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REVIEW

Natural-based coagulants/flocculants for microplastics and nanoplastics removal via coagulation–flocculation: a systematic review

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Abstract

Microplastics (MPs) and nanoplastics (NPs) are emerging contaminants that can act as vectors for toxic pollutants, posing serious risks to aquatic ecosystems. Coagulation–flocculation–sedimentation (CFS) is a widely used technique for MPs and NPs removal, and natural-based coagulants/flocculants offer a more sustainable alternative to conventional chemicals. However, a comprehensive evaluation of their performance, mechanisms, and influencing factors remains lacking. This systematic review, conducted in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, critically assesses the applicability of plant, animal, and microbial-derived natural coagulants/flocculants for MPs and NPs mitigation in aquatic systems. These materials are applied either directly as substitutes for chemical coagulants, chemically modified, or as coagulant aids. Key coagulation mechanisms include charge neutralization, electrostatic patch, adsorption bridging, sweep flocculation and netting-bridging. Removal efficiency is governed by factors such as pH, dosage, interfering substances, stirring conditions, MPs and NPs properties, and temperature. Although natural-based materials demonstrate a promising potential for sustainable plastic remediation, challenges related to material variability and availability, storage stability, environmental impact and process scalability remain. Addressing these limitations is essential to advance their practical implementation and long-term viability in real water and wastewater treatment applications.

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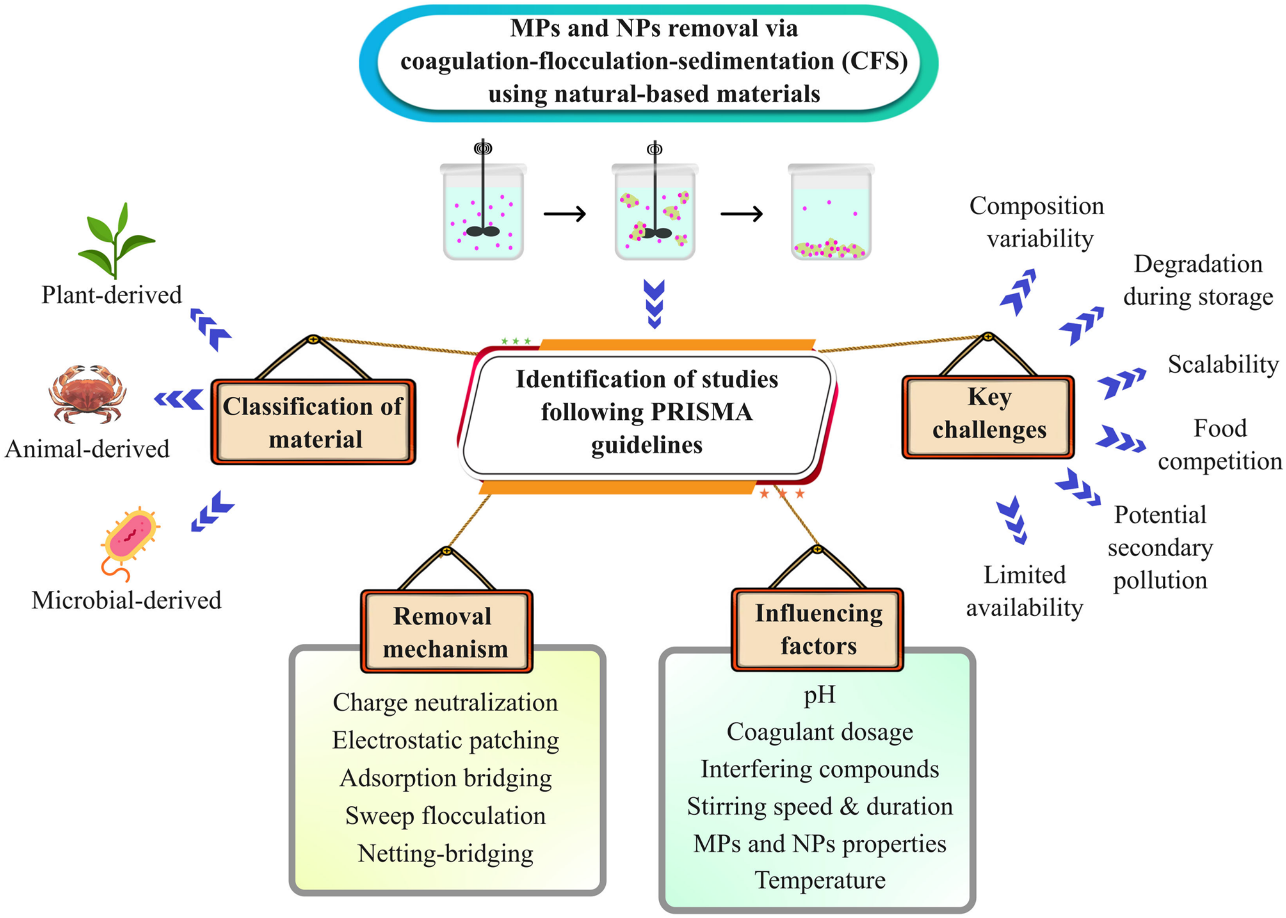
Graphical abstract



Keywords Microplastics · Nanoplastics · Water treatment · Coagulation and flocculation · Natural coagulant

