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Review

From Natural to Industrial: How Biocoagulants Can Revolutionize Wastewater Treatment

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Abstract: The environmental impacts of industrial processes have increased the demand for sustainable alternatives in wastewater treatment. Conventional chemical coagulants, though widely used, can generate toxic residues and pose environmental and health risks. Biocoagulants, derived from natural and renewable sources, offer a biodegradable and eco-friendly alternative. This review explores their potential to replace synthetic coagulants by analyzing their origins, mechanisms of action, and applications. A total of 15 studies published between 2020 and 2025 were analyzed, all focused on industrial wastewater. These studies demonstrated that biocoagulants can achieve similar, or the superior, removal of turbidity (>67%), solids (>83%), and heavy metals in effluents from food, textile, metallurgical, and paper industries. While raw materials are often inexpensive, processing costs may increase production expenses. However, life cycle assessments suggest long-term advantages due to reduced sludge and environmental impact. A textile industry case study showed a 25% sludge reduction and improved biodegradability using a plant-based biocoagulant compared to aluminum sulfate. Transforming this waste into inputs for wastewater treatment not only reduces negative impacts from disposal but also promotes integrated environmental management aligned with circular economy and cleaner production principles. The review concludes that biocoagulants constitute a viable and sustainable alternative for industrial wastewater treatment.

Keywords: natural coagulant; eco-friendly; green chemistry

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1. Introduction

The advancement of industrial activities on a global scale, although driven by technological innovations and growing market demand, has contributed significantly to the intensification of environmental impacts, especially water pollution. The release of untreated or inadequately treated effluents has increased the concentration of contaminants in water bodies, affecting the quality of groundwater and surface water, in addition to posing risks to human health, fauna, and flora [1,2].

Among the various technologies available for water and effluent treatment, coagulation/flocculation stands out as one of the most widely used steps, considered essential to increase process efficiency and reduce operating costs [3]. This is a physicochemical process that involves the addition of coagulants that neutralize the repulsive charges on the colloidal particles and produce a floc, resulting in a higher sedimentation rate [4].

Despite their wide application and good efficiency in water and effluent treatment, traditional chemical coagulants, such as aluminum sulfate and ferric chloride, have certain disadvantages [5]. The use of aluminum raises concerns due to potential toxic effects,

including the development of neurological diseases such as Alzheimer's [6]. In addition, synthetic coagulants and flocculants, in general, also attract attention due to other environmental risks, such as the persistence of residues in treated water and the generation of toxic and non-biodegradable sludge [7]. Furthermore, compared to other treatment technologies, such as membranes, while highly efficient, they require significant energy, high costs, and frequent maintenance [8].

Considering this scenario, there is growing interest in more sustainable alternatives, such as coagulants and flocculants of biological origin, which are substances derived from living organisms, characterized by their natural origin, organic composition, biodegradability, and high performance in water and effluent treatment processes. These bioproducts can be extracted from plants (such as *Moringa oleifera*), microorganisms, and animals and have a lower impact on health and the environment, unlike synthetic products, which leave harmful residues in the treated water and the sludge generated [9,10].

In line with global recommendations made through the Sustainable Development Goals (SDGs), especially SDGs 6 (Clean Water and Sanitation), 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 14 (Life Below Water), the use of these natural agents contributes to reducing water pollution, promoting water reuse and minimizing environmental impacts [11]. Although several studies have already highlighted the properties of natural coagulants and flocculants, there is still a limited amount of research investigating these agents in their use for the treatment of industrial effluents. Although previous reviews, such as those by Owodunni and Ismail [1] and Badawi et al. [12], have contributed significantly to the understanding of plant-based biocoagulants and their market potential, they have addressed a broad range of effluent types, including domestic and synthetic samples—without a specific focus on industrial wastewater. In contrast, this review is distinguished by its exclusive analysis of biocoagulant applications in industrial effluents, compiling 15 studies published between 2020 and 2025. This focused approach provides a comprehensive and updated overview of real-case industrial applications, highlighting the mechanisms of action, treatment performance, and practical challenges associated with the implementation of biocoagulants in complex industrial matrices. As such, the present work fills an important gap in the literature by aligning technical depth with practical applicability in industrial wastewater treatment.

Therefore, this review aims to provide a comprehensive discussion about biocoagulants derived from plant, animal, and microbial sources, with emphasis on their application in real industrial effluents. It also examines the physicochemical interactions between biocoagulants and complex effluent matrices, revealing existing research gaps. The review also proposes future research directions, including mechanistic investigations, the simulation of multi-compound interactions, and validation under real treatment conditions. This information is important to ensure the practical application of biocoagulants in industrial wastewater treatment.

2. Methodology

A bibliographic search was performed to select the most relevant articles for this review. The research was conducted in renowned databases, such as Scopus, ScienceDirect, and Google Scholar, using the keywords "biocoagulant", "natural coagulant", "coagulation", "flocculation", and "industrial effluent treatment". The saturation criterion was adopted as the interruption point, that is, the search was terminated when new results no longer provided relevant information. The inclusion criteria considered (i) relevance to the topic, covering studies on the use of biocoagulants in effluent treatment, and (ii) recent publications, i.e., those published between 2015 and 2025. A total of 107 articles were selected to provide scientific and technical background for the review, including both original

research and review papers. From this broader set, 15 articles published between 2020 and 2025 were selected for in-depth analysis as they specifically addressed the application of biocoagulants in real industrial wastewater scenarios. These 15 studies formed the core of the discussion, enabling a focused assessment of removal efficiency, industrial sectors, and practical challenges associated with biocoagulant use in industrial contexts. The review included both original articles and reviews, allowing a broader approach to the topic [13].

