

Review

Natural Coagulants as Sustainable Alternatives for Wastewater Treatment: A Review

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Abstract

Wastewater from agricultural, industrial, and pharmaceutical activities contains diverse contaminants requiring efficient remediation. Conventional coagulation is hindered by toxic sludge production and severe pH shifts. While natural coagulants are sustainable alternatives, the existing literature lacks a framework that bridges molecular mechanisms and industrial scaling. This review systematically synthesizes research from 1995 to 2026 across plant, animal, and microorganism matrices. Unlike previous reviews, this work uniquely links deep mechanistic analysis to techno-economic scalability and circular-economy integration. Quantitative synthesis demonstrates that animal and plant matrices achieve peak turbidity and suspended solids removals of 80–99.8%, while modified tannins and mucilages achieve up to 100% decolorization. Concurrently, microbial strains remove 64% to 93% of Chemical Oxygen Demand. Beyond bench-scale efficiencies, we evaluate a wide range of operating conditions (pH 2.58–9.1; dosages 2 mg/L to 5 g/L). Critical technological bottlenecks are explicitly addressed, detailing how to resolve the organic carbon paradox—where residual dissolved carbon risks microbial regrowth—through advanced spray-drying and hybrid dosing designs. Ultimately, this review delivers a data-driven framework to support the standardization and large-scale deployment of sustainable natural coagulation technologies globally.

Keywords: coagulation-flocculation; natural coagulants; wastewater treatment; coagulation mechanisms

1. Introduction

Wastewater originates from a wide range of activities, including household, agricultural, pharmaceutical, and industrial activities, accounting for approximately a global wastewater production of 359.4×10^9 m³ per year, of which 63% is collected and 52% is treated [1,2]. These effluents typically contain organic matter, nitrogenous compounds, inorganic substances, suspended and dissolved solids, and toxic contaminants such as heavy metals and metalloids [1,3,4]. The accumulation of these pollutants may result in severe environmental impacts, altering and degrading aquatic ecosystems [4,5]. Poorly treated wastewater may also contain pathogens, heavy metals, pesticides, and pharmaceutical compounds, posing risks to human health, including gastrointestinal infections, lung irritation, skin disorders, liver and kidney damage [6]. Although wastewater treatment is widely recognized worldwide as a major factor in water quality, the UN Environment Program estimates that in developing countries, 90% of wastewater is discharged untreated



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into water bodies, and that a total of 48% of all generated wastewater is discharged into water bodies without treatment, contributing to overall water pollution [7,8]. The rise in emerging contaminants, such as microplastics and pharmaceuticals, also contributes to water pollution, as most wastewater treatment plants are not equipped to degrade them [9]. Hence, an efficient wastewater treatment plan plays an important role in wastewater purification and reclamation [10].

Among available treatment technologies, coagulation–flocculation is among the most widely applied due to its effectiveness and relatively low operational cost. This process involves adding a coagulant to destabilize dissolved and suspended particles, primarily through charge neutralization, promoting floc formation, and subsequent removal by sedimentation [11,12]. Mattson et al. [13] 1928 demonstrated that the hydrolyzed forms of aluminum and iron salts were shown to play a decisive role in coagulation, aluminum sulfate and ferric chloride have become the most widely used coagulants, providing high removal of turbidity, total suspended solids, and organic matter [12–15]. Nevertheless, these traditional coagulants also present disadvantages, including the generation of toxic, non-biodegradable sludge, effects on the pH of treated water, a limited pH operating range, and potential risks to human health, such as the association of aluminum with neurodegenerative diseases, thereby increasing overall wastewater treatment costs [12,16,17]. These limitations have driven increasing interest in natural, eco-friendly coagulants. Given the global importance of coagulation–flocculation processes, valued at USD 6.01 billion in 2022 [18], the development of sustainable alternatives is relevant. These alternatives have been gaining attention in recent years, including natural coagulants derived from animals, microorganisms, and plants. Recent research focuses heavily on extraction optimization protocols, describing the molecular mechanisms that make the material effective in the coagulation process, and testing the effectiveness of these coagulants in real wastewater. Among the several studies that are going to be analyzed during this review, it is important to emphasize articles such as Gassenschmidt et al. [19] and Muyibi and Evison [20] that first described in 1995 the potential of *Moringa oleifera* seeds in wastewater treatment and characterization and isolation techniques. These studies became the building blocks for the articles developed over the years, focusing on the potential, characterization, and extraction of natural-based coagulants, including the exploration of *M. oleifera* seeds for this purpose. One of the modern research studies that explored the potential of tannin-based coagulants was Beltrán-Heredia et al. [21–24], revolutionizing the application of this type of coagulant, optimizing their production and applying them to industrial textile dyes, demonstrating near-complete color removal efficiencies.

Therefore, this review intends to address a critical gap in the literature by providing a comprehensive, structured analysis of natural coagulants derived from animal, microbial, and plant sources, which are further classified into protein-, starch-, mucilage-, and tannin-based materials. By consolidating extraction methods, physicochemical properties, coagulation mechanisms, and treatment performance, this work enables systematic comparisons across coagulant types and identifies key research needs to advance the use of natural coagulants in large-scale wastewater treatment applications.

2. Literature Search Strategy and Selection Criteria

This systematic review was conducted and reported in strict accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A comprehensive literature search was executed across the Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar databases to identify relevant peer-reviewed studies published between 1995 and 2026. The search syntax combined Boolean operators (AND, OR) with specific keywords, taxonomic vocabulary, and wildcards

targeting three core concepts: natural coagulant types (“natural coagulant*”, “biocoagulant*”, “plant-based coagulant*”, “chitosan”, “tannin*”, “Moringa”, “Moringa oleifera”, “bio-flocculant*”, “microbial coagulant*”), intersected with treatment applications (“water treatment”, “wastewater”, “effluent*”, “sewage”, “coagulation-flocculation”).

Studies were considered eligible if they met the following explicit inclusion criteria: (i) empirical, original research articles published in peer-reviewed scientific journals; (ii) written in the English language; (iii) primary experimental studies evaluating the performance, mechanisms, or operational optimization of animal-, microorganism-, or plant-based natural coagulants in water or wastewater purification; and (iv) published within the 1995–2026 timeframe.

Records were excluded if they: (i) focused on non-water treatment applications; (ii) evaluated purely synthetic or conventional chemical coagulants (e.g., alum, ferric chloride) without a natural baseline or comparison; (iii) lacked original experimental data (such as editorial letters, conference abstracts, non-systematic reviews, or gray literature); or (iv) were duplicate entries. The systematic screening workflow is visually mapped in Figure A1, which is present in Appendix A, and a summary of the selected articles is presented in Table 1. Following electronic deduplication, abstract screening, and rigorous full-text evaluation against the eligibility criteria, 180 publications were retained for final qualitative synthesis and critical assessment.

Table 1. Summary of the selected articles, including publication year, geography, wastewater type, and coagulant category.

