a) after defatted; (b) seed powder [66].

Table 4. Examples of biocoagulants and their morphology observed under SEM.

Natural coagulant	Particle size (μm)	Particle diameter (μm)	Morphology	Removal efficiency	References
Walnut seeds	-	-	Platelet networks with a rough and porous surface	99.5% turbidity	[16]
Moringa oleifera	-	-	Layered mesoporous structure	84% turbidity	[84]
Cassava peels	1.64 to 15.27	10 to 60	Nonporous smooth joined together and round-oval	60.19% turbidity, 57.79% TSS, 30.19% COD	[85]
Chickpea	-	20 to 40	Rough and porous surface	86% turbidity, 87% TSS, 56% COD	[30]
Cowpea	-	-	Rough and porous surface with compact-net structure	99.26% dye removal	[86]
G. ulmifolia bark	-	-	Porous rough surface	95.8% turbidity, 76.0% COD, 81.2% BOD	[87]
Rice starch	-	-	Nonporous smooth solid surfaces	50% turbidity	[78]
Wheat starch	-	-	Nonporous smooth solid surfaces	11% turbidity	[78]
Corn starch	-	-	Nonporous smooth solid surfaces	>10% turbidity	[78]
Potato starch	-	-	Nonporous smooth solid surfaces	>10% turbidity	[78]
Margaritarea discoidea	-	-	Dispersed frothy globules	98% turbidity	[62]
Eggshell	-	-	Irregular shape, mesoporosity, white droplet-shaped clusters	96.21% turbidity	[52]

3.1. Properties of natural coagulants

The performance of coagulants in wastewater coagulation is influenced by various factors, including the morphology of the coagulant particles, surface charge, functional groups present, and molecular weight. Maximizing these factors contributes to the efficient removal of suspended solids and contaminants in wastewater treatment processes.

3.1.1. Morphology

Surface morphology analysis helps identify the presence of pores, including micropores, macropores, and mesopores, which facilitate the bonding of colloidal particles during coagulation. Studies in Table 4 have shown that coagulants with porous or mesoporous structures and rough surface morphologies exhibit high coagulation efficiency, achieving turbidity removal rates of 84% to 96%. In Fig. 4, walnut seed powder, with its porous and rough surface, enhances the bridging mechanism and offers improved adsorption capacity [16]. In contrast, natural coagulants with nonporous, smooth surfaces have lower coagulation potential. The contribution of the bridging mechanism in coagulation and flocculation processes is supported by observations of platelet networks and dispersed globules on the surfaces of coagulants [16]. Modifying the surface morphology, such as through grafting, can increase the density of pores and improve coagulation effectiveness [83]. In the study on eggshells as a biocoagulant, the rough and irregular surfaces with pores help form large flocs. Additionally, white droplet-shaped clusters with many pores are found on the filmed surfaces [52].