3. Biocoagulants

Bio-based coagulants, also known as biocoagulants, are obtained from natural sources such as plants, microorganisms, and animals. These compounds have specific properties that favor the coagulation and flocculation processes, contributing significantly to the removal of pollutants, such as turbidity, suspended solids, color, and organic compounds. In addition, biocoagulants remain promising alternatives due to their economic advantages (which include the potential use of by-products as soil conditioner/fertilizer), biodegradability, production of less sludge, good performance, and easy access [9,14–16].

During coagulation, the process of destabilization of colloidal particles occurs, reducing the repulsive forces between suspended particles. In the flocculation stage, the compounds (mainly of high molecular weight) facilitate the agglomeration of destabilized particles, promoting the formation of larger and denser flakes, facilitating physical–chemical separation by sedimentation, mainly, or by filtration [17].

Figure 1 illustrates the coagulation/flocculation process with biocoagulants. This figure highlights the pollutants (solids, heavy metals, organic matter, dye, and ions) present in the industrial effluent and, after the insertion of the biocoagulant, the coagulation stage with rapid mixing followed by flocculation with slow mixing to prevent the breakage of the flakes formed. The sedimentation stage shows the formation of sludge at the bottom of the container and a lighter color due to the removal of pollutants.

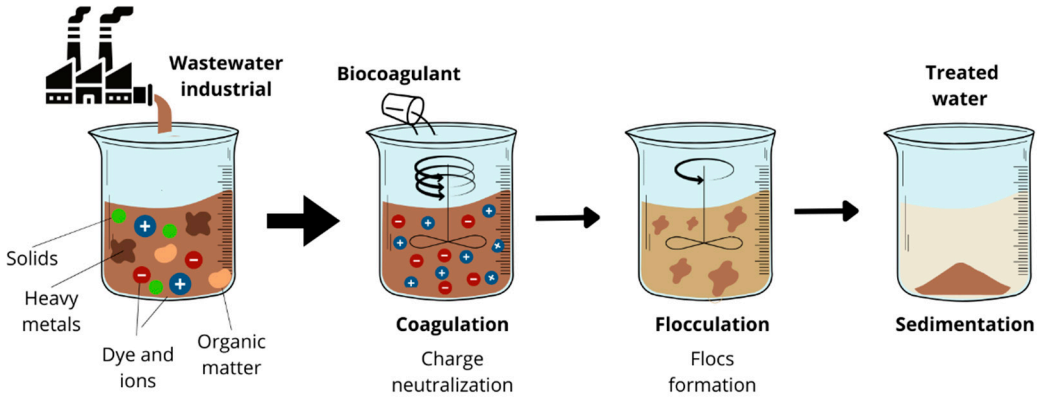


Figure 1. Illustrative diagram of the coagulation and flocculation process of industrial effluents using biocoagulants.

Biocoagulants act through the presence of active compounds, and their efficiency is directly associated with their structural characteristics, especially the presence of functional groups, such as hydroxyl, carboxyl, and amine, which play key roles in the coagulation/flocculation processes. These functional groups help neutralize the charges present, which is predominant in the coagulation stage, and in the formation of bonds between particles, which is the main characteristic of the flocculation process. However, the active compounds within the different types of coagulant/flocculant agents vary, and thus, the working mechanisms of each of them also vary [15]. The coagulation/flocculation mechanisms promoted by coagulants of organic origin can occur through different path-

ways, such as charge neutralization, the formation of bridges between particles, and the adsorption [18], coagulant sweeping [9], and compression of the double layer [19].

Furthermore, the study by Zourif et al. [18] highlighted that coagulation mechanisms can result from a combination of different processes, varying according to the compounds isolated from the coagulant material used. For example, when comparing palm petiole residue (PPW) with its extracted lignin, the authors observed that PPW used neutralization and adsorption as the mechanisms, while lignin used bridging and adsorption as its main mechanisms. These differences in the composition of biocoagulants directly influence coagulation mechanisms. PPW depends on metal salts to neutralize the charge, which bind to negatively charged contaminants, reducing electrostatic repulsion and allowing agglomeration. Meanwhile, lignin, in turn, focuses on its organic content to promote bridging, which occurs when long chains of organic compounds adsorb onto multiple particles at once, forming flakes and evidencing the absence of metals that could play a neutralizing role [18].

3.1. Main Sources of Biocoagulants and Production Methods

Figure 2 presents an illustration of the different origins of biocoagulants used in the treatment of industrial effluents. Biocoagulants can be derived from animals, microorganisms, and, most commonly, plants [20]. The choice of material must include advantageous characteristics, such as coagulant action, availability, safety, effectiveness, and cost [21,22].

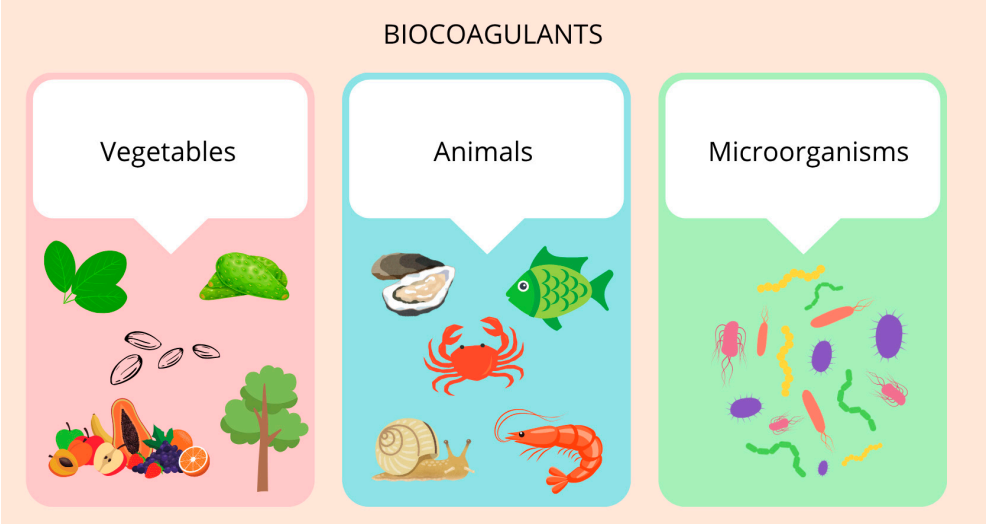


Figure 2. Illustration of the origins of biocoagulants.