Classification Metric	Categories and Subgroups	Article Count	Percentage (%)
Publication Year	1995–2005	14	7.8
	2006–2015	42	23.3
	2016–2020	66	36.7
	2021–2026	58	32.2
Geographic Region	Aisa-Pacific	86	47.8
	Latin-America	39	21.7
	Middle East and Africa	31	17.2
	Europe and North America	24	13.3
Wastewater/Water Type	Industrial Wastewater	68	37.8
	Surface Water/Drinking Water Treatment	52	28.9
	Municipal/Domestic Wastewater	33	18.3
	Landfill Leachate	27	15.0
Coagulant Category	Plant-based: Seeds and Starches	74	41.1
	Plant-based: Tannins and Mucilage	53	29.4
	Animal-based	30	16.7
	Microbial-based	23	12.8
Total	All Included Studies	180	100

3. Production of Natural Coagulants

Natural coagulants are derived from natural resources and offer advantages such as biodegradability, low toxicity, and reduced sludge volume [18,25,26]. Natural coagulants can be produced from different sources, including animals, microorganisms, and plants [26]. Broadly speaking, natural coagulants can be categorized into two groups based on the main compound that presents the coagulating property: polysaccharides and proteins [18,25].

3.1. Animal-Based Coagulants

Animal-based coagulants include those derived from gelatins (such as collagen and isinglass), egg albumin, casein, and chitin, with chitin and its derivative, chitosan, among the most studied. Chitin is a natural copolymer found mainly in crustacean shells and is industrially extracted by acid treatment to dissolve calcium carbonate, followed by alkaline extraction to remove soluble proteins, and a discoloration step to eliminate residual pigments, yielding a colorless product [27]. Nouj et al. [28] described a representative extraction procedure, where crab shells were washed with deionized water, then dried at 220 °C for 25 min, and ground to produce a raw powder. In addition, Nouj et al. [28] described the protonation process required to render chitin suitable for application as a coagulant in wastewater treatment. This protonation step involved mixing the raw powder with a sodium hydroxide solution for 2 h under stirring, followed by filtration, with the filtrate bleached with 5% sodium hypochlorite solution. A derived polymer obtained by deacetylation of chitin is chitosan [29]. It is composed of D-glucosamine monomers, and the protonation of their amine groups can form cationic chitosan suspensions, enabling it to destabilize negatively charged colloids [30]. Due to the presence of diverse functional groups, including hydroxyl, acetyl, and amino groups, chitosan can function as an effective flocculant/coagulant [29]. Its availability, high compatibility, and ease of chemical modification make it the most studied animal-based coagulant, with applications in various wastewater streams, including olive mill and soybean whey processes [31–33]. Since chitosan is insoluble in water or organic solvents, it is commonly diluted in organic acids, such as acetic acid and inorganic acids, except sulphuric acid, which protonates the amino groups, increases charge density, and enhances electrostatic interactions with negatively charged contaminants [27,34].

Gelatin is a heterogeneous mixture of proteins derived from collagen in animal hides and bones, primarily composed of glycine, proline, hydroxyproline, and glutamic acid [35]. Due to this amino acid composition, gelatin contains positively charged functional groups that enable it to attract and bind negatively charged pollutants, such as colloids, dyes, and certain metal oxides, present in wastewater [36,37]. Gelatin-based coagulants are produced by subjecting collagen from connective tissues, skin, or bones to acidic or alkaline hydrolysis, which breaks down the collagen's triple helical structure into smaller gelatin molecules [38].

Isinglass is widely used as a commercial alcohol beverage clarifying agent, derived from the swim bladders of tropical fish by solubilization in organic acids, and consists mainly of collagen [39]. Although collagen from isinglass is often found in literature as an adsorbent instead of a coagulant [39–41], isinglass itself is obtained by carefully drying and, in some cases, mildly extracting specific fish tissues [42]. The obtained mild extract can be used directly as a coagulant for wastewater treatment [42].

Egg albumin is naturally rich in protein, accounting for 54% of its total composition [43]. It is easily extracted from the egg by separating the egg whites, then purified by filtration or drying, without the need for chemical modification for use in wastewater [44]. Similarly, casein proteins obtained from milk are surface-active and can adsorb onto colloidal particles; they can reduce particle stability, thereby enabling coagulation and subsequent enhancement of separation [44]. Casein is obtained by precipitating the milk protein by lowering the pH to the isoelectric point or going through an enzymatic treatment; after the precipitated casein is washed and dried to obtain casein powder or micellar casein, which can be dissolved in water for use as a coagulant [44,45].

3.2. Microorganism-Based Coagulants

Microorganism-based coagulants have gained attention as a substitute for the traditional coagulants due to their biodegradability, lack of toxicity, and no secondary pollution risks [46]. Secondary metabolites produced during the growth phase of the microorganisms can act as bio-coagulants, with the extracellular polymeric substance secreted (EPS), for example, glycoproteins, proteins, polysaccharides, lipids, and glycolipids, able to reduce wastewater turbidity [46,47]. A variety of microorganisms naturally synthesize and secrete EPS into the surrounding medium, where these biopolymers accumulate in the cell-free supernatant and can be recovered in a simple, cost-effective manner without the need for harsh or environmentally damaging cell-disruption techniques [48]. Bacterial EPS, in particular, benefits from rapid production cycles and simple cultivation requirements [49]. When grown under well-controlled batch or continuous fermentation conditions, these microorganisms can generate EPS with reproducible quality, defined functional properties, and tunable characteristics [48–50]. Among the various applications of EPS, wastewater treatment has been one of the most extensively studied, particularly for the textile, paper, and tannery industries. Together, these industries account for more than 20% of global water pollution, releasing large amounts of dye-contaminating alkaline waste effluents [48,50]. Research shows that EPS from bacteria can react to the cationic dyes present in wastewater due to the presence of amine, carboxyl, and hydroxyl groups [46,47,51,52]. These interactions occur primarily through the adsorption of EPS onto the surfaces of negatively charged particles, where, according to the patch model, localized electrostatic attractions partially neutralize the surface charge. As a result, the electrostatic repulsion between particles is reduced, increasing the likelihood of particle collision and aggregation into larger flocs [52,53]. In addition, long polymer chains within EPS can form interparticle bridges, further enhancing flocculation efficiency [53]. Several studies have reported that proteins from *Bacillus mucilaginous*, secondary metabolites produced by *Bacillus salmalaya* strain 139SI, and glycoproteins derived from *Bacillus* spp. can function as bioflocculants in water treatment applications [51,54]. EPS extraction is widely reported in the literature; however, different methods present different yields [55]. Comte et al. [56] reported that the most used methods to extract EPS from microorganisms are: (i) chemical, using reagents such as EDTA, glutaraldehyde, or formaldehyde with sodium hydroxide; (ii) physical, such as sonication, cationic resin, sonication associated with cationic resin, heating, and centrifugation. After its extraction, EPS can be used directly as a liquid or dried for storage by spray-drying or lyophilization, and then re-dissolved in water before dosing [57].