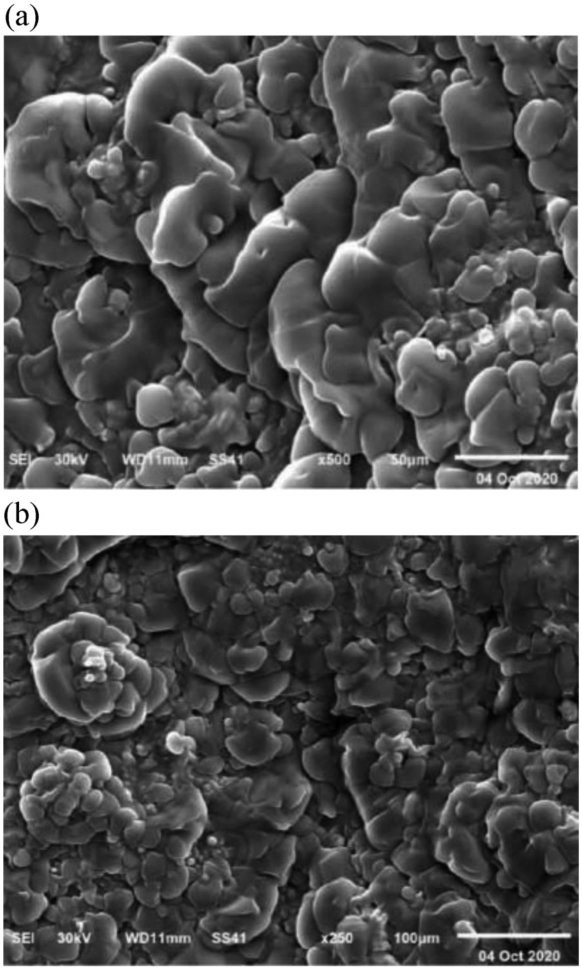

Fig. 4. SEM micrograph of walnut seed powder (a) 500x (b) 250x [16].

3.1.2. Molecular weight

According to Ang and Kiatkittipong [83], the physical features of coagulants, such as their molecular weight, can be an indicator of the mechanisms and activities that contribute to improved coagulation activity. Sun and Zhou [88] found that the high molecular weight of natural coagulants improves aggregation, leading to an increase in coagulation activity. A higher molecular weight natural coagulant forms a polymer bridge with greater binding to particle surfaces versus a lower molecular weight coagulant, which promotes a weaker bridge [83]. This results in denser and larger flocs with stronger bonds, allowing for better settling and increased coagulation efficiency [89]. A large molecular weight also allows natural coagulant chains to extend further away from particle surfaces, promoting the formation of bridges [90]. Bhandari and Ranade [91] found that polymers with large molecular weights and regulated basicity, charged groups, and charge density are important factors in enhancing coagulation. Muylaert and Bastiaens [92] reported that a large molecular-weight polyelectrolyte, such as lignosulfonate, is an effective bridging agent.

The molecular mass of a natural coagulant influences the flocculation process it undergoes. Coagulants with smaller molecular weights, like polyethyleneamine, typically undergo flocculation through a charge patch mechanism [92]. It is widely documented that the large molecular weight of natural coagulants is the dominant factor in bridging processes, where high molecular weight polymers may be used to bridge colloidal particles featuring loops and tails at any pH value [90].

3.1.3. Zeta potential

The surface charge, also known as zeta potential, plays a crucial role in the flocculating activity of a solution, as noted by [93]. This is particularly important as it indicates the point where the electrokinetic surface charge is neutral, thereby influencing coagulation efficiency [94]. When particles are suspended in a liquid, their electrical charge is measured by the zeta potential. A negatively charged flocculant with a weak zeta potential may form a cluster with ions because the repulsion forces created during this process are smaller than the Van der Waals forces developed during the process [95]. According to Ang and Kiatkittipong [83], surface charge analysis estimates the flocculating activity of a natural coagulant. A higher negative surface charge enhances the flocculation of positively charged colloidal particles, while a higher positive surface charge promotes the flocculation of negatively charged colloidal particles. Surface charge determines the treatment group of suspended particles, enabling the removal of specific contaminants using appropriate coagulants. By employing chemically and structurally modified natural coagulants, it is possible to substantially increase the zeta potential to either highly positive or negative values. For example, 3-CHPTAC can be grafted onto cellulose nanocrystals (CNC). This modification enhances the coagulant's performance [83]. The snail shell's surface point of zero charge (pH_{PZC} 7.9) was identified to assess its role in removing dye molecules from water and to optimize dye removal based on pH. At pH levels above the pH_{PZC}, cation interaction is favored, while anion interaction is preferred at pH levels below the pH_{PZC}. This suggests that below pH 7.9, the snail shell surface is positively charged, and above pH 7.9, it becomes negatively charged [46].