3.1.1. Vegetable Origin

Plant-based biocoagulants are the most promising due to their abundant availability and reliable performance. Parts that can be used as coagulants include seeds, leaves, roots, fruits, mucilage, grains, gum, and sclerotia [14]. These biocoagulants can act as stand-alone coagulants or coagulation aids for the removal of heavy metals, turbidity, and organic compounds from various types of effluents [23]. Furthermore, the biodegradability of these compounds ensures environmentally friendly sludge management, making it a sustainable alternative to face the challenges of treating industrial effluents in an appropriate and environmentally friendly manner [24].

The use of by-products and plant residues to obtain biocoagulants has been increasing [20]. The use of seeds, pits, bark, leaves, and stems as biocoagulants is indicative of the circular economy and the biorefinery concept.

The efficiency of lignocellulosic biocoagulants is related to the presence of functional groups and specific mechanisms of action. These biocoagulants contain functional groups,

such as hydroxyl (-OH), carboxyl (-COOH), and amino (-NH_2), whose inherent charges favor the coagulation–flocculation process [25,26]. Some examples of use in industrial effluents are peanut shells [27] and coconut fibers and sugarcane bagasse [25].

Tannins, present in various plant peels, generally exhibit an anionic nature. These compounds require a cationization process so that they can be applied as biocoagulants, with the Mannich reaction being the most recognized cationization method [20]. Examples already applied in the treatment of industrial effluents are cassava peels [28], the bark of spruce trees (*Picea abies*) [29], pitahaya peels [30], palm petiole waste [18], *Cyperus esculentus* chaff [24], and chestnut shells [20]. In this same sense, the use of *Crescentia cujete* fruit shells can be a potential alternative in the treatment of industrial effluents since Boakye et al. [31] found that, as it is composed of hemicellulose materials, this biocoagulant showed high efficiency in water treatment.

Among the seeds, those of *Moringa oleifera* are the most used as biocoagulants due to the presence of a high-molecular-weight cationic protein, which acts as a clarifying agent [32–38]. However, other seeds of the mucuna [39], *Ricinus communis* L. [40], cottonseed [41], *Parkinsonia aculeata* [42], custard apple [43], avocado [5], and *Moringa stenopetala* B [21] have been gaining prominence among industrial effluents. Cottonseed [41] and grape [44] seeds are efficient when applied as biocoagulants in synthetic turbid waters.

Several studies have shown that seed extracts from various plants can serve as effective biocoagulants in water treatment, demonstrating a positive possibility for evaluation in the treatment of industrial effluents. Husen et al. [45] found that flaxseed is efficient for treating surface water, especially in rural areas. Mathupreetha et al. [46] obtained satisfactory results when using yard-long beans (*Vigna unguiculata* subsp sesquipedalis) and snake gourd (*Trichosanthes cucumerina*) as biocoagulants in water treatment.

The use of leaves as industrial biocoagulants has gained prominence due to the presence of active functional groups that aid in the coagulation and flocculation of contaminants, in addition to availability and low cost [22,47]. *M. esculenta*, *P. sarmentosum*, and *T. gigantea* leaves [47]; *Acacia greggii*, *Albizia lebbeck* (L.), *Aloe barbadensis*, *Azadirachta indica*, *Bougainvillea glabra*, *Clerodendrum inerme*, *Conocarpus lancifolius*, *Dianthus caryophyllus*, *Eucalyptus camaldulensis*, *Eucalyptus citriodora*, *Nerium oleander*, *Moringa oleifera*, and *Phoenix dactylifera* [48]; and *Aloe vera* leaves [22] are examples of some leaves that, due to the presence of polysaccharides (cellulose and hemicellulose), proteins, and phenolic compounds, have helped in the flocculation and removal of industrial contaminants.

Mucilages are polysaccharide biomaterials consisting mainly of arabinose, galactose, rhamnose, and xylose [49]. The hydroxyl (–OH), carbonyl (CO), and carboxyl (–COOH) groups present in the mucilage structure provide its coagulant action [50]. Mucilage has already been extracted from *Opuntia ficus* [51,52], flaxseed [23], chia [53], *Alyssum* [54], *Lallemantia* [55], dragon fruit peel (*Hylocereus undatus*) [56], *Austrocylindropuntia* [44], and *Aloe vera* [21,57,58] to treat industrial effluents efficiently and economically.

Starch is a biocoagulant that has been standing out due to the presence of some functional groups, such as carboxyl and hydroxyl groups that are linked to its polysaccharide ring, after effective modification [59]. Modified starches with fatty acid chlorides are suitable for heavy metal removal due to their negative charge. When starch is modified with dodecanoyl chloride, better hydrocarbon removal efficiencies are achieved [60]. Modified starches of corn and potato by the acetylation method showed a good removal of pollutants in industrial effluents due to improved solubility in a study [37].

Leal Castañeda et al. [60] found that the removal of heavy metals, turbidity, and chemical oxygen demand (COD) is more efficient when using modified starch than when using native quinoa starch. The authors mention that the chemical modification helped in facilitating a greater affinity with oily agents on the surface of the granule, obtaining

more compact and more stable agglomerates or flakes than those generated with native starch. In the same sense, ref. [61] covalently linked β-cyclodextrin to the starch backbone by esterification to increase the number of hydroxyl groups, and subsequently, the starch was modified using amine functional groups to introduce cationic properties and increase effective flocculation.