Introduction

Water is essential to daily life, serving critical roles in consumption, sanitation, and numerous industrial processes. However, natural water bodies, such as oceans, rivers, lakes, etc., are often contaminated by various pollutants, leading to significant declines in water quality. Two key United Nations Sustainable Development Goals (SDGs), namely SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water), emphasized the urgent need to reduce aquatic and marine pollution and minimize the release of hazardous substances to ensure water safety for all life forms (Hegarty et al. 2021; Andriamahefazafy et al. 2022). Among the most significant water pollutants are microplastics (MPs), defined as plastic particles ranging from 1 µm to 5 mm, and nanoplastics (NPs), which are smaller than 1 µm (Acarer 2023). These plastic particles are either specifically manufactured in these sizes or result from the physical, chemical, or biological degradation of larger plastic debris (Wang et al. 2021). Due to their high surface area, strong hydrophobicity and high affinity for various pollutants, including heavy metals and synthetic dyes, MPs and NPs act as carriers or vectors of toxic substances in aquatic environments (Costigan et al. 2022). In addition, their ingestion by aquatic organisms, which often mistake them for food, facilitates their transfer through trophic levels, ultimately posing ecological and health risks across the entire food web (Mamun et al. 2023).

Low-trophic organisms are particularly vulnerable to MPs and NPs pollution due to their direct interactions with suspended particles in water bodies, and their miniscule size increases the likelihood of particle ingestion or surface adhesion (Alfonso et al. 2024). MPs and NPs ingestion by zooplankton, larvae, and other small invertebrates has been reported to reduce feeding efficiency and impair nutrient assimilation, while MPs and NPs adhesion to organisms such as phytoplankton may interfere with light absorption and photosynthesis (Chouchene et al. 2023). These stressors are commonly associated with reduced growth, lower reproductive output, altered metabolic activity, oxidative stress, DNA damage, and internal accumulation of plastic particles (Gola et al. 2021). These accumulated plastics may carry adsorbed contaminants, including heavy metals, pathogens, and organic pollutants, facilitating their transfer to higher trophic levels (Amelia et al. 2021). Consequently, high-trophic organisms are mainly affected by consuming contaminated low-trophic organisms (Blackburn and Green 2022). Numerous studies have reported that the consumption of MPs and NPs particles may lead to gut abrasion, translocation of plastics particles to tissues, oxidative damage and inflammation, reproductive dysfunction, and increased susceptibility to infection due to plastics-associated contaminants (Bhuyan 2022).

Addressing the pervasive issue of MPs and NPs pollution requires the advancement of innovative and efficient remediation technologies aligned with global sustainability objectives. Among established treatment methods, the coagulation–flocculation–sedimentation (CFS) process has emerged as a widely adopted and practical approach for MPs and NPs removal from aquatic systems, owing to its operational simplicity, high removal efficiency and economic aspects (Gao and Liu 2022). In this method, tailored coagulants and/or flocculants are introduced into contaminated water under optimized stirring conditions and durations, facilitating the aggregation of dispersed MPs and NPs particles into larger, settleable flocs through various entrapment mechanisms, depending on the nature of the coagulant and flocculant used (Nabi et al. 2022). These aggregated flocs, containing MPs and NPs, subsequently settle by gravity and are readily separated from the treated effluent (Chandra and Walsh 2024). Commonly employed coagulants such as aluminum sulfate (alum), iron chloride, polyaluminum chloride (PAC), polyaluminum ferric chloride (PAFC), as well as flocculants such as polyacrylamide (PAM), polysilicic acid (PSA), have been demonstrated to successfully remove MPs and NPs with varying degree of efficiency through mechanisms such as charge neutralization, sweep flocculation and adsorption bridging (Ali et al. 2023). The adaptability and stability of the CFS process make it a promising component of integrated strategies for plastic pollution control in water treatment systems.

Despite their widespread use, aluminum- and iron-based coagulants have several drawbacks that limit their long-term applicability in water treatment processes. These chemical coagulants have been associated with (1) the presence of residual metals in treated water, which can lead to undesirable effects such as discoloration (in the case of iron) (Owodunni and Ismail 2021) and linked to Alzheimer's disease (in the case of aluminum exposure) (Dey and Singh 2022); and (2) the generation of large volumes of metal-containing sludge, requiring proper handling and disposal strategies (Nayeri and Mousavi 2022). In this context, substituting conventional chemical coagulants and flocculants with natural-based alternatives is appealing as it eliminates the risks associated with metal residues and sludge toxicity (Diver et al. 2023). Natural-based coagulants and flocculants are typically abundant in nature, biodegradable and require minimal processing, thereby enhancing sustainability and reducing the overall operational costs of the CFS process (Badawi et al. 2023). In recent years, the utilization of natural-based coagulants and flocculants for MPs and NPs removal has been reported in a limited number of studies; therefore, their potential remains underexplored. A deeper understanding of their mechanisms, efficacy and scalability is thus critical in selecting appropriate bio-based materials for their implementation in plastic pollution remediation.