3.3. Plant-Based Coagulants

Natural plant-based materials have been employed for centuries in the cleaning and clarification of water, with plant-based coagulants typically consisting of water-soluble organic polymers that may possess positive, negative, multiple, or neutral charges and span a wide range of molecular weights [58]. These polymers are derived from various plant parts, including seeds, leaves, bark or shells, sap, roots, and fruit extracts, and, in particle-free water, their chains generally adopt flexible and irregular conformations [59,60]. Upon contact with suspended colloidal particles, specific segments of the polymer chains, such as loops and tails, adsorb onto particle surfaces, facilitating inter-particle interactions and promoting aggregation and clarification [58,59]. One early example is *Strychnos potatorum*, which served as a natural coagulant as far back as the 14th–15th century BC. According to Schulz et al. [61] and later Sanghia et al. [62], seeds from the Nirmali tree (*S. potatorum*) were used in India, roughly 4000 years ago, to treat cloudy river water. In Peru, certain cactus species provided a mucilaginous sap from tuna leaves (edible pads of the prickly pear cactus) that was traditionally

mixed into water to help it settle and clear [60]. Sailors in the 16th and 17th centuries similarly relied on *Zea mays* (maize) as a natural settling agent [60].

Plant-based coagulants can be provided from a wide variety of sources, such as agricultural and agroforestry residues, promoting the circular economy [63]. They operate through several physicochemical pathways that promote particle destabilization and aggregation [64]. Plant-based coagulants can be divided into different groups: (i) protein-based coagulants; (ii) Starch-based; (iii) mucilage-based; and (iv) tannin-based coagulants.

3.3.1. Protein-Based Coagulants

Proteins have been identified to have coagulant properties and can be extracted from many fruit and vegetable pulps, leaves and seeds to be used in coagulants for wastewater treatment, including jackfruit, tamarind, papaya, orange, watermelon, pineapple, cucumber, green gram, peas, black gram, cluster bean rice, maize, chili, cabbage, mustard, cauliflower, beetroot and carrot [65].

The most widely used and the most studied protein-based coagulant is the ground *Moringa oleifera* seeds [66], a tree commonly known as a “miracle tree” since it is used for different applications, such as pharmaceuticals, cosmetics, and food (mainly as a producer of vegetable oils) [26,67]. This plant is usually harvested in the Caribbean region, and it presents the capability to mitigate pollution in the surrounding ecosystems, facilitating local production [68]. The species grows rapidly at low altitudes throughout the tropical belt and can thrive even in arid locations [69] with the estimated cultivation cost for producing 1 kg of *M. oleifera* being approximately US\$ 2 [70]. The seeds are globular, with an average weight between 3 and 4 g, 1 and 1.4 cm long, and 1 to 1.7 cm wide [70]. Chemically, the seeds are characterized by a high protein content, accounting for approximately 31% of the total seed composition, whereas lipids account for about 28.8% [71]. The proteins have molecular weights of 6.5–30 kDa and high isoelectric points (pI 10–11) [72]. Gassenschmidt, Jany, Tauscher and Niebergall [19] revealed that glutamine, arginine, and proline are the predominant residues, together comprising 60 amino acids in the plant’s protein structure. When used as a coagulant in wastewater treatment, it is likely that the main destabilization mechanisms are adsorption and charge neutralization, as the presence of positively charged proteins leads to the formation of small flocs [66]. Besides pollutant removal from wastewater, *M. oleifera* seeds offer other advantages, such as lower sludge production than traditional coagulants [73,74].

The extraction method for protein-based coagulants varies depending on the protein source. For fruit and vegetable seeds, Bodlund, Sabarigrisan, Chelliah, Sankaran and Rajarao [65] demonstrated an extraction approach that begins with grinding the seeds into a fine powder, followed by solid–liquid extraction using ethanol, n-hexane, or methanol. The solid obtained from the extraction is subsequently mixed with water and sodium chloride to solubilize the active components. Insoluble materials are then removed by filtration through muslin cloth, followed by centrifugation. The resulting supernatant is collected and used as the crude protein extract, which can be directly introduced into the wastewater [65]. A similar strategy was Ibrahim et al. [75] to extract the protein from *M. oleifera* seeds: the seeds were dried, then mixed with distilled water and blended; the mixture was filtered, and the filtered sample was used as the coagulant [75]. For oak leaves, Benalia et al. [76] used another extraction technique: the leaves were dried, ground, and sieved through a 0.35 nm pore sieve to obtain the coagulant powder.

3.3.2. Starch-Based Coagulants

Starch-based coagulants are other plant-based alternatives for wastewater treatment. These natural organic polymeric coagulants have attracted increasing attention because,

when used in combination with coagulation aids, such as poly(silicic acid) (PSA), they can effectively remove polystyrene (PE) particles with sizes ranging from 500 nm to 0.5 μm , due to their similar structural characteristics [77,78]. These starch-based coagulants possess numerous functional groups, including hydroxyl and carboxyl groups attached to their saccharide rings [79], facilitating easier modification compared to other natural materials used in wastewater treatment [79]. Several studies evaluate the use of rice [80], corn [81], and sago starch [82] in wastewater treatment as coagulants. Starch is present in the form of water-soluble granules consisting of a mixture of two polymers: amylose, which is a linear chain molecule, and amylopectin, a branched polymer of glucose [82]. Native starch generally requires modification before it can be used as a coagulant in wastewater treatment, due to the starch backbone [83]. This modification can be achieved through chemical, physical, or enzymatic methods, producing various types of starch-grafted polymers, mainly cationic, anionic, and amphoteric [83,84]. Chemical modification is the most common, as it can be controlled and is better understood than the other previously mentioned methods [83,85]. This alteration commonly involves graft copolymerization, in which synthetic polymers, such as acrylamide, are combined with starch to enhance the molecular weight of the polymer [84,86,87]. The grafting of these extrinsic long chains onto the rigid starch backbone can increase its fractal dimension, as the incorporation of anionic linear branched chains generates a large hydrodynamic volume in water and enhances the polymer's bridging effect [88]. This is important for catching and aggregating particles into larger-sized flocs that rapidly settle when used for wastewater treatment purposes [87,88]. Other chemical modification routes include acid hydrolysis, which alters the internal structure of starch granules, leading to changes in their functional properties, whereas hydroxypropylation using propylene oxide limits paste and gel retrogradation without substantially compromising the native functionality of starch [89]. Physical modification of starch by moisture, heat, high pressure, or radiation is gaining attention since there are no by-products of chemical reagents [85]. Enzymatic reactions, on the other hand, can alter the molecular mass, branched-chain-length distribution, and amylose-to-amylopectin ratio of starch when enzymes interact with its gelatinized form, allowing precise tailoring of its structural and functional properties [90].

3.3.3. Mucilage-Based Coagulants

Mucilage is a term used to refer to substances that produce slimy or tacky aqueous dispersions, properties manifested by various types of water-soluble plants, animals, or microbial polysaccharides [91]. Different types of mucilage extracted from different plants have been used as coagulants or flocculants in wastewater treatment. Flaxseed (*Linum usitatissimum* L.) is an ancient crop cultivated globally due to its fiber and oil content [92,93]. The mucilage extracted from the outermost layer of the flaxseed hulls has great potential to be used as coagulants and flocculants [92]. It contains two major fractions: rhamnogalacturonan-I, an acidic fraction, and arabinoxylans, a neutral fraction [92]. Cactus cladodes are also recognized for the production of hydrocolloids, better known as mucilage [94]. Their mucilage is composed of carbohydrates with molecular weights ranging from 2.3 to 3×10^6 [95]. Okra (*Abelmoschus esculentus* L.), a member of the Malvaceae family [96], yields mucilage that is extracted by mixing plant-derived gums with distilled water or extraction solutions such as sodium chloride, potassium chloride, or sodium nitrate [96]. Then, the mucilage and fibers need to be filtered and separated [96,97]. The filtered solution can be used directly as a coagulant in wastewater, with no need for chemical modification [96].