Other examples of plant biocoagulants are orange waste pectin [62]; *Hibiscus esculentus* L. (okra), *Detarium microcarpum* (sweet dater) and *Xanthosoma* (cocoyam) [26]; cactus cladode [63]; fenugreek (*Trigonella foenum-graecum*) [58,64]; *Opuntia ficus indica* (cactus) [65]; pine cones (*Pinus nigra*) [66]; and stems of *Acanthus sennii* C. [21]. These materials reduce environmental impact as they are biodegradable and obtained from renewable sources, being effective in removing turbidity, color, organic matter, and even heavy metals.

The synergistic action of two or more natural coagulants may be more advantageous in removing contaminants. El Mouhri et al. [42] used, together, *Parkinsonia aculeata* seeds as biocoagulants and *Hibiscus esculentus* as a bioflocculant to minimize the concentration of pollutants in tannery wastewater. El Gaayda et al. [44] evaluated the use of grape seed powder as a biocoagulant and *Austrocylindropuntia* mucilage as a bioflocculant to eliminate the azo dye Congo red and turbidity from synthetic wastewater.

3.1.2. Animal Origin

Chitosan is a polysaccharide that comes from the deacetylation of chitin. This polysaccharide has been extensively studied as a biocoagulant and coagulation aid [67]. Chitosan as a biocoagulant has already been extracted from oyster shells of the species *Crassostrea virginica* [26] and *Egeria radiate* [68] and from snail shells of the species *Tympanotonos Fuscatus* [69], *Zonitoides nitidus* shells [70], and *Helix pometia* [71] for use in the treatment of industrial effluents. Furthermore, Okey-Onyesolu et al. [72] used fish bone chitosan-protein.

Crab shells, by-products of fishing, can undergo deproteinization to transform them into chitin and, subsequently, into chitosan. A new alternative for the recovery and valorization of this process is to use the liquid resulting from deproteinization as a biocoagulant for effluent treatment [73].

Shrimp by-products are widely used to obtain chitosan, which can be used to remove pollutants and microplastics from effluents. Iber et al. [74] used chitosan from the dried legs of giant freshwater prawns (*Macrobrachium rosenbergii*) as they are inedible and are discarded, thus creating a source of environmental pollution. Eamrat et al. [75] used alum as a coagulant and chitosan from shrimp shells (*Litopenaeus vannamei*) as a biocoagulant aid, finding high removal efficiencies of contaminants from surface waters.

3.1.3. Microbial Origin

Microorganisms play an essential role in bioremediation, a process responsible for removing pollutants from water [76]. Microorganisms act as biocoagulants, mainly producing substances that help bind together (agglutinate) particles suspended in water or effluents.

Microalgae stand out in coagulation/flocculation processes due to the presence of functional groups, such as carboxyl, sulfonate, hydroxyl, and amine, in their cell walls. *Chlorella vulgaris* is an efficient, accessible, and low-cost biocoagulant capable of removing a wide variety of pollutants, such as polyethylene microplastics [76]. Although it is an environmentally friendly biocoagulant, there have been no studies involving industrial effluents.

Studies involving the production of biocoagulants/bioflocculants of microbial origin focus on their isolation from aquaculture effluents [77–79]. Kurniawan et al. [77,78] evaluated the use of extracellular polymeric substances (EPSs) from bacteria produced by *Serratia marcescens*. The EPS produced by the bacteria worked better as a bioflocculant

than as a biocoagulant, in which the application of EPS needed to be accompanied by a coagulant/biocoagulant.

3.1.4. Extraction and Purification Techniques

Biocoagulant preparation may involve mechanical, chemical, and purification processes [14]. The powder form is the most widely used among biocoagulants, and in some cases, the powders can later be mixed with distilled water, centrifuged, and filtered to extract the active agents [47].

Biocoagulants of plant origin are crushed, washed, dried, ground, and sieved [18]. Drying and grinding greatly affect the performance of a biocoagulant due to the removal of moisture and greater contact with the carrier medium during dissolution while size reduction favors its efficiency [14]. Biocoagulants of animal origin (chitosan) require demineralization steps to remove salts that may impair purity and reactivity, deproteinization to eliminate proteins that may hinder coagulation, and deacetylation to expose the amino groups (-NH_2), essential for the efficiency of chitosan as a biocoagulant [75].

In the chemical preparation of biocoagulants, the oil needs to be removed before the extraction of active ingredients to avoid low extraction yields of active compounds. The de-oiling of *Moringa oleifera* seeds has shown an 18% higher protein content. Salt and alcohol extractions have been mentioned as superior extraction methods for obtaining carbohydrates and proteins from plant biocoagulants compared to water extraction, with up to a 5% increase in turbidity removal [14].

3.2. Application of Biocoagulants in Industrial Wastewater Treatment

Growing environmental concerns related to wastewater treatment have intensified research on biodegradable and natural coagulants, leading to the development of novel biocoagulants and exploration of their potential applications. Therefore, Table 1 presents different types of effluents treated using biocoagulants. Although the physicochemical composition of an industrial effluent depends on the type of developed product and applied technology, the agriculture and food processing sources of industrial effluents usually contain a high concentration of organic matter. Indeed, these effluents can contain high levels of biological oxygen demand (BOD), COD, total suspended solids (TSS), turbidity, nitrate, and phosphate [80,81]. For instance, the evaluation of effluent composition and the physicochemical properties of the biocoagulant is important to elucidate the mechanisms underlying coagulant–effluent interactions. Figure 3 shows the mechanisms involved in the coagulation/flocculation process.