Similar to conventional coagulants and flocculants, the efficiency of MPs and NPs removal via the CFS process using natural-based materials is significantly influenced by various operational parameters, e.g., pH, stirring speed and duration, type and dosage of coagulants/flocculants, the presence of interfering substances and the physicochemical characteristics of MPs and NPs particles (concentration, size, and polymer type) (Chen et al. 2022; Ojha et al. 2024). Optimizing these parameters is crucial, as deviations can alter floc formation, aggregation mechanisms and particle stability, eventually lowering removal efficiency (Tijjani Usman et al. 2023). Unlike conventional chemical coagulants and flocculants, natural-based materials exhibit substantial variability in their chemical compositions, charge densities, and molecular structures, which govern their interactions with MPs and NPs particles (Kurniawan et al. 2022). This implies that standardizing the application of natural-based materials across different treatment scenarios is challenging. Therefore, comprehensive characterization of the coagulation behavior of individual natural-based materials under varying conditions is essential to ensure consistent performance and facilitate their integration into water treatment systems.

The current study provides a comprehensive systematic review of the application of natural-based coagulants for the removal of MPs and NPs from aqueous environments via the CFS method. Previous systematic reviews on CFS have primarily focused on chemical or synthetic coagulants, whereas this review specifically emphasizes the removal efficiency and underlying mechanisms of natural-based coagulants. To ensure transparency, rigor and reproducibility in the selection of relevant literature, this review adheres to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines. The structure of this review comprises multiple sections, including an overview of various natural-based coagulants and their respective performances, proposed mechanisms, current key challenges and limitations, and future research directions. Ultimately, this review aims to identify critical knowledge gaps and provide a perspective on the potential of natural-based coagulants in advancing sustainable water treatment technologies and supporting environmental sustainability goals.

Methodology

Systematic reviews serve as a critical methodology for objectively assessing published studies to produce comprehensive, evidence-based conclusions. Several systematic reviews have been published in the context of MPs and NPs removal via the CFS method; however, these studies primarily focus on the use of chemical and synthetic coagulants. To date, only one known review has addressed natural-based coagulants; however, its primary emphasis was on prospective applications and future perspectives based on their performance in removing other pollutants rather than a focused evaluation of their efficacy in MPs and MPs removal. This highlights a significant gap and the need for a dedicated systematic review that rigorously examines the use of natural-based coagulants for the CFS treatment of plastic pollutants in aquatic environments.

The preferred reporting items for systematic reviews and meta-analyses (PRISMA) framework was adopted in this study for its ability to ensure objectivity, transparency, and reproducibility in systematic reviews. The PRISMA methodology's key stages comprise identification, screening, retrieval, eligibility assessment and inclusion criteria, which provide a comprehensive and targeted literature search. This structured approach is highly valuable for emerging research fields like MPs and NPs removal via the CFS method using natural-based coagulants. Utilizing PRISMA also enables future researchers to replicate, validate and build upon its findings. The methodology employed in this review is summarized in Fig. 1, with detailed descriptions of each step provided in the subsequent sections.

Identification

A comprehensive literature search was conducted across three major academic databases: Scopus, Web of Science (WoS) and PubMed. The final search was performed on 12 March 2025, employing Boolean operators to refine results and ensure extensive coverage of studies on the coagulation–flocculation of MPs and NPs using natural-based materials. The specific search strings used for each database are presented in Table 1. To account for variations in terminology (e.g., "microplastics" vs. "micro-plastics", "biocoagulant" vs. "bio-coagulant"), etc., wildcard operators '*' were included in the search terms, e.g., "micro*plastics", "bio*coagulant", etc., to maximize inclusion of relevant literature. Note that PubMed restricts the use of wildcards to terms with at least four preceding letters; therefore, the term "biocoagulant" was used without truncation in that database to maintain search validity.