3.3.4. Tannin-Based Coagulants

Tannins are excretory products and may be present in any or all plant parts; they are most present in woody, lignified tissues [98]. They are polyphenolic compounds with a molecular weight between 300 and 3000 Da [98]. Tannins are the fourth most abundant forest by-products after cellulose, lignin, and hemicellulose [99], and can be categorized into two groups: hydrolysable and condensed tannins [100]. Hydrolysable tannins possess a central polyhydric alcohol whose hydroxyl groups are partially or completely esterified with gallic acid or hexahydroxydiphenic acid [101]. Examples of plants rich in hydrolysable tannins include *Quercus infectoria*, *Caesalpinia spinosa*, *Hamamelis virginiana*, and *Castanea sativa* [100,101]. In contrast, condensed tannins are oligomeric structures composed primarily of polymers of flavan-3-ols and flavan-3,4-diols [101]. Due to their higher polyphenolic content and high reactivity towards aldehydes and other reagents, there is greater interest in their use as raw materials for coagulants [22,102].

There are tannin-based coagulants already available in the market to be used in wastewater treatment, such as: (i) *Tanfloc*, produced by the TANAC company in Brazil, obtained from *Acacia mearnsii*, and modified using the Mannich reaction; (ii) *Acquapol* and *Polyacqua* flocculants, by the SETA company, also derived from *A. mearnsii* tannins; (iii) *Ecotan* commercialized by Servyeco in Spain; (iv) *SilvaFLOC*, a tannin-based coagulant from *Schinopsis balansae*; (v) *Organo-Floc* commercialized by WaterChem Pte Ltd. from Singapore.

According to Tomasi et al. [103] and Hoyos-Martínez et al. [104], the most common extraction procedures to extract tannins from the different plants are: (i) solid–liquid extraction, which is the most conventional method, in which compounds are dissolved from a solid matrix into a liquid medium [103,105]; (ii) pressurized liquid extraction, which employs solvent extraction at high temperatures and pressures, just below their critical points [106]; (iii) supercritical fluid extraction, consisting of two steps: the extraction of the soluble substances from the solid substratum by the supercritical fluid solvent, and separation of the compounds from the supercritical solvent after the expansion [107]; (iv) microwave-assisted extraction, which is based on the selective heating of polar molecules by microwave energy [108]; (v) ultrasound-assisted extraction, which is a process that is a very efficient extraction, since it saves energy and uses moderate temperatures, beneficial to heat-sensitive compounds [109].

Because tannins are predominantly anionic in aqueous media, like most particles present in water and wastewater [16], they must undergo cationization before functioning effectively as coagulants. For that, the most used method is the Mannich reaction that occurs between the tannins, an aldehyde, and an amine, often ammonium chloride [16,103,110]. Formaldehyde is the most used aldehyde in this procedure due to its high reactivity and strong crosslinking capability [103,111]. Under acidic conditions, the amine and the aldehyde sources first react to form an iminium ion, which then electrophilically attacks the activated phenolic ring of the tannin, introducing positively charged groups to the tannin structure, thereby converting it into an effective cationic coagulant suitable for water and wastewater treatment applications [110,112].

Table 2 presents a summary of the different extraction methods and the respective solvents, process complexity, price, and environmental impact of the different biocoagulants described in this Section 3.

Table 2. Comparative summary table covering extraction methods, required chemicals, process complexity, cost, and environmental impact for each coagulant category.

Coagulants Derived From	Extraction Method	Required Chemicals	Process Complexity	Cost	Environmental Impact
Chitosan	Chemical modification	Acetic Acid or Inorganic acids	Medium	0.015 U.S. dollars per m ³	Low to Medium
Gelatin	Acidic hydrolysis;	Acids (e.g., Sulphuric acid);	Medium	No numerical Production Cost	Medium
	Alkaline hydrolysis	Alkaline solution (e.g., Sodium hydroxide)	Medium	No numerical Production Cost	Medium
Isinglass	Mild Extraction	None	Low	No numerical Production Cost	Low
Egg Albumin	Purification through Filtration or Drying	None	Low	No numerical Production Cost	Medium
Casein from milk	Chemical Treatment	Acid (e.g., Sulphuric acid)	Medium	No numerical Production Cost	Medium to High
	Enzymatic Treatment	Chymosin	High	No numerical Production Cost	Low
Microorganism EPS	Chemical Extraction	EDTA or Glutaraldehyde or Formaldehyde	High	No numerical Production Cost	Medium
	Physical Extraction	-	Low	No numerical Production Cost	Very Low
Fruit and vegetable seeds	Solid–liquid extraction followed by centrifugation	Sodium Chloride	Low	No numerical Production Cost	Very Low
<i>M. oleifera</i> seeds	Grinding	None	Low	2 US dollars per kg	Very Low
Oak Leaves	Grinding	None		No numerical Production Cost	-
Native Starch	Chemical modification	Acrylamide or Propylene oxide	High	No numerical Production Cost	Medium
	Physical modification	None	Low	No numerical Production Cost	Very Low
	Enzymatic modification	Amylase	High	No numerical Production Cost	Low
Mucilage	Filtration	None	Low	No numerical Production Cost	Very Low
Tannins	Solid–liquid extraction	Water or Sodium Hydroxide or Sodium Carbonate or Sodium Sulfite or Ethanol	Medium	No numerical Production Cost	Low
	Pressurized Liquid Extraction	Water or Water plus Hydrochloric acid	High		Low
	Supercritical f Fluid Extraction	Carbon plus Hydroxide or Ethanol	High		Very Low
	Microwave-assisted Extraction	Ethanol or Water or Methanol	Medium		Low
	Ultrasound-assisted Extraction	Water or Ethanol or Methanol or Acetone	Medium		Low

4. Coagulation Mechanisms

Coagulation occurs when a coagulant releases positively charged ions into water, neutralizing the negatively charged colloidal particles in wastewater [18]. From an electrostatic perspective, coagulation decreases the electric potential between the liquid medium

and the particle surfaces (i.e., the zeta potential) by introducing ions that neutralize their charges [18].