Mohamed Noor et al. [38] studied the effect of magnetic *Moringa oleifera* as a biocoagulant for the coagulation/flocculation of a palm oil effluent. The authors used magnetite powder (Fe_3O_4) to provide ferromagnetic properties and to improve the efficiency of the biocoagulant. The incorporation of magnetite nanoparticles into *Moringa oleifera* to produce a magnetic biocoagulant enhanced its performance in the treatment of the palm oil mill effluent. Compared to raw *Moringa oleifera*, the magnetic *Moringa oleifera* presented higher removal efficiency. The TSS, color, and COD removal values of magnetic *Moringa oleifera* were 83.0%, 35.6%, and 85.2%, respectively, whereas those for the raw *Moringa oleifera* were 52.2%, 16.4%, and 12.3%, respectively. This improvement was attributed to the presence of Fe^{2+} ions in magnetite. The zeta potential values of raw *Moringa oleifera* (5.7 mV) and magnetic *Moringa oleifera* (4.4 mV) were similar. Indeed, at a pH of the palm oil mill effluent of 8.49, the ions from magnetite tend to form hydrolyzed or precipitated species, which could have enhanced coagulation/flocculation via sweep and bridging mechanisms. However, the ionization behavior of Fe^{2+} and Fe^{3+} species at the pH of the effluent should be further investigated to understand their role in modifying the biocoagulant.

Table 1. Summary of industrial effluent types evaluated for biocoagulant treatment.

Source of Industrial Effluent	Industrial Effluent	Biocoagulant	Optimal Dosage	Main Results	References
Agriculture and Food Processing	Wet coffee processing	*Moringa stenopetala* B. seed, *Acanthus sennii* C. stems, and *Aloe vera* L.	750 mg L^{-1}	Color and turbidity removal rates of 99.9% and 98.7%, respectively	[21]
	Palm oil mill	*Moringa oleifera*	1000 mg L^{-1}	TSS, color, and COD removal rates of 83.0%, 35.6%, and 85.2%, respectively	[38]
	Cheese whey	*Opuntia ficus-indica*	4400 mg L^{-1}	Turbidity and COD removal rates of 98.9% and 83.8%, respectively	[82]
	Fish processing	Protein-rich liquid from the chitin extraction process	17.5 mL L^{-1}	Turbidity, BOD, and COD removal rates of 98.9%, 92.1%, and 78.9%, respectively	[73]
	Tofu industry	*B. licheniformis*	20 mg L^{-1}	Turbidity, COD, and BOD removal rates of 70.0%, 75.9%, and 80.2%, respectively	[83]
	Brewery	Custard apple seed	2000 mg L^{-1}	Nitrate, color, and phosphates removal rates of 98.0%, 99.6%, and 97.8%, respectively	[43]
	Compost leachate (from organic fertilizer production)	*Salvia hispanica* mucilage	40,000 mg L^{-1}	COD and turbidity removal rates of 39.8% and 62.4%	[53]
	Aquaculture	*Serratia marcescens*	10 mg L^{-1}	Turbidity and TSS removal rates of 80.1% and 92.2%, respectively	[78]
Textile and Chemical	Textile industry	Chestnut shell	100 mg L^{-1}	Color and aluminum removal rates of 31% and 15%, respectively	[20]
	Car wash	Flaxseed mucilage	100 mg L^{-1}	Surfactant and COD removal rates of 80.8% and 57.0%, respectively	[23]
	Paint industry	*Hibiscus esculentus*, *Detarium microcarpum*, *Xanthosoma*	100 mg L^{-1}	Turbidity removal rates of 84–95%	[26]
	Tannery	*Moringa oleifera*	2000 mg L^{-1}	TSS removal rate of 89.9%	[84]
Metallurgical and Heavy Industry	Steel processing	*Moringa oleifera*	10 mg L^{-1}	Turbidity removal rate of 90%.	[37]
	Ceramic industry	Devilfish	200 mg L^{-1}	Turbidity, COD, and TSS removal rates of 67.4%, 56.9%, and 50%, respectively	[85]
Pulp, Paper, and Packaging	Raw pulp and paper mill	*Cassia obtusifolia* seed gum	750 mg L^{-1}	TSS and COD removal rates of 86.9% and 36.2%, respectively	[86]

BOD: Biological Oxygen Demand; COD: Chemical Oxygen Demand; TSS: Total Suspended Solids. The *Serratia marcescens* at pH 6–7 showed zeta potential of −18.77 mV, protein content of 1.3 µg mL^{-1}, and carbohydrate content of 0.47 mg L^{-1}. The main compounds identified in the monosaccharide composition and organic compound analysis included one alcohol-based compound and three carboxylic-acid-based compounds. Therefore, the deprotonation of these functional groups and other hydroxyl and carboxyl moieties from proteins and carbohydrates could have resulted in the negative surface charge of the biocoagulant. The authors suggest that the negative charge of biocoagulant could support biocoagulant–effluent mechanisms, such as bridging and patch. Although bridging relies on the particle formation by chain entanglement with colloid particles, patch depends on the charge of the compounds within the effluent, requiring positive sites or the presence of cations to interact with the negatively charged functional groups from the biocoagulant. Therefore, further characterization of the effluent is important to understand the mechanisms involved in turbidity and total-suspended-solids removal.