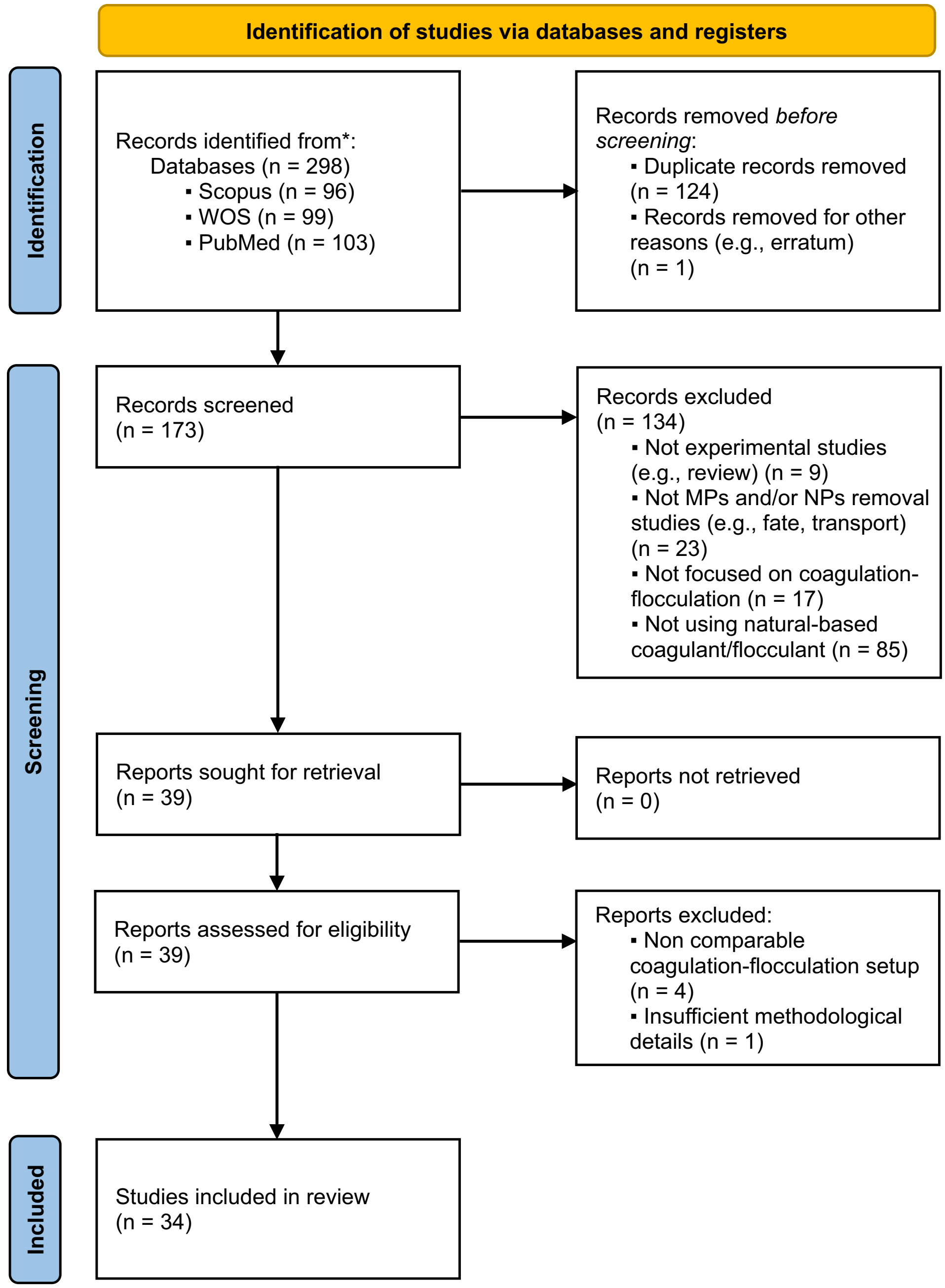
To ensure this review includes the most recent advancements in this field, only peer-reviewed publications from 2020 to 2025 were considered. This timeframe was selected based on the observation that applying natural-based remediators in MPs and NPs coagulation–flocculation gained considerable research traction only in recent years. Only peer-reviewed articles and conference proceedings published in English were considered, while review articles were excluded from the search results. At this initial stage, a total of 298 records were retrieved from the database search. These records were subsequently subjected to manual sorting for reference management and deduplication. Following deduplication, 124 duplicates were omitted, along with a correction notice (erratum), leaving 173 records for further screening and eligibility assessment.

Screening

Following the identification stage, the titles and abstracts of 173 articles were carefully screened based on predefined inclusion and exclusion criteria. Studies were excluded if they met any of the following conditions: (1) did not focus on MPs and/or NPs removal, e.g., study on fate and transport, (2) investigated MPs and NPs removal using methods other than coagulation–flocculation, (3) employed non-natural (synthetic or chemical-based) coagulants or flocculants, or (4) misclassified as original research articles but were, in fact, review articles. Based on these criteria, 134 records were removed. For this review, all studies employing natural-based coagulants and flocculants were included, regardless of the experimental matrix; however, it should be noted that the majority of studies used artificially spiked MPs and/or NPs systems, whereas only a few employed samples derived from natural or environmental waters.

Following the exclusion, the remaining 39 records that met the initial inclusion criteria were retrieved to confirm full-text accessibility. Although some articles were behind paywalls or were out of institutional access, all 39 reports were successfully retrieved and assessed for eligibility prior to inclusion in the systematic review. Full-text articles of the retrieved records were further assessed and excluded on the following criteria: (1) use of incomparable coagulation–flocculation setups, e.g., stirring using vortex mixers, absence of distinct rapid and slow mixing stages, etc., (2) insufficient methodological details that prevent reproducibility, and (3) studies limited to theoretical modelling without experimental validation. The final selection of studies was determined

Fig. 1 PRISMA flow diagram for identification, screening and eligibility selection of related reports



through consensus among the authors, with any disagreements resolved through discussion. Ultimately, 34 studies were deemed eligible and included in this systematic review.

Data extraction and analysis

The 34 included studies were rigorously analyzed by the authors based on key parameters relevant to MPs and NPs removal via coagulation–flocculation with natural-based coagulants or flocculants. Data extraction was conducted using a standardized form by capturing critical details such as coagulant type, experimental conditions (e.g., water matrix, MPs and NPs size and polymer type, and MPs and NPs concentration), process-influencing factors (pH, coagulant/flocculant dosage, mixing speed and duration), removal efficiency, and the proposed removal mechanisms. The studies were classified based on the application method of the coagulant: (1) unmodified natural coagulants, (2) chemically modified natural coagulants, (3) natural coagulants used as coagulant aids. The extracted data were quantitatively synthesized to identify trends within and between categories and to highlight existing knowledge gaps. Quantitative data, such as removal performance, were extracted where available; nonetheless, a formal meta-analysis was not performed due to the different

Table 1 Search string and filter applied for the identification of records

Database	Search filed	Search string
Scopus	Title, abstract, keyword	(micro*plastics OR nano*plastics) AND (removal OR elimination) AND (coagulation OR flocculation) AND (coagulant OR flocculant OR natural coagulant OR bio*coagulant)
Web of Science	All field	
PubMed	All field	(micro*plastics OR nano*plastics) AND (removal OR elimination) AND (coagulation OR flocculation) AND (coagulant OR flocculant OR natural coagulant OR biocoagulant)
Filter applied		
Year	2020–2025	
Language	English only	
Article type	Research articles and conference proceedings only (review articles excluded)	

methodologies used across the studies (e.g., differences in quantification approaches such as turbidity measurements or spectroscopy-based techniques). The findings were integrated to provide insights into the effectiveness and limitations of natural-based coagulants, as well as future research directions for their application in MPs and NPs remediation.