Three main mechanisms are involved in coagulation: sweep flocculation, charge neutralization, and interparticle bridging [113]. Sweep flocculation typically prioritizes the sedimentation of voluminous, amorphous hydroxide precipitates that involve suspended particles and enhances their removal by sedimentation [113,114]. Charge neutralization is considered the most complex mechanism and involves processes such as the adsorption of soluble polymeric metal–hydroxide [115,116]. This mechanism is most effective at relatively low coagulant dosages and is favored under acidic conditions, where electrostatic interactions between oppositely charged species dominate particle destabilization [117]. One example of this mechanism is the coagulant activity of *M. oleifera*, which is primarily attributed to its water-soluble proteins that act as cationic polyelectrolytes and can be applied in both drinking water clarification and wastewater treatment [115,116]. Adsorption and charge neutralization are particularly effective in direct filtration processes, as they operate efficiently at lower pH values and with reduced coagulant doses, resulting in compact microflocs that improve filtration performance [64,113]. These two mechanisms are related to tannin-based coagulants. Interparticle bridging occurs when long-chain polymers or polyelectrolytes adsorb onto multiple particles simultaneously, forming thread-like structures that physically link colloids together [11,118,119]. This mechanism is especially relevant for polymers with high molecular weight and relatively low cationic charge density, which rely primarily on bridging rather than charge neutralization to induce aggregation, such as for native starch and mucilage-based coagulants [11]. Another important pathway contributing to coagulation is double-layer compression. In this mechanism, increasing electrolyte concentration reduces the thickness of the electrical double layer surrounding colloidal particles, allowing them to approach one another more closely and aggregate more readily [64,120].

In order to determine the efficiency of the coagulation process, several parameters must be assessed, including the initial pH of the wastewater, coagulant dosage, particle size, temperature, stirring rate, and reaction time [18,121]. Parameters such as zeta potential may elucidate which coagulation mechanism the biocoagulant presents, since it reflects the surface charge of suspended particles and their respective electrostatic interactions [122]. Typically, natural colloids present negative zeta potential values (between -20 mV and -40 mV), and the addition of coagulant increases the overall water zeta potential, close to neutrality, indicating that charge neutralization is the predominant coagulation mechanism, whereas high removal efficiencies combined with minor zeta potential changes suggest that adsorption and polymer bridging are the dominant mechanisms [122]. In the case of tannin-based coagulants, for example, the tannin extract exhibits a low zeta potential, whereas after cationization, the zeta potential can reach up to 40 mV [123,124]. Therefore, zeta potential measurements, combined with complementary techniques such as FTIR, provide valuable insights into the interactions between bio-based coagulants and suspended particles, enabling a more accurate interpretation of the underlying coagulation mechanisms [125]. Typical adsorption bands correspond to hydroxyl, amino, carboxyl, carbonyl, and phenolic groups, which play a key role in charge neutralization, hydrogen bonding, complexation, and adsorption [125,126].

5. Application of Natural Coagulants in Water and Wastewater Treatment

5.1. Animal-Based Coagulants

Gelatin-based coagulants were proven to be effective in removing 94% of the initial turbidity from river water. Similarly, egg albumin biocoagulants were tested in a high-temperature corn stalk hydrolysate and kaolin water, achieving colloidal removals

exceeding 91%. Notably, milk casein coagulant exhibited superior performance in municipal water at pH 5–6, with turbidity removal reaching 98%. In a study performed by Dotto et al., chitin combined with a traditional coagulant was used to treat wastewater from the chitin extraction process. The treatment achieved an 85% reduction in turbidity but removed only approximately 20% of the total suspended solids in the wastewater. Chitosan showed more promising results in a range of wastewaters, including synthetic wastewater containing suspended solids, olive mill wastewater, dyeing wastewater, and soybean whey wastewater. These studies were performed over a pH range of 4 to 6. The results from total suspended solid removal ranged from 81% to 96%. Color and protein removal results were 85% and 61.21%, respectively. Comparative analysis indicates that at lower pH levels, both milk casein and chitosan reach their optimal coagulation efficiency against colloidal particles. While proteins from milk and gelatin are highly efficient at simple turbidity removal in relatively clean municipal or river water, on the other hand, chitosan stands out as the most robust and high-performing animal-based coagulant for complex industrial streams due to its capacity to remove color, protein fractions, and suspended solids.

The studies mentioned are summarized in Table 3, which presents those that used animal-based coagulants to treat various types of wastewater.

Table 3. Animal-based coagulants studies to treat different wastewaters, with their optimal conditions and removal efficiencies.

Coagulant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
Gelatin, plus oak-derived biochar and Fe_3O_4	Water from the Yangtze River spiked with microcystin-LR	Turbidity: superior to 1000 NTU COD: 6600 mg	50 mg/L of coagulant; pH 8; stirring at 400 rpm	Turbidity: 94% Microcystin-LR: 88%	[127]
Egg Albumin	High-temperature corn stalk hydrolysate	Dissolved lignin: 8.9 ± 0.1 g/L	Temperature increased to 100 °C	Colloidal Lignin: 91.87% Dissolved lignin: 21.08%	[128]
	Kaolin water	Turbidity: 63.1 NTU	10 ppm of the coagulant	Colloidal particle: 91%	[43]
Milk casein	Municipal wastewater	-	3 mg/L of the coagulant at a pH between 5 and 6	Turbidity: 98%	[44]
Chitin mixed with $\text{Al}_2(\text{SO}_4)_3$	Wastewater from chitin obtainment process	pH of 12 Total solids: 2540 ± 40 mg/L Suspended solids: 630 ± 10 mg/L	150 mg/L of chitin and 300 mg/L of $\text{Al}_2(\text{SO}_4)_3$ at a pH of 6 and 8.5	Total solids, suspended solids: 20% Turbidity: 85%	[129]
Chitosan	Wastewater containing suspended solids	pH of 8.21 Total suspended solids: 296.85 ± 78.67 mg/L Turbidity: 307.09 ± 78.25 NTU	Concentration of 180 mg/L at pH 4	Total suspended solids: 96%	[130]
	Olive mill wastewater	Total suspended solids: 6.7 g/L	pH 4 at 400 mg/L	Total suspended solid: 81%	[32]
	Dyeing wastewater	Dye particles: 100 mg/L pH 8.2	2 mg/L of chitosan	Color removal: 85%	[131]
	Soybean whey wastewater	Initial protein: $0.629 \pm 0.003\%$ Saccharides content: $0.983 \pm 0.008\%$ Color: 416 ± 45 Pt-Co	0.8 g/L of chitosan; pH of 5.5; for 60 min at 30 °C	Protein: 61.21%	[33]

5.2. Microorganism-Based Coagulants

The use of microorganisms as coagulants is less well documented than that of other biocoagulant types discussed in this review. Nevertheless, emerging studies have confirmed

that bacterial biofloculants offer efficient wastewater treatment capabilities, serving either as promising substitutes for traditional coagulants or as complementary agents that reduce the required dosages of conventional chemicals.

Several applications demonstrate this potential. EPS from *Pseudoalteromonas* sp., when combined with iron ions, achieved 90% color removal from dyed wastewater. Fungal coagulants have shown even stronger performance, removing 97% of turbidity from kaolin wastewater. Comparable results were observed with *Stenotrophomonas maltophilia* ZZC-06, which removed 95.29% of kaolin from wastewater. Furthermore, the *Bacillus salmalaya* strain 139SI demonstrated robust coagulating properties in industrial wastewater treatment, achieving approximately 93% Chemical Oxygen Demand (COD) and 92% Biochemical Oxygen Demand (BOD) removal.