3.1.4. Functional group

The chemical characteristics of polymers used in natural coagulants significantly impact their flocculating activity [83]. Functional groups like NH,

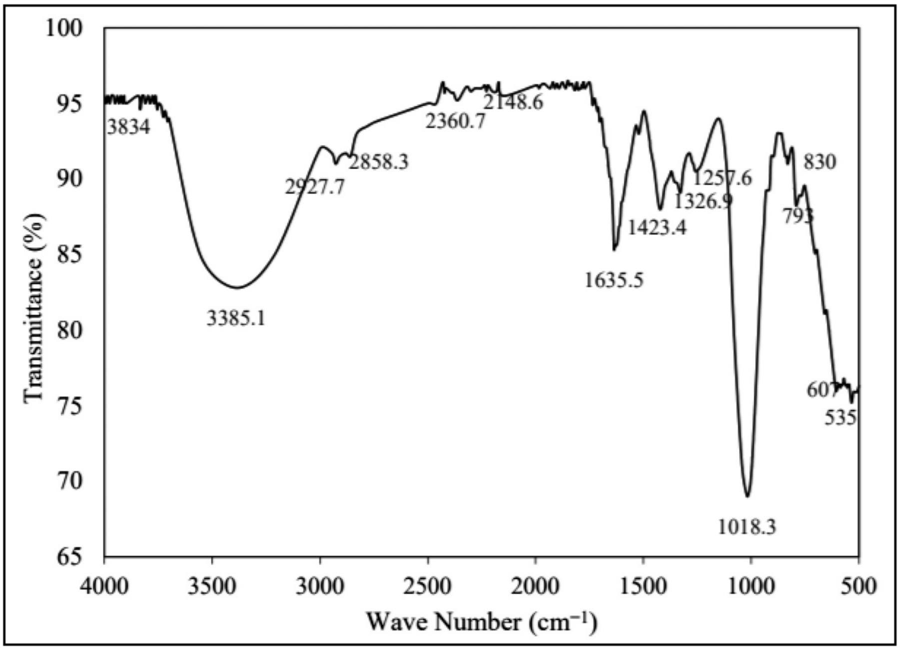

Fig. 5. *Aloe vera* FTIR spectrum [96].

C=O, COO, and OH play a crucial role in coagulation. Increasing positive charges enhances the coagulant's effectiveness by promoting stronger electrostatic attractions with contaminants [92]. Infrared spectra analysis helps identify these functional groups in natural coagulants. In Fig. 5, *Aloe vera* demonstrates peaks indicating the presence of functional groups such as OH stretching, carbonyl function (C=O), CH_3, primary aromatic amines, and carboxyl group (COOH), which contribute to turbidity removal through intermolecular bonding, enhanced coagulation activity, and the availability of adsorption sites for suspended solids [96].

3.1.5. Surface area

The BET surface area plays a crucial role in determining the efficiency of coagulation processes, particularly when natural substances like leaf powder (LP) are used as coagulants [97]. In coagulation, the surface area of the coagulant material influences its capacity to adsorb contaminants such as suspended particles from water. A higher BET surface area typically signifies more active sites for adsorption, potentially leading to enhanced coagulation efficiency. Conversely, a lower BET surface area, like the 0.08 m^2/g observed for LP in the study, indicates fewer active sites, which could result in reduced adsorption capacity and consequently diminished coagulation efficiency as suggested by Mohtar [98]. The relatively modest BET surface area of LP might constrain its effectiveness in removing impurities during the coagulation process, as there is less surface area available for interactions with suspended particles in water. Iloamaeke [99] investigated the use of *Mercenaria mercenaria* (MM) and its modified form (MMM) for color removal from industrial effluent, and the BET surface area was found to play a significant role in enhancing coagulation efficiency [100]. The BET surface area represents the total surface area per unit mass available for adsorption, and it is crucial for interaction with contaminants like colloidal particles in wastewater [52]. In the study, MM's surface area increased from 55.0 m^2 g^{-1} to 64.0 $m^2 g^{-1}$ after modification to MMM, leading to improved coagulation efficiency. The relationship between BET surface area and coagulation efficiency is directly proportional: as the BET surface area increases, coagulation efficiency improves, resulting in more effective removal of contaminants from wastewater. Jorge [101] studied the effectiveness of five plant-based coagulants in removing methylene blue from aqueous solutions, including seeds of *Chelidonium majus L.*, *Dactylis glomerata L.*, *Festuca ampla Hack.*, *Tanacetum vulgare L.*, and rachises of *Vitis vinifera L.* It was observed that the low surface areas of plant-based coagulants (ranging from 0.03 to 0.50 m^2 g^{-1}) have a negative impact on their coagulation performance by reducing their adsorption capacity, thereby limiting their ability to capture contaminants effectively. The limited surface area slows down the rate of colloid attachment and floc growth, resulting in a slower aggregation process, which leads to the formation of weaker and