Results and discussion

List of included studies

A total of 34 studies centered on the current state of MPs and NPs removal via the CFS method using natural-based materials were identified and included in this systematic review, following PRISMA guidelines. Table 2 summarizes these studies, with their respective database sources, and is arranged in descending order by year of publication to highlight recent advancements.

More than one-third of the included studies were retrieved from a single database, suggesting that searching multiple databases is essential to ensure comprehensive coverage of the relevant literature. Although the search was conducted for publications within the 2020–2025 window, no eligible studies were published in 2020. However, there is a clear upward trend in research interest in this topic, with 15 studies reported in the most recently completed year (2024) and 7 published within the first two months of the current year (2025). This growing number of studies on MPs and NPs removal using natural-based materials via the CFS method reflects the increasing attention on this emerging topic. The findings from these 34 studies are critically and systematically reviewed in the present article.

Classification of natural-based coagulants/flocculants

Based on the studies in this systematic review, natural-based coagulants/flocculants were classified according to their biological origin: plant, animal or microbial. These materials were further categorized by their application strategies in the CFS processes: (1) as unmodified natural coagulants that are substitutes for conventional chemical coagulants, (2) as chemically modified natural coagulants that are substitutes for conventional chemical coagulants, aiming to enhance performance, (3) as coagulant aids used in conjunction with conventional chemical coagulants, and (4) as chemically modified coagulant aids. The reviewed studies investigated the removal of various MPs and NPs composed of various polymer types, including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyamide (PA), polyester (PES), polyacrylonitrile (PAN), polymethyl methacrylate (PMMA), polyphenylene sulfide (PPS), and polyisobutylene (PIB), indicating the applicability of natural-based coagulants across a broader range of plastic pollutants.

Plant-derived

Plant-based coagulants/flocculants are the most extensively reported in studies of MPs and NPs removal via the CFS process, mainly due to their wide variety, cost-effectiveness and natural abundance in the environment. These plant-based materials are employed in the CFS process in two ways: (1) direct application in powdered form, with or without chemical modification, or (2) extraction of coagulative compounds, e.g., proteins, which are then employed as the active coagulant. Figure 2 shows several plant-based materials investigated for MPs and NPs removal through the CFS method, while Table 3 summarizes the types of

Table 2 List of included studies based on the proposed search criterion

No.	Article	Database			References
		Scopus	WOS	PubMed	
1.	Tailored cellulose-based flocculants for microplastics removal: mechanistic insights, pH influence, and efficiency optimization		✓		Magalhães et al. (2025)
2.	Utilization of chitosan as a natural coagulant for polyethylene microplastic removal	✓			Prasetyo et al. (2025)
3.	Fibrous super-bridging agents simultaneously improve contaminants removal and sludge dewatering via a very compact three-in-one process		✓		Mebarki et al. (2025)
4.	Greener microplastics removal: progressive replacement of iron-based coagulants with sodium alginate and chitosan to enhance sustainability	✓	✓	✓	Facchino et al. (2025)
5.	Assessment and treatment of microplastics in different environmental compartments of Kallar Kahar Lake—a case study			✓	Tabinda et al. (2025)
6.	Rhamnolipid: nature-based solution for the removal of microplastics from the aquatic environment			✓	Sönmez et al. (2025)
7.	Removal of microplastics by algal biomass from aqueous solutions: performance, optimization, and modeling			✓	Lotfigolsefidi et al. (2025)
8.	Optimizing biocoagulant aid from shrimp shells (*Litopenaeus vannamei*) for enhancing microplastic removal from aqueous solutions	✓	✓		Eamrat et al. (2024)
9.	Coagulative removal of polyethylene microplastics using polyaluminum chloride in conjunction with laminarin	✓	✓		Chen et al. (2024b)
10.	Removal of pristine and UV-weathered microplastics from water: *Moringa oleifera* seed protein as a natural coagulant	✓	✓		Panigrahi et al. (2024)
11.	Behaviour of *M. aeruginosa*–microplastic composite pollutants in coagulation and sludge storage	✓		✓	Yu et al. (2024)
12.	Insights on microplastic contamination from municipal and textile industry effluents and their removal using a cellulose-based approach		✓	✓	Magalhães et al. (2024)
13.	Microplastic removal using Okra (*Abelmoschus esculentus*) seed from aqueous solutions	✓	✓		Eydi Gabrabad et al. (2024a)
14.	Enhanced removal of polystyrene microplastics through coagulation using polyaluminum ferric chloride with Opuntia Milpa Alta particles	✓	✓		Zhang et al. (2024)
15.	Efficient, quick, and low-carbon removal mechanism of microplastics based on integrated gel coagulation-spontaneous flotation process	✓	✓	✓	Li et al. (2024)
16.	Enhancing the coagulation process for the removal of microplastics from water by anionic polyacrylamide and natural-based *Moringa oleifera*	✓		✓	Avazpour and Noshadi (2024)
17.	Coagulative removal of polystyrene microplastics from aqueous matrices using $FeCl_3$-chitosan system: experimental and artificial neural network modeling			✓	Raj et al. (2024)
18.	Efficacy of bacterial cellulose hydrogel in microfiber removal from contaminated waters: a sustainable approach to wastewater treatment		✓	✓	Rodrigues et al. (2024)
19.	Using *Spirulina platensis* as a natural biocoagulant for polystyrene removal from aqueous medium: performance, optimization, and modeling			✓	Eydi Gabrabad et al. (2024b)
20.	A novel hydrophobic chitosan-polyaluminum chloride composite flocculant for effectively simultaneous removal of microplastic and antibiotics composite pollution		✓		He et al. (2024)
21.	Enhanced removal of polyethylene microplastics from water through polymeric ferric sulfate with laminarin	✓	✓		Chen et al. (2024a)
22.	Sustainable production of bacterial flocculants by nylon-6,6 microplastics hydrolysate utilizing *Brucella intermedia* ZL-06		✓	✓	Zhao et al. (2024)
23.	Enhancing the removal efficiency of microplastics in drinking water treatment	✓	✓		Tang et al. (2024)
24.	Investigating the efficiency of oak powder as a new natural coagulant for eliminating polystyrene microplastics from aqueous solutions			✓	Esmaeili Nasrabadi et al. (2023b)
25.	Utilizing *Chlorella vulgaris* algae as an eco-friendly coagulant for efficient removal of polyethylene microplastics from aquatic environments	✓	✓	✓	Esmaeili Nasrabadi et al. (2023a)
26.	Removal of microplastics from water by coagulation of cationic-modified starch: an environmentally friendly solution	✓	✓	✓	Gao et al. (2023)