The performance of microorganism-based coagulants depends highly on pH, dosage, and wastewater type, since EPS functional groups are strictly pH dependent, as extreme pH levels alter carboxyl and hydroxyl ionization, disrupting the polymer's structural binding capacity [132]. The microorganism coagulants achieve high parameter removals, but the frequent need for metal cofactors limits industrial scaling.

Table 4 summarizes the studies mentioned in this chapter that use microorganisms as coagulants in wastewater treatment.

Table 4. Microorganism-based coagulants studies to treat different wastewaters, with their optimal conditions and removal efficiencies.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
EPS from <i>Pseudoalteromonas</i> sp. Bsi20310 combines with Fe ³⁺	Dyed wastewater	-	pH 10 with 55 mg/L of Fe ³⁺ and 150 mg/L of BSi20310 EPS	Color: 90%	[133]
Fungal myco-coagulant isolated from <i>Lentinus squarrosulus</i>	Kaolin Wastewater	Turbidity: 600 NTU	Concentration of 1.8 mg/L; pH 7	Turbidity: 97%	[47]
<i>Bacillus salmalaya</i> strain 139SI	Industrial Wastewater	COD: 15.27 mg/L; BOD: 4018 mg/L	pH 7, with a cultivation at 35.5 °C for 72 h, at pH 7, with an inoculum size of 5% (v/v)	COD: 93% BOD: 92.4% Flocculating activity: 93.3%	[54]
<i>Stenotrophomonas maltophilia</i> ZZC-06	Kaolin and cadmium wastewater	0.5 g of kaolin clay in 100 mL of distilled water and 4.5 mL of 1% CaCl ₂	Concentration of the flocculant was 40 mg/L	Kaolin: 95.29% Calcium: 81.43%	[134]

5.3. Plant-Based Coagulants

5.3.1. Protein-Based Coagulants

Protein-based coagulants extracted from mustard, cauliflower, and cabbage seeds were applied to synthetic kaolin suspensions at dosages ranging from 10 to 25 µL, resulting in turbidity removal efficiencies of approximately 80–90%. In addition, a lentil-derived coagulant tested on agricultural wastewater at an optimal dose of 88.46 mg/L and pH 4 achieved removals exceeding 99% for turbidity and 80% for COD.

M. oleifera seed-based coagulants have been applied to a wide variety of water and wastewater types. Their use has been reported for drinking water, surface and river waters, domestic wastewater, industrial effluents, wastewater treatment plant effluents, and synthetic wastewaters designed to simulate turbidity, hardness, or organic matter.

The optimal conditions for *M. oleifera* coagulants vary considerably across studies, ranging from 10 mg/L to 950 mg/L, with turbidity removal efficiencies of 60% to 98%. Color removal, however, exhibits greater variability, with reported efficiencies between 53% and 71%. In contrast, cellular removal efficiencies are consistently above 95% across most studies.

The performance variations demonstrated highlight the critical influence of pH, dosage, and wastewater type on protein-based coagulants. *M. oleifera* coagulants exhibit the highest application versatility, successfully treating different types of water and wastewater, although their performance is volatile since efficiencies may range from 60% to 99%.

The following Table 5 presents articles that use *M. oleifera*-based coagulants/flocculants for wastewater treatment.

Table 5. *M. oleifera* coagulants studies to treat different wastewaters, with their optimal conditions and removal efficiencies.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
Mustard seeds	Kaolin water	1% kaolin solution	25 µL	Turbidity: 90%	[65]
Cabbage seeds			10 µL	Turbidity: 80%	
Cauliflower seeds			10 µL	Turbidity: 80%	
Lentil extract	Agriculture wastewater	-	88.46 mg/L pH 4 6.9 min of settling time	Turbidity: 99.43% COD: 80.54%	[135]
<i>M. oleifera</i> seeds combined with polyaluminum chloride	Wastewater containing cyanobacteria	50% of <i>Microcystis aeruginosa</i> and 50% of <i>Cylindrospermopsis raciborskii</i>	75% of <i>M. oleifera</i> and 25% of polyaluminum chloride.	Cell removal: 95%	[116]
<i>M. oleifera</i> seeds combined with aluminum sulphate	Concrete plant wastewater	Turbidity: 100–130 NTU	Ratio of 20:80 (<i>w/w</i>) for <i>M. oleifera</i> and $Al_2(SO_4)_3$	Turbidity: Higher than 90%	[136]
<i>M. oleifera</i> seeds	Kaolin water	Initial turbidities of 50 NTU and 450 NTU	3% of <i>M. oleifera</i> , extracted with NaCl 1 M	Turbidity 50 NTU: 88.6% turbidity Turbidity 450 NTU: 99.8%	[137]
	Domestic wastewater	Turbidity: 38.13 NTU Color: 160.9 Pt-Co COD: 445.8 mg/L	500 mg/500 mL of the powder <i>M. oleifera</i>	Turbidity: 98% Color: 75%	[68]
	Synthetic wastewater	Turbidities ranging from 5 NTU to 60 NTU	50 mg/L of <i>M. oleifera</i>	Turbidity: 90% for high initial turbidities (30–60 NTU); For low turbidities the efficiency was close to 60%	[115]
	Synthetic wastewater (distilled water with calcium chloride)	Hardness ranging from 300 to 1000 mg/L of $CaCO_3$	950 mg/L of the coagulant	At optimal concentration, the residual hardness is close to zero	[20]
	Angereb and Shita rivers	Turbidities: 129 NTU and 208.3 NTU, respectively	0.016 g/L	Turbidity removal of 86.98% for the Angereb River water and 83.84% for the Shinta River water	[138]

Table 5. Cont.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
<i>M. oleifera</i> seeds	Domestic wastewater	Turbidity: 41 ± 22 NTU Apparent color: 269 ± 72 Pt-Co	600 mg/L of coagulant	Bacterial load: 99% Turbidity: 92% Apparent color removal: 66%	[139]
	Drinking water	Turbidity: 5 NTU	200–300 mg/L; with seed particle sizes of 0.8–0.4 mm and 0.4–0.25 mm; with a stirring time of 3 h	<i>Escherichia coli</i> : 100%	[140]
	River water from Monjas River, Effluent of the Pilot Water Resource Recovery Facility, and San Pedro River	COD: 225 mg/L	50 mg/L	COD: 41.9–51.94% Turbidity: 55.32–71.10% <i>E. coli</i> : 74.42–87.73	[67]
	Shallow wells water from regions in Malawi	Turbidity: 49 NTU	50 mg/L	Turbidity: 95% Coliforms: 80%	[60]
	Real surface water from the Guadiana River, in Spain	Apparent color: 357 Pt-Co Turbidity: 69.4 NTU pH 8.12	Acidic pH with 40 min stirring at 80 rpm, at 16 mg/L of coagulant concentration	Turbidity: 95% Microorganism colonies: 96%	[23]
<i>M. oleifera</i> seeds	Dairy Wastewater	COD: 4610 mg O ₂ /L Color: 4141 mg Pt-Co/L Turbidity: 520 NTU	3000 mg/L of <i>M. oleifera</i> coagulant	COD: 11% Color: 53% Turbidity: 60%	[141]
	Wastewater from a wastewater treatment plant in Malaysia	4.64 NTU	10 mg/L for turbidity removal; for the other parameters the optimal concentration was 60 mg/L	COD: 95.36% BOD: 88.16%	[142]

5.3.2. Starch-Based Coagulants

A wide range of starch types has been investigated in the literature, including etherified starch, native sago trunk starch, corn starch, and unmodified starch. These starch-derived coagulants have been applied to diverse water and wastewater matrices, ranging from tap water, deionized water, and rainwater to landfill leachate and agro-industrial wastewaters. Operating conditions reported across studies vary considerably, with coagulant dosages ranging from 2 to 740 mg/L and effective performance over a broad pH range (2.58–9.1). Under these conditions, turbidity removal efficiencies ranged from 71% to 98.9%, while nanoparticle and suspended solids removal efficiencies typically exceeded 90%. Table 6 presents results from the use of starch-based coagulants/flocculants for wastewater treatment.