Table 5. Studies of various wastewater pH for coagulation activity.

Plant-based coagulant	Wastewater source	pH	Parameter	Removal (%)	References
Walnut seed	Synthetic turbid water	11	Turbidity	99.5	[16]
Moringa oleifera	Synthetic turbid water	7	Turbidity	99	[71]
	Surface water	7	*Chlorophyll a*	85	[65]
	Raw turbid water	7.5	Turbidity	84	[73]
	Coffee fermented wastewater	5–7	*E. coli*	88	
Orange peel	Dairy wastewater	7.5	Turbidity	97	[74]
Jackfruit seeds	Sewage wastewater	4	Turbidity	87.4	[107]
Roselle seeds	Synthetic wastewater	4	Turbidity	93	[67]
	Industrial wastewater	10	Turbidity	87	
Mango seeds	Sewage wastewater	69	Turbidity	90	[107]
Banana pith	Raw river water	4	Turbidity	80	[75]
Banana trunk	Sewage wastewater	7	Turbidity	90.2	[107]
Phaseolus vulgaris	Synthetic wastewater	7	Turbidity	95	[76]
Corn starch	Synthetic wastewater	4	Turbidity	98	[77]
Rice starch	-	3	Microalgae	80	[78]
Papaya seed	Textile wastewater	2	Color	85	[111]
Bamboo	Electroplating industry wastewater	5.5	Sulphate	93	[112]
			TDS	97	
			Nickel	99	
Watermelon seed	Sewage wastewater	5	BOD	92	[108]
			TSS	93	
Cactus	Synthetic wastewater	7	Turbidity	50.5	[109]
			COD	63.6	
Aloe vera	Raw Water	6	Turbidity	88.23	[96]
Chitosan	Fish processing wastewater	10	Turbidity	98	[113]
			BOD	53	
Periwinkle shell coagulant	Petroleum Produced Water	4	Turbidity	83.57	[51]

smaller flocs with poorer settling abilities, ultimately decreasing the overall efficiency of removing suspended solids from water [102].

3.2. Operational parameters affecting the coagulation efficiency

The natural coagulant activity in water treatment is influenced by factors like pH and dosage of coagulation parameters. pH levels impact the charge on particles and coagulants, affecting their interaction and floc formation. Optimal pH conditions enhance coagulation, ensuring effective charge neutralization and floc growth. Coagulant dosage is also crucial, as the right amount facilitates particle destabilization and removal.

3.2.1. Influence of pH

Table 5 compiles studies investigating the impact of pH levels on coagulation activity. pH plays a crucial role in the solubility of substances and particles in wastewater, making it essential to study its effect on coagulation. Different wastewater types exhibit varying pH values, necessitating a coagulant suitable for the initial pH conditions. The isoelectric point (pI), representing the pH at which particles in wastewater are most stable, typically consists of negatively charged particles [67]. Plant-based natural coagulants, such as mucilaginous extracts from *Abelmoschus esculentus* [103] and *Opuntia ficus-indica* [83], have emerged as potential options due to their negatively charged ions facilitating adsorption and bridging as primary coagulation mechanisms for particle destabilization [104]. Manipulating pH can significantly enhance coagulation efficiency by influencing polymer properties, particle charges, and the solvent or wastewater [105]. Polysaccharides and proteins derived from vegetables and legumes have been identified as active coagulation agents [8]. Galacturonic acid, found in mucilage from *Abelmoschus* [103] and *Opuntia ficus-indica* [83], plays a potent coagulation role with charge density depending on pH [106]. Neutral pH ranges have shown higher solid particle removal efficiency in various plants, including *Moringa oleifera*, orange peel, banana trunk, *Phaseolus vulgaris*, cantaloupe seed, and cactus mucilage [65, 71, 72, 74, 76, 107–109]. Proteins in legumes such as *Lupinus albus*, *Mucuna pruriens*, and *Cicer arietinum* exhibit pH-dependent coagulation activity [8, 110].