Table 2 (continued)

No.	Article	Database			References
		Scopus	WOS	PubMed	
27.	Use of *Saccharomyces cerevisiae* as new technique to remove polystyrene from aqueous medium: modeling, optimization, and performance		✓		Zahmatkesh Anbarani et al. (2023)
28.	Chitosan enhances poly aluminum chloride flocculation system removal of microplastics: effective, stable, and pollution free		✓		Huang et al. (2023)
29.	Fiber-based super-bridging agents enable efficient contaminant removal via settling and screening: impact on microplastics, textile fibers, and turbidity	✓	✓		Alioua and Lapointe (2023)
30.	Evaluation of the nanoplastics removal by using starch-based coagulants: roles of the chain architecture and hydrophobicity of the coagulant	✓	✓		Hu et al. (2023)
31.	Removal of classical and emerging contaminants in water treatment using super-bridging fiber-based materials	✓			Lapointe et al. (2023)
32.	Efficient removal of nano- and micro-sized plastics using a starch-based coagulant in conjunction with polysilicic acid	✓	✓	✓	Hu et al. (2022)
33.	Super-bridging fibrous materials for water treatment	✓	✓		Lapointe et al. (2022)
34.	Sustainable removal of microplastics and natural organic matter from water by coagulation–flocculation with protein amyloid fibrils		✓	✓	Peydayesh et al. (2021)

Fig. 2 Examples of plant-based materials studied for coagulative removal of MPs and NPs

plant-derived coagulants/flocculants reported in the literature, along with the types of MPs and NPs studied and the corresponding maximum removal efficiencies. When natural materials were employed as coagulant aids, the accompanying conventional coagulants are included and denoted in italics.

The utilization of plant-derived materials alone for the coagulative removal of MPs was reported in three studies, using okra seed, *Moringa oleifera* seed extract and oak powder (Esmaeili Nasrabadi et al. 2023b; Avazpour and Noshadi 2024; Eydi Gabrabad et al. 2024a). Among these, the first two materials attained an average MPs removal efficiency below 70%, indicating the limitations of unmodified plant-based coagulants. On the contrary, oak powder exhibited a relatively higher removal efficiency, which can be attributed to the larger MPs particle size utilized in the study, allowing for more effective interaction with the natural coagulant. Chemical modifications of plant-based materials such as starch and cellulose were also investigated; however, these modifications generally did not lead to significant enhancement of the performance. Similar removal efficiencies were reported even with larger MPs particles, suggesting that chemical enhancement may not always enhance coagulation performance. Applying plant-derived material as a coagulant aid, in combination with conventional coagulants, is identified as the most effective approach, as several studies have reported removal efficiencies exceeding 90%. This trend is further demonstrated in Table 3, where the majority of studies (14 out of 29) employing plant-derived materials as coagulant aids showed higher performance compared to other application strategies.

The enhanced removal performance observed when plant-derived materials are applied as coagulant aids can be ascribed to their ability to promote the formation of larger flocs, which facilitate interactions and the subsequent settling of MPs and NPs particles. For instance, Zhang et al.