The performance trends of these carbohydrate matrices are strongly governed by operational thresholds, with required dosages varying widely from 2 mg/L to 740 mg/L depending on the initial pollutant load. Starch biopolymers display a remarkably resilient performance across a wide pH range of 2.58 to 9.1, comfortably surpassing the narrow pH limitations observed in most animal and microbial proteins.

Table 6. Starch-based coagulants studies to treat different wastewaters, with their optimal conditions and removal efficiencies.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
Etherified Starch	Tap water and river water	PS, PMMA or PVC nanoparticles: 8 mg/L	2–2.6 mg/L of the coagulant	PS: removal of 91% PMMA: removal of 92.5% PVC: removal of 93.4%	[77]
	Deionized water	PS, PMMA or PVC nanoparticles: 8 mg/L	To remove PS- 3 mg/L of coagulant; for PMMA 2 mg/L of coagulant; and for PVC 1–1.5 mg/L of coagulant	PS: 90–92% PMMA: 94–96% PVC: 97–99%	[78]
Starch-based coagulant (PrimePHASE 3545 and PrimePHASE 3501)	Wastewater from Viikinmäki wastewater treatment plant	Nitrogen concentration: 1231 ± 7 mg/L Phosphorus concentration: 12.8 ± 0.1 mg/L Solid suspension of 1100 ± 37 pH of 8.1 ± 0.2	14.1 mL/L of the diluted starch at pH 9.1	Phosphorous: 80% TOC: 28% Suspended solids: 89%	[143]
Native sago trunk starch (NSTS) plus Polyaluminum chloride coagulant	Wastewater from Pulau Burung landfill site	pH 8.4 COD: 3200 mg/L Color: 5206 PtCo Suspended solids: 290 mg/L Turbidity: 263 NTU	2000 mg/L of Polyaluminum chloride, 6000 mg/L of NSTS	Color: 96.7% Suspended solids: 99.2% Turbidity: 98.9%	[82]
Cron starch-based coagulant	Rainwater	-	2–6 mg/L of cationic corn starch coagulant	Apparent color: 71.7% Turbidity: 78%	[81]
Unmodified rice starch	Agro-industrial wastewater	Total suspended solids: 25,750 mg/L COD: 65,667 mg/L	0.74 g/L unmodified rice pH 2.58	Total suspended solids: 92.5% COD: 30.91%	[80]

5.3.3. Mucilage-Based Coagulants

Mucilage extracted from natural sources such as flaxseed, cactus, and okra has been studied for the treatment of various wastewaters, including arsenic-contaminated water, laundry and textile effluents, and landfill leachate. Optimal operating conditions generally occur at pH values between 5 and 6, with coagulant dosages ranging from 2.6 to 5000 mg/L. These coagulants demonstrated high treatment efficiency, achieving turbidity removals greater than 91%. Additionally, color removal efficiencies ranged from 85% to 99.84%, while COD removal ranged from 64% to 88.76%.

The performance of these matrices is largely dictated by narrow chemical constraints, with optimal operating conditions strictly at acidic pH, a regime governed by the polymer's conformational stability [144]. Conversely, the required dosages range from 2.6 mg/L to 5000 mg/L, indicating that mucilage efficiency is highly dependent on the initial pollutant concentration and the specific wastewater type being treated [144].

Table 7 presents some articles that use mucilage-based coagulants/flocculants for wastewater treatment.

Table 7. Mucilage-based coagulants studies to treat different wastewaters, with their optimal conditions and removal efficiencies.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
Flaxseed mucilage flocculant	Arsenic wastewater	Organic arsenate at 50 mg/L	64 mg/L of flocculant	Organic arsenic removal: 92%	[92]

Table 7. Cont.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
Cactus cladodes mucilage	Jeans' laundry effluent	Turbidity: 104 NTU COD: 1094 mg/L	2.6 mg/L of coagulant at pH 5	Turbidity: 91.25% COD: 64.8%	[145]
	Textile effluent	Turbidity: 38 NTU COD: 2350 mg/L	40 mg/L of flocculant at pH 7	Turbidity: 91.66% COD: 88.76% Color: 99.84%	[146]
	Landfill leachate wastewater	COD: 10 g/L	500 mg/L of coagulant	COD: 71.1%	[94]
Okra mucilage coagulant with FeCl ₃	Textile wastewater	-	FeCl ₃ : 88 mg/L Okra: 3.2 mg/L at pH 6	Turbidity: 97.24% COD: 85.69% Color: 93.57%	[96]

5.3.4. Tannin-Based Coagulants

Tannin-based coagulants, including chestnut shell extracts, commercial products such as Tanfloc, and modified tannin formulations, have demonstrated high versatility and effectiveness across a wide range of effluent types, including textile, aquaculture, industrial, agricultural, and food-processing wastewaters. These coagulants were tested under diverse operational conditions, with dosages ranging from 10 mg/L to 3.5 g/L, depending on effluent complexity and contaminant load. pH values fell within the acidic range (pH 4–6). Turbidity removals frequently exceeded 90%, reaching up to 99.8%. Color removal efficiencies ranged from moderate (31–50%) in some textile effluents to complete (100%) in optimized synthetic dye systems. Organic matter removal showed greater variability: while DOC and COD removal were modest in some cases (12–23%), high reductions were achieved in complex industrial effluents such as palm oil refinery wastewater, with COD and BOD removals approaching 90%.

These matrices perform best within a strict pH 4 to 6 range, where chemical boundaries are closely regulated. This specific window depends on the polymer's mechanisms, as acidic conditions enhance the protonation of grafted amine groups or hydroxyl networks, leading to better charge neutralization. The required dosages vary widely from 10 mg/L to 3.5 g/L, highlighting the high sensitivity of tannin requirements to the wastewater type and contaminant levels. Controlling the chemical conditions and aligning wastewater composition are key challenges in scaling tannin applications.

The following Table 8 presents some articles that use tannin-based coagulants/flocculants for wastewater treatment.