Table 6. Studies with different utilization of coagulant dosage.

Plant-based coagulant	Wastewater source	Dosage	Parameter	Removal %	References
Walnut seed	Synthetic turbid water	3.0 mL/L	Turbidity	97.8	[16]
Moringa oleifera	Synthetic turbid water	250 mg/L	Turbidity	99	[71]
	Surface water	50 mg/L	Chlorophyll a	85	[65]
	Raw turbid water	50 mg/L	Turbidity	84	[72]
	Coffee fermented wastewater	2–3 g/L	*E. coli*	88	[73]
Orange peel	Dairy wastewater	0.2 g/L	Turbidity	97	[74]
Jackfruit seeds	Sewage wastewater	125 mg/L	Turbidity	87.4	[107]
Roselle seeds	Synthetic wastewater	40 mg/L	Turbidity	93, 87	[67]
	Industrial wastewater	60 mg/L	Turbidity		
Mango seeds	Sewage wastewater	100 mg/L	Turbidity	90	[107]
Banana pith	Raw river water	100 mg/L	Turbidity	80	[75]
Banana trunk	Sewage wastewater	50 mg/L	Turbidity	90.2	[107]
Phaseolus vulgaris	Synthetic wastewater	1 mL/L	Turbidity	95	[76]
Corn starch	Synthetic wastewater	0.5 mg/L	Turbidity	98	[77]
Rice starch	Culture suspensions	120 mg/L	Microalgae	80	[78]
Papaya seed	Textile wastewater	570 mg/L	Color	85	[111]
Bamboo	Electroplating industry wastewater	1500 mg/L	Sulphate	93	[112]
			TDS	97	
			Nickel	99	
Watermelon seed	Raw turbid lake water	1000 mg/L	Color	15	[118]
	Sewage wastewater	72.3 mg/L	Suspended	89	
			solids	92	
			BOD	93	
			TSS		
Cantaloupe seed	-	76.7 mg/L	BOD	80	[108]
			TSS	88	
Cactus	Tannery wastewater	40 g/mL	Turbidity	50.5	[109]
			COD	63.6	
Aloe vera	Raw Water	0.1 mL/L	Turbidity	88.23	[109]
Chitosan	Fish processing wastewater	12 mL/L	Turbidity	98.32	[113]
			BOD	53.50	

3.2.2. Influence of dosage

Table 6 presents dosage information from various studies on plant and animal-based coagulants. Precise dosage control is essential for effective coagulation in water treatment, as incorrect dosages can compromise the quality of treated water. Establishing optimal dosages is key to maximizing turbidity removal while minimizing treatment costs. For example, Zedan [16] identified that the ideal dosage of walnut seed extract for turbidity removal in water is 3.0 ml.L^{-1}. Exceeding this amount reduces coagulation efficiency due to charge reversal and the resuspension of colloidal particles. Both underdosing and overdosing can negatively affect coagulation, leading to suboptimal turbidity removal [3, 114]. The performance of coagulants is highly dependent on accurate dosage, making it crucial to find the right balance for efficient water treatment [115]. Additionally, initial turbidity and particle concentration influence the amount of coagulant required, with higher initial turbidity demanding higher doses [3]. Incremental increases in dosage within the optimal range improve turbidity removal, but doses beyond the optimal level can result in increased residual turbidity [116, 117].