Table 3 Application strategies of plant-derived materials for MPs and NPs removal via the CFS method

Coagulants/Flocculants	Dosage (mg/L)	MPs or NPs type	MPs or NPs concentration (g/L)	Treatment time	Removal (%)	References
Unmodified, complete substitutes for conventional coagulants						
Okra seed	10–70	PS (< 100 µm), PVC (< 85 µm)	0.02–0.1	RS = 150 rpm, 3 min SS = 20 rpm, 20 min SE = 1 min	PS = 64.76 PVC = 80.11	Eydi Gabrabad et al. (2024a)
Moringa oleifera seed extract	40–240	PA, PS, PE (< 500 µm)	0.2	RS = 300 rpm, 1.5 min SS = 40 rpm, 10 min SE = 45 min	PA = 67.25 PS = 57.60 PE = 15.68	Avazpour and Noshadi (2024)
Oak powder	100–400	PS (300–850 µm)	0.1–0.9	RS = 400 rpm, 1 min SS = 100 rpm, 15 min SE = 30 min	89.1	Esmaeili Nasrabadi et al. (2023b)
Chemically modified, complete substitutes for conventional coagulants						
Cationic and hydrophobic cellulose	500–10000	PET (< 0.25 mm)	0.1	RS = 550 rpm, 15 min SS = 200 rpm, 30 min SE = 30 min	79.53	Magalhães et al. (2025)
Cationic cellulose from Eucalyptus wood waste pulp	0.01	PET (< 200 µm)	0.5	RS = 1000 rpm, 10 min SS = 500 rpm, 60 min SE = N/a	-	Magalhães et al. (2024)
Modified starch	1–5	PE (< 6.5–106 µm)	0.00005–0.01	RS = 198 s^{-1}, 1 min SS = 40 s^{-1}, 14 min SE = 30 min	30.50	Tang et al. (2024)
Modified starch	0–180	PE, PVC, PET, PP (150 µm), PS (75–1500 µm), UV-weathered	0.5	RS = 500 rpm, 1 min SS = 200 rpm, 14 min SE = 30 min	62.43	Gao et al. (2023)
Coagulant aids						
Cellulose fiber + *alum, PAM*	0–250	PS (28 nm), PES (840 µm), PE (140 µm)	PS = 0.0008 PES, PE = 1000 MP/L	SMS = 200 rpm, 2 min SE = 30 min	PS = 72 PES = 95 PE = 91	Mebarki et al. (2025)
Potato starch + *alum, $FeCl_3$*	12.5–22.5	PET, PPS, PIB	37–65 MPs/500 mL	RS = 250 rpm, 2 min SS = 100 rpm, 13 min SE = 60 min	PET = 80 PPS = 74 PIB = 71	Tabinda et al. (2025)
Laminarin + *PAC*	0–40	PE (50–150 µm)	0.1 g (d.w.)	RS = 300 rpm, 1 min SS = 70 rpm, 10 min SE = 30 min	91.5	Chen et al. (2024b)
Moringa oleifera protein + *sand, PAM*	0.75–10	PE (Pristine: 35–50 µm, UV-weathered: 40.6 µm)	0.5	RS = 240 rpm, 2 min SS = 70 rpm, 10 min SE = 1 min	66.18–69.45	Panigrahi et al. (2024)

Table 3 (continued)

Coagulants/Flocculants	Dosage (mg/L)	MPs or NPs type	MPs or NPs concentration (g/L)	Treatment time	Removal (%)	References
Opuntia Milpa Alpa cactus + *PAFC*	5–20	PS (2–10 µm)	0.1	RS = 200 rpm, 1 min SS = 90 rpm, 25 min SE = 30–60 min	94.84	Zhang et al. (2024)
Laminarin + *PAC, PAFC*	6–24	PP (10–300 µm), PS (50–800 µm), PET (1–300 µm), UV-weathered	0.01–0.05	RS = 200 rpm, 30 min SS = 500 rpm, 15 min SE = 10 min	79–96	Li et al. (2024)
Moringa oleifera seed extract + *aluminum sulfate*	40–240	PA, PS, PE (< 500 µm)	0.2	RS = 300 rpm, 1.5 min SS = 40 rpm, 10 min SE = 45 min	PA = 92.99 PS = 80.48 PE = 28.94	Avazpour and Noshadi (2024)
Laminarin + *polymeric ferric sulfate*	0–20	PE (< 50–500 µm)	0.1 g (d.w.)	RS = 300 rpm, 1.5 min SS = 70 rpm, 10 min SE = 30 min	93.8	Chen et al. (2024a)
Modified starch + *PAC, PAM*	1–5	PE (< 6.5–106 µm)	0.00005–0.01	RS = 198 s^{-1}, 1 min SS = 40 s^{-1}, 14 min SE = 30 min	80.13	Tang et al. (2024)
Tannic acid + *PAC*	0–100	PET, PE, PVC, PS, PP (< 100–500 µm)	0.1 g (d.w.)	RS = 300 rpm, 0.5 min SS = 50 rpm, 10 min SE = 30 min	~ 10–65	Huang et al. (2023)
Cellulosic fiber from recycled paper + *alum, PAM*	50–500	PE (15–140 µm), PES fiber (837 µm)	–	RS = 110 rpm, 1 min SS = 110 rpm, 1 min SE = 10 s–3 min	78–80	Alioua and Lapointe (2023)
Modified starch + *polysilicic acid*	0–3.25	PS, PMMA, PVC (500 nm)	0.008	RS = 300 rpm, 4 min SS = 50 rpm, 12 min SE = 30 min	PS = 94.38 PMMA = 95.45 PVC = 96.84	Hu et al. (2023)
Modified starch + *polysilicic acid*	0–2.5	PS (100 nm–5 µm)	0.008	RS = 300 rpm, 5 min SS = 50 rpm, 12 min SE = 30–60 min	88.03–97.07	Hu et al. (2022)
Cellulosic fiber from recycled paper, potato starch + *alum, PAM*	50–200	PE (15–140 µm), PS (200 nm)	500 MPs/L	RS = 300 rpm, 2 min SS = 150 rpm, 4 min SE = 5 s–5 min	> 80	Lapointe et al. (2022)
Chemically modified coagulantaids						
Sodium alginate + $FeCl_3$	0.2–2	PS (40 µm), PE & PET (20–500 µm)	0.3	RS = 500 rpm, 1 min SS = 90 rpm, 15 min SE = 30 min	PS = 89.53 PE = 90.77 PET = 95.53	Facchino et al. (2025)