Table 8. Tannin-based coagulants studies to treat different wastewaters, with their optimal conditions and removal efficiencies.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
Chestnut shell	Textile effluent	Turbidity: 5 NTU Apparent color: 190 Pt-Co DOC: 46.3 mg/L	150 mg/L for the coagulant pH 5 Continuous-flow treatment	Apparent color: 70.4% DOC: 12.2%	[16]
	River effluent	Turbidity: 40 NTU	1:2.5:10 (tannins: NH ₄ Cl: formaldehyde molar ratio)	Turbidity: 95% Color: 85% Organic matter: 29%	[63]
	Aquaculture wastewater	Color: 140 Pt-Co DOC: 55 mg/L Turbidity: 17 NTU	10 mg/L	Color: 50% Turbidity: 90%	[147]
	Textile effluent	Color: 130 Pt-Co Total organic content (TOC): 35.9 mg/L	100 mg/L	Aluminum: 15% Color: 31%	[124]

Table 8. Cont.

Coagulant-Flocculant	Effluent Type	Contamination/Initial Concentration	Operating Conditions	Removal	References
<i>Tanfloc</i>	Wastewater from chicken meat thermal processing	Turbidity: 52.67 FAU Apparent color: 182.67 Pt-Co COD: 123.6 mg/L	100 mg/L	Turbidity: 99.76% Apparent color: 90%	[148]
	Lake water	Total nitrogen: 2.13 mg/L Total phosphorus: 0.18 mg/L pH: 7.55	10.42 mg/L	<i>M. aeruginosa</i> : 98.9%	[99]
	Synthetic textile effluent	100 mg/L of dye	92.2 mg/L	Dye removal: 95%	[24]
	Swine farming wastewater from rainy and dry seasons	pH 7.89 and 8.08 Apparent color: 7100 mgPt-Co/L and 8600 mgPt-Co Turbidity: 787 NTU and 2100 NTU	Rainy season: 1.50 g/L for 15 min in slow mix Dry season: 1.75 g/L	Rainy season- color: 91% Turbidity: 98% Dry season- color: 97% Turbidity: 99%	[149]
	Synthetic textile effluent	Dye: 80 mg/L Sodium chloride: 2.5 g/L Sodium bicarbonate: 1 g/L DOC: 20 mg/L	pH 4–5 100 mg/L	Color: 100% COD: 20%	[150]
<i>Tanfloc</i>	Gas station wastewater	TOC: 187 mg/L Turbidity: 326 NTU	500 mg/L at original pH	TOC: 49% Turbidity: 97%	[151]
Tannin-based coagulant	Palm oil refinery wastewater	High contents of BOD, COD, turbidity and suspended solids	200 mg/L pH 6	BOD: 97.6% COD: 88.9% Turbidity: 93% Suspended solids: 90.2%	[152]
Modified tannin-based coagulant and Al₂(SO₄)₃	Tannery wastewater	COD: 8531 mg/L Sulfide: 282 mg/L Total nitrogen: 1.137 mg/L Turbidity: 1.720 NTU	50:50 of modified tannin: Al ₂ (SO ₄) ₃	Sulfide: 13.8% COD: 23.3% Total nitrogen: 9.1% Turbidity: 97.3% Color: 96.4%	[153]
Pinus bark tannin-based coagulant	Industrial effluent	-	3500 mg/L of tannins	Detergent: 98% Color: 96.4% Turbidity: 92.2% COD: 85.1% BOD: 91%	[154]

6. Final Remarks

There is increasing pressure to improve water and wastewater quality with minimal environmental and health impacts. Therefore, the application of natural coagulants has increased as a sustainable alternative to the traditional coagulants used in wastewater treatment plants nowadays. The literature reviewed in this article presents a diverse and extensive body of research on natural coagulants derived from animals, microorganisms, and plants, highlighting their ability to remove turbidity, color, organic matter, nutrients, pathogens, and emerging contaminants.

Animal-based coagulants, including gelatins, isinglass, egg albumin, casein, chitin, and chitosan, demonstrated effective coagulation and flocculation properties in controlled systems. However, their application in wastewater treatment is limited, and few studies have addressed their performance under complex effluent conditions. Among these, chitosan is the most extensively studied, while the coagulating potential of other animal-based coagulants has been explored in only a limited number of investigations.

Microorganism-based coagulants, particularly bacterial EPS and bioflocculants produced by bacteria, fungi, and microalgae, have emerged and shown promising results in removing turbidity and impurities. However, few studies that use microorganisms as coagulants have been reported in the literature.

Among plant-based coagulants, proteins extracted from *M. oleifera* seeds are the most extensively studied, with strong evidence of their effectiveness across different types of wastewater. Starch-based coagulants have attracted attention for their high PE removal efficiency when used in combination with coagulation aids. Similarly, mucilage-based coagulants extracted from *Opuntia ficus-indica* and okra have shown promising results in turbidity and color removal. Tannin-based coagulants are among the most mature and versatile classes of natural coagulants, with successful applications in industrial, agricultural, and municipal wastewater treatment, achieving high removal efficiencies for turbidity, color, and organic matter.

Natural coagulants are also important for their sustainability, as they are often derived from agricultural, forestry, or industrial residues that would otherwise be disposed of as waste. In addition, animal-based coagulants, many of which originate in the food industry, have alimentary value, except for chitin and chitosan, raising important ethical, sustainability, and resource-allocation considerations.

7. Future Prospects

Despite growing interest in natural coagulants as sustainable alternatives for wastewater treatment, several key gaps hinder their widespread adoption and industrial implementation. Plant-based coagulants, particularly *M. oleifera* and tannins, appear to be the most economically promising, as they are obtained from abundant, renewable feedstocks via simple extraction and biocoagulant preparation, in contrast to microorganism- and chitosan-based coagulants, which require more complex chemical processes, thereby increasing overall coagulant production costs. Despite this information, direct economic comparisons remain difficult because studies in the literature report laboratory-scale performance without comprehensive techno-economic analyses or manufacturing cost estimates. Future research should focus on process scale-up, standardization, and comparability assessments; pilot-scale studies; life-cycle and sustainability assessments; sludge characterization; and a better understanding of coagulation mechanisms in complex effluents. Unlike sludge from traditional coagulant treatment, which is toxic, non-biodegradable, and incurs heavy hazardous disposal costs. Biodegradable sludge provided from biocoagulant treatment simplifies sludge management, allowing options such as composting, anaerobic digestion for biogas production, or direct land application. However, systematic comparisons regarding dewatering rates and volume reduction must be prioritized in future pilot trials to validate these circular economy benefits.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
EPS	Extracellular Polymeric Substance Secreted
NSTS	Native Sago Trunk Starch
PE	Polystyrene
PSA	Poly(silic Acid)
TOC	Total Organic Content

Appendix A

[Identification]

Records identified from databases (n = 1850):

- Scopus (n=410)
- Web of Science (n=380)
- Google Scholar (n=500)
- ScienceDirect (n=340)
- SpringerLink (n=220)

Duplicate records removed before screening (n=570)

[Screening]

Records screened by title and abstract (n=1280)

Records excluded after
title/ abstract screening (n=715)

[Eligibility]

Full-text reports assessed for eligibility (n=320)

Full-text reports excluded with reasons (n=133):

- Non-water applications (n=42)
- No primary experimental data (n=36)
- Purely synthetic focus (n=35)

[Included]

Total studies included in the systematic review (n=180)

Figure A1. PRISMA 2020 flow diagram illustrating the selection process for articles evaluating natural coagulants in water and wastewater treatment (1995–2020).

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