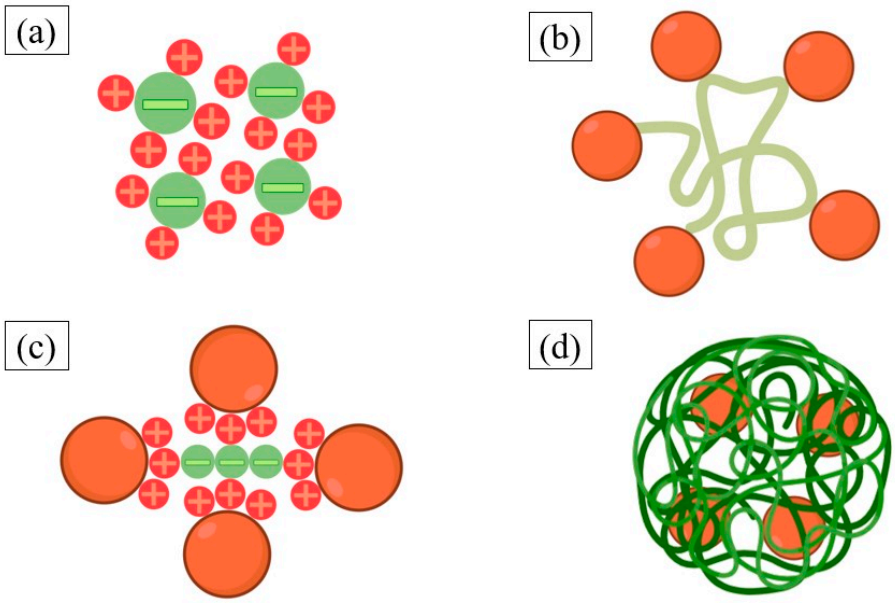


Figure 3. Mechanisms of coagulation/flocculation: (**a**) charge neutralization; (**b**) bridging; (**c**) patch; (**d**) sweep.

Garomsa et al. [43] studied the effect of the custard seed as a biocoagulant for the electrocoagulation of a brewery effluent. The effectiveness of both electrochemically generated ions and biocoagulants was related to the pH. At a pH of 7, aluminum ions (Al^{3+}) released from the electrode reacted with hydroxide ions (OH^-), forming insoluble $Al(OH)_3$. Moreover, custard apple seed powder showed a point of zero charge (PZC) of 7.67. Therefore, at a pH of 7, the surface of the biocoagulant became positively charged, which could have favored the electrostatic attraction of negatively charged pollutants, such as phosphate, nitrate, and anionic colorants, thereby enhancing the coagulation/flocculation and removal efficiency. Furthermore, at the pH of 7, $Al(OH)_3$ could have formed stable amorphous flocs, which could have removed nitrate, color, and phosphates primarily via the sweep mechanism.

Kurniawan et al. [78] studied the effect of *Serratia marcescens* as a biocoagulant for the coagulation/flocculation of an aquaculture effluent. The biocoagulant was characterized by its zeta potential, total carbohydrate and protein content, monosaccharide composition, and polysaccharide linkage types and the presence of organic molecular and intermediate

Textile and chemical industrial effluents exhibit a complex and variable composition, including synthetic dyes, surfactants, detergents, salts, heavy metals, and other chemical compounds. This composition often leads to elevated levels of COD, turbidity, TSS, and intense coloration [20,23,26,84]. As a result, treating these effluents can be a challenging process. Therefore, the application of novel biocoagulants should be further investigated as a potential solution. Tomasi et al. [20] studied the effect of chestnut shells as a biocoagulant for the coagulation/flocculation of a textile effluent. The authors used chestnut shells to extract tannin. Tannin-based biocoagulants were developed by chemically modifying extracted tannins through aminomethylation. This optimized process of reacting the tannins with ethanolamine as an amine compound resulted in a zeta potential of 27.7 mV at a pH of 4. The coagulation/flocculation of textile effluent was performed at a pH of 5, resulting in the removal of 31% of color and 15% of aluminum. At this pH, both the biocoagulant and aluminum ions are positively charged, which could have resulted in electrostatic repulsion, hindering their interaction and reducing removal efficiency. In addition, textile effluents are complex mixtures. Although many synthetic dyes are anionic and could be removed via charge neutralization, these molecules could be sterically

hindered or stabilized by compounds, such as surfactants, limiting the biocoagulant–dye interaction. Moreover, the presence of inorganic salts and metals, such as sodium chloride and aluminum, can interfere with the coagulation/flocculation process by competing for binding sites or enhancing steric stabilization. Therefore, it is important to characterize the effluent composition and simulate the interactions between synthetic dyes and other compounds to better understand the mechanisms involved in the coagulation/flocculation process to improve the performance of the developed biocoagulants.

Marichamy et al. [84] studied the effect of the *Moringa oleifera* seed as a biocoagulant for the coagulation/flocculation of a tannery effluent. The authors used salt solutions (NaCl and KCl) to extract proteins from *Moringa oleifera*, which were subsequently used as biocoagulants. The results demonstrated that the removal efficiency of TSS was influenced by both the pH and coagulant dosage. Maximum TSS removal (89.87%) was verified at a pH of 7 and a dosage of 40 mL using NaCl-extracted protein. The authors argued that at acidic pH, the high concentration of protons (H^+) competitively interacted with negatively charged pollutants, reducing the efficacy of the protein coagulant. On the other hand, at alkaline pH, floc disintegration resulted in decreased removal. The higher effectiveness of the NaCl extract was attributed to the stronger salting-in effect of sodium ions, which enhanced protein extraction. Indeed, it should be mentioned that considering that the amino acids within proteins have amino, carboxylic, and polar side chain groups, their charge is pH-dependent, influencing their ability to interact with pollutants via electrostatic attraction and, consequently, the charge neutralization mechanism. At a pH of 7, many compounds within effluent constituents, such as anionic surfactants, chromate ions (Cr^{+6} and $CrO_4{}^{-2}$), and sulfides (HS^-), are negatively charged, which can favor their interaction with positively charged proteins. Although the high TSS removal could be attributed to these electrostatic interactions, to fully understand this mechanism, further investigation into the ionization curves of these effluent compounds and the isoelectric point of the extracted proteins should be conducted. The relation of these findings could provide information about the competition between the biocoagulant and other cations for pollutant binding, as well as elucidate differences in protein extraction efficiency between the salt solutions.