Table 3 (continued)

Coagulants/Flocculants	Dosage (mg/L)	MPs or NPs type	MPs or NPs concentration (g/L)	Treatment time	Removal (%)	References
Sodium alginate, sodium carboxymethylcellulose + *PAC*	0–100	PET, PE, PVC, PS, PP (< 100–500 µm)	0.1 g (d.w.)	RS = 300 rpm, 0.5 min SS = 50 rpm, 10 min SE = 30 min	~ 15–90	Huang et al. (2023)
Fe-grafted cellulose fiber + *alum, PAM*	200	PS (20 nm), PES fiber (385 µm)	PS = 0.0008 PES = 1000 MPs/L	SMS = 110 rpm, 2 min SE = 0.5–3 min	79–99	Lapointe et al. (2023)

RS rapid stirring, *SS* slow stirring, *SMS* single mixing stage, *SE* settling, *d.w.* dry weight

(2024) reported that *Opuntia Milpa Alta* cactus was ineffective for MPs removal on its own, as its negatively charged surfaces electrostatically repelled MPs particles, leading to an increase in turbidity. However, applying these cactus particles with PAFC resulted in floc enlargement and higher adsorption of PS MPs onto various functional groups, e.g., hydroxyl and amino groups, leading to a greater removal efficiency than PAFC alone. The formation of larger flocs was more pronounced with fibrous cellulose-based materials, as demonstrated by several studies (Lapointe et al. 2022; Alioua and Lapointe 2023; Mebarki et al. 2025). When applied together with conventional coagulants like alum and polyacrylamide, these fibrous materials significantly increased floc size by a factor of 7–10, resulting in a decrease in the required coagulant dosage and allowing the produced flocs to be screened easily without the need for sedimentation. This approach not only enhances process efficiency but also reduces required coagulant dosage, thereby lowering the potential environmental and health risks associated with conventional metal-based coagulants. However, the removal performance achieved is inconsistent across different MPs and NPs polymer types, as shown in Table 3. This inconsistency presents a critical barrier in real-world applications, where wastewater streams typically comprise a complex mixture of plastic particles rather than a single type. Therefore, identifying plant-derived materials capable of efficiently eliminating a broad range of MPs and NPs types is essential to advance their integration into large-scale water and wastewater treatment systems.

Animal-derived

Among the natural-based coagulants investigated, animal-derived coagulants/flocculants are the least diverse category of materials utilized for MPs and NPs removal via the CFS method, with only chitosan and protein amyloid fibrils reported. Despite the limited variety, chitosan has emerged as the most widely studied animal-based material, with 7 studies demonstrating its applicability in removing MPs and NPs particles. Figure 3 shows the animal-derived materials employed in MPs and NPs coagulative removal via the CFS method. Table 4 summarizes their performance, including the types of MPs and NPs treated. As with plant-based materials, in cases where animal-based materials were used as coagulant aids, the associated conventional coagulants are italicized in Table 4.

Chitosan, derived from the acetylation product of chitin, is commonly extracted from crustacean shells (Huang et al. 2023). It is widely applied in MPs and NPs removal via the CFS method due to the presence of amino (-NH_2) groups, which confer a positive surface charge, promoting effective electrostatic interactions with negatively charged MPs and NPs particles (Raj et al. 2024). As summarized in Table 4, chitosan shows high versatility, demonstrating effective removal of MPs and NPs when used unmodified, chemically modified, or as a coagulant aid. When applied as a direct for conventional coagulants without modification, chitosan was capable of removing large-sized PE particles (34–50 µm), as reported by Prasetyo et al. (2025); nonetheless, the efficiency significantly dropped for smaller-sized particles, e.g., 1 µm PS (Raj et al. 2024). On the other hand, another animal-derived material, protein amyloid fibrils, synthesized from hen egg white lysozyme, was able to achieve 98.2% removal of smaller PS samples (500 nm). This highlights its superior performance in fine particle coagulation. Nonetheless, this material needs more elaborate preparation steps than the widely available chitosan, which can be used directly or with simple dissolution, making it less frequently used.

Chitosan has also been modified via quaternization and hydrophobization, in which the latter method achieved higher removal performance, conceivably due to enhanced hydrophobic interactions with hydrophobic MPs particles (He et al. 2024). When applied as a coagulant aid, chitosan has been reported to increase floc size, and due to its large specific surface area and strong adsorption capacity, its capability to capture MPs and NPs particles effectively increases (Eamrat et al. 2024). However, it should be emphasized that