4. Conclusion and future studies

4.1. Conclusion

All in all, coagulation and flocculation play a crucial role in the water and wastewater treatment process. Although chemical coagulants are more frequently used at an industrial level than natural coagulants, they have many concerning side effects, such as hazardous sludge, waste byproducts, and the possibility of chemical residue that remains after treatment, which could pose a health risk to humans. On the other hand, although using natural coagulants is still not as popular in industries as chemically produced coagulants, it is a much safer option because it does not produce toxic sludge that could harm the environment. Natural coagulants also do not leave hazardous chemical residue, which could pose a health risk to humans. Hence, natural coagulants should be encouraged on a larger scale as a substitute for chemical coagulants.

As for the mechanism of natural coagulants, the coagulation mechanism implied is mainly limited to polymer bridging and charge neutralization. The natural coagulants were reported to have originated from animal-based coagulants, microorganism-based coagulants, and plant-based coagulants. This study has summarized many potential natural coagulants derived from locally available plants and plant wastes, such as okra, aloe vera, banana plant wastes, orange peel, jackfruit peel, roselle seeds, and others. Many vegetables and legumes are also being widely studied for their application in water remediation. However, not many studies have reviewed the properties of a good natural coagulant. This study concludes that for natural coagulants to function effectively, they need to possess several properties. These properties can be identified by examining their surface morphology using SEM, their molecular mass, zeta potential, and functional groups using an FTIR instrument. A good natural coagulant must have a rough, porous surface morphology, a higher molecular weight, a high zeta potential, and the presence of functional groups, especially COO^- and OH^-, as well as a high surface area.

Lastly, this review also showed that coagulation activity is greatly influenced by several factors, with the most crucial being pH influence and dosage. The coagulation activity and efficiency can be increased by regulating the dosage and pH to reach optimal conditions. The optimal pH depends on the type of natural coagulants used as well as the condition of the wastewater. However, it is noted that an extremely acidic or basic pH is not favorable for coagulation activity. From this review, it is evident that the utilization of plant-based coagulants in primary treatment for turbidity removal and secondary treatment for organic pollutant removal, such as BOD, COD, and TSS, has been examined in a large number of studies throughout the years. The study of biocoagulants from various species of plants and animals for the tertiary treatment of water and wastewater has the potential to be an attractive field of future research.

In conclusion, using biomass-based natural coagulants offers a sustainable and efficient substitute for chemical coagulants in water purification. This overview emphasizes the considerable promise of plant-based and animal-based coagulants in eliminating diverse pollutants. Nevertheless, challenges persist regarding standardization, scalability, and a full comprehension of their mechanisms. Further research is crucial to tackle these issues and encourage the extensive use of natural coagulants in water treatment procedures.

4.2. Future studies

This comprehensive review has pinpointed several knowledge gaps in our current understanding and application of coagulation processes, emphasizing the necessity for further research to: (I) predict coagulation process performance for water pollution removal across various operational conditions; (II) explore pollution removal from mixed effluents; (III) deepen understanding of the coagulation mechanisms of diverse natural coagulants, whether plant- or animal-based; and (IV) assess the potential of natural coagulants for widespread industrial utilization. Addressing these research voids is crucial for enhancing the effectiveness and sustainability of coagulation processes in water treatment, ensuring their adaptability across diverse applications. Subsequent investigations in these domains will offer valuable insights, guiding the development of more efficient coagulation strategies for water pollution mitigation. Natural coagulants, being biodegradable and less toxic than chemical counterparts, mitigate environmental and health hazards. However, the assessment of potential long-term effects and secure residue disposal is imperative. Future studies could focus on exploring novel natural coagulants, like cactus mucilage and banana peel extracts, for heavy metal and organic contaminant removal. Additionally, research should evaluate the feasibility and economic viability of integrating chitosan and *Moringa oleifera* in large-scale water treatment facilities.

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