Metallurgical and heavy industry are primarily composed of inorganic compounds and heavy metals, along with some organic compounds. This composition can result in moderate COD, high TSS, elevated turbidity, and significant concentrations of heavy metals [87,88]. Lester-Card et al. [37] studied the effect of *Moringa oleifera* as a biocoagulant for the coagulation/flocculation of a steel processing effluent. The authors compared the turbidity removal efficiency of the biocoagulant with a synthetic polymer (poly-powder Nalco 9908). At their respective optimal dosages, the polymer (1.5 mg L^{-1}) and the biocoagulant (10 mg L^{-1}) achieved 90% turbidity removal. The high performance of the biocoagulant was attributed to the protein extraction medium used for *Moringa oleifera*. When pure water was used instead of a 0.2 M NaCl solution, the PZC of the extracted biocoagulant increased from 4.8 to 11.5. The lower PZC verified with NaCl extraction was attributed to chloride ion (Cl^-) adsorption onto the positively charged groups of the proteins. At the pH of the effluent (7.9), the zeta potential was measured at −17.8 mV, indicating a negatively charged suspension. The protein extract obtained with water exhibited a broader range of positively charged groups, which enhanced its ability to neutralize the negative charges in the effluent. This charge neutralization mechanism was supported by the zeta potential of the effluent after biocoagulant treatment, which changed to −4.32 mV. Therefore, the extraction medium of biomolecules for biocoagulant applications can influence their final characteristics, leading to distinct physicochemical properties.

Pulp and paper mill effluents usually contain large amounts of organic matter, leading to elevated levels of TSS, turbidity, COD, and BOD. Subramonian et al. [86] studied the effect of *Cassia obtusifolia* seed gum as a biocoagulant for the coagulation/flocculation of raw pulp and paper mill effluents. *Cassia obtusifolia* gum demonstrated higher TSS (89.9%) and COD (33.9%) removal under acidic pH (3–5). The authors also compared the performance of the biocoagulant with aluminum sulfate. The coagulant exhibited higher TSS (93.5%) and COD (34.5%) removal under neutral/alkaline pH (6–8). Therefore, at optimized pH, the biocoagulant showed similar performance compared to the traditional coagulant. The zeta potential of effluent after coagulation/flocculation with biocoagulant remained relatively stable, even when the biocoagulant dosage increased from 0 to 2000 mg L^{-1} (−11.5 to −8.5 mV). Based on this result, the authors suggested that the mechanism of biocoagulant action could be interparticle bridging and adsorption rather than charge neutralization. Moreover, the effect of pH could be related to the chemical modification or degradation of organic compounds within the effluent, which could have increased their reactivity or accessibility, thereby enhancing their interaction with the biocoagulant.

4. Sustainability and Environmental Impacts

The use of natural coagulants has emerged as a promising alternative to traditional chemical coagulants, especially from an environmental perspective. Among the main benefits is the use of widely available and renewable raw materials. These inputs not only reduce dependence on synthetic substances but also contribute to a more sustainable approach, being biodegradable, potentially carbon neutral, non-toxic, and with a better cost-benefit ratio, considering the costs associated with sludge treatment and disposal [16,89].

It is worth noting that, unlike chemical coagulants, which often generate non-biodegradable waste rich in toxic substances, biocoagulants result in sludge that is less harmful to the environment. This waste has lower potential for contaminating water bodies and soil, especially due to the lower probability of leaching heavy metals, which is considered potential environmental pollution when sludge of chemical origin is disposed of in common landfills, a problem that may arise from this form of disposal over time [15].

Furthermore, sludge produced from the use of biocoagulants tends to be biodegradable and rich in nutrients, which allows it to be used in other production chains such as agriculture and the formulation of biofertilizers. This possibility reinforces the alignment of biocoagulants with the principles of the green economy and cleaner production, contributing to the mitigation of environmental damage and risks to human health and aquatic ecosystems [10]. The application of sludge after the treatment of industrial effluents with biocoagulants in agriculture is in line with the SDGs.

The intensification of agricultural and industrial activities, driven by population growth and the growing demand for food and resources, has increased the generation of agro-industrial waste. In many developing countries, this waste is still disposed of inefficiently, either by abandonment in the field or by open burning, resulting in significant environmental impacts, such as greenhouse gas emissions and soil and water contamination [90]. Transforming this waste into inputs for wastewater treatment not only reduces the negative impacts associated with its disposal but also promotes an integrated approach to environmental management, aligned with the principles of the circular economy and cleaner production.

In this scenario, in addition to aspects related to the origin and reuse of raw materials, it is essential to consider the life cycle of biocoagulants and their respective ecological footprints, aiming to guarantee sustainability in all phases of their use. As mentioned above, the use of natural biocoagulants is widely considered a sustainable alternative to synthetic coagulants. However, despite the benefits, there are still significant gaps in the complete

understanding of the environmental impacts associated with their life cycle. The active compounds present in biocoagulants, such as proteins and polysaccharides, are susceptible to degradation over time and may change during storage, in addition to being subject to microbiological contamination and environmental variations during the extraction and purification stages. Furthermore, although they are generally considered safe due to their natural origin, data on environmental toxicity and effects on living organisms are still limited, especially in the case of chemically modified biocoagulants. The introduction of functional groups or chemical grafts can significantly alter their properties and, potentially, their environmental safety [89,91,92].

5. Challenges and Future Directions

Regarding the challenges and future perspectives, illustrated in Figure 4, the technical and economic evaluation of large-scale biocoagulant production for industrial effluent treatment remains limited. Indeed, the annual production capacity, production costs, processing conditions, raw material pre-treatments, and extraction yield influence the final unit cost of biocoagulants. Moreover, one obstacle to their practical application and commercialization is the difficulty in maintaining stability and preserving the active components over time. In addition, toxicity assessments are often overlooked, despite their importance. Therefore, more comprehensive studies are needed to evaluate the toxicity and environmental footprint of biocoagulants, ensuring their safe and sustainable use in wastewater treatment.

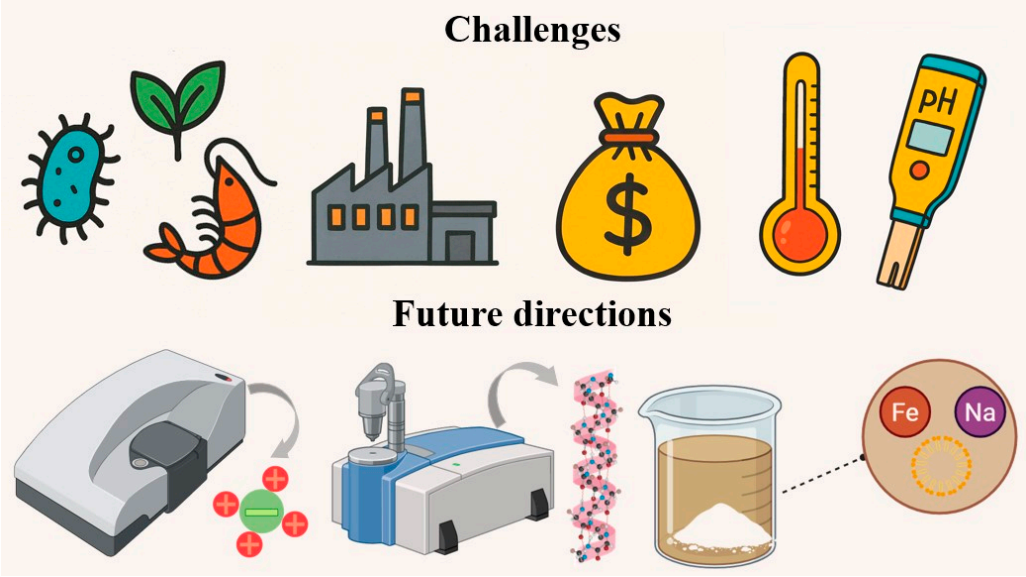


Figure 4. Illustration of challenges and future directions.

Another major challenge is the variability in biocoagulant composition. Future research should focus on characterizing the molecular structure, functional groups, and charge behavior of the biomolecules involved. This includes investigating the influence of extraction parameters on the physicochemical properties of biocoagulants to improve reproducibility and treatment performance. Although many studies have suggested coagulation/flocculation mechanisms, such as charge neutralization or interparticle bridging, there is often insufficient experimental evidence to confirm these interactions. Therefore, greater emphasis should be placed on the comprehensive characterization of both the biocoagulant and the effluent, before and after treatment, to better elucidate these mechanisms.

Furthermore, understanding the interactions between biocoagulants and effluent compounds, such as surfactants, salts, and heavy metals, is necessary as these compounds

can compete for binding sites or cause steric hindrance. For instance, future studies should include simulations involving two or more interacting compounds present in real industrial effluents, followed by validation with actual effluent samples. In addition, the chemical modification and functionalization of biocoagulants should be explored to enhance their performance under a wider range of pH and ionic strength conditions. Associated with this, the use of hydride systems through the combination of biocoagulants with magnetic fields or synthetic polymers can be a promising alternative for increasing the efficiency of contaminant removal.

A growing area is artificial intelligence (AI). Future research should explore the integration of advanced technologies to optimize the performance of biocoagulants according to the specific characteristics of industrial effluents. Tools such as machine learning algorithms can assist in modeling and predicting coagulation efficiency under varying conditions, allowing the development of personalized treatment strategies. In addition, the application of nanotechnology, through the functionalization of biocoagulants with nanoparticles or magnetic materials, can increase coagulation activity, recovery, and reuse potential. These innovations offer a promising path to overcome current limitations, such as dosage optimization, separation difficulties, and scalability, thus improving the environmental and economic viability of biocoagulants in industrial effluent treatment.

Among the various sectors responsible for the complex generation of effluents, the pharmaceutical industry deserves special attention due to the presence of high concentrations of persistent organic pollutants, such as active pharmaceutical ingredients, antibiotics, hormones, and solvents [93]. These substances are often resistant to conventional treatments and can lead to the development of antimicrobial resistance and ecotoxicity in aquatic environments. The treatment of these effluents presents great challenges in terms of efficiency, safety, and environmental impact, and there have been no studies using biocoagulants in this sector. Therefore, biocoagulants can be investigated as a complementary or pre-treatment step, aiming to reduce the organic load, turbidity, and toxicity before advanced treatments such as membrane filtration, oxidation, or adsorption.

6. Conclusions

Biocoagulants represent a promising and environmentally sustainable alternative to conventional chemical coagulants in industrial wastewater treatment. They have demonstrated effectiveness in different industrial effluents, including those from the food, textile, metallurgical, and paper sectors. Beyond their treatment efficiency, their use aligns with global efforts to reduce environmental impact and promote green technologies. Therefore, this review has discussed the main sources of biocoagulants, including animals, microorganisms, and, most commonly, plants. Moreover, it has addressed the extraction and purification of biomolecules used as biocoagulants, which involve mechanical, chemical, and purification processes. The applications of biocoagulants in wastewater treatment have also been explored, with a focus on understanding the mechanisms underlying biocoagulant–effluent interactions responsible for the removal of total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), turbidity, heavy metals, and other pollutants.

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Abbreviations

The following abbreviations have been used in this manuscript:

SDGs	Sustainable Development Goals
$^{-}$OH	Hydroxyl
$^{-}$COOH	Carboxyl
$^{-}NH_2$	Amino
CO	Carbonyl
EPSs	Extracellular Polymeric Substances
TSS	Total Suspended Solids
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
Fe_3O_4	Magnetite powder
PZC	Point of Zero Charge
Fe^{2+} and Fe^{3+}	Iron ions
Al^{3+}	Aluminum ion
$Al(OH)_3$	Aluminum hydroxide
NaCl	Sodium chloride
KCl	Potassium chloride
H^+	Proton
Cr^{+6}	Chromate ion
HS^-	Sulfides
Cl^-	Chloride ion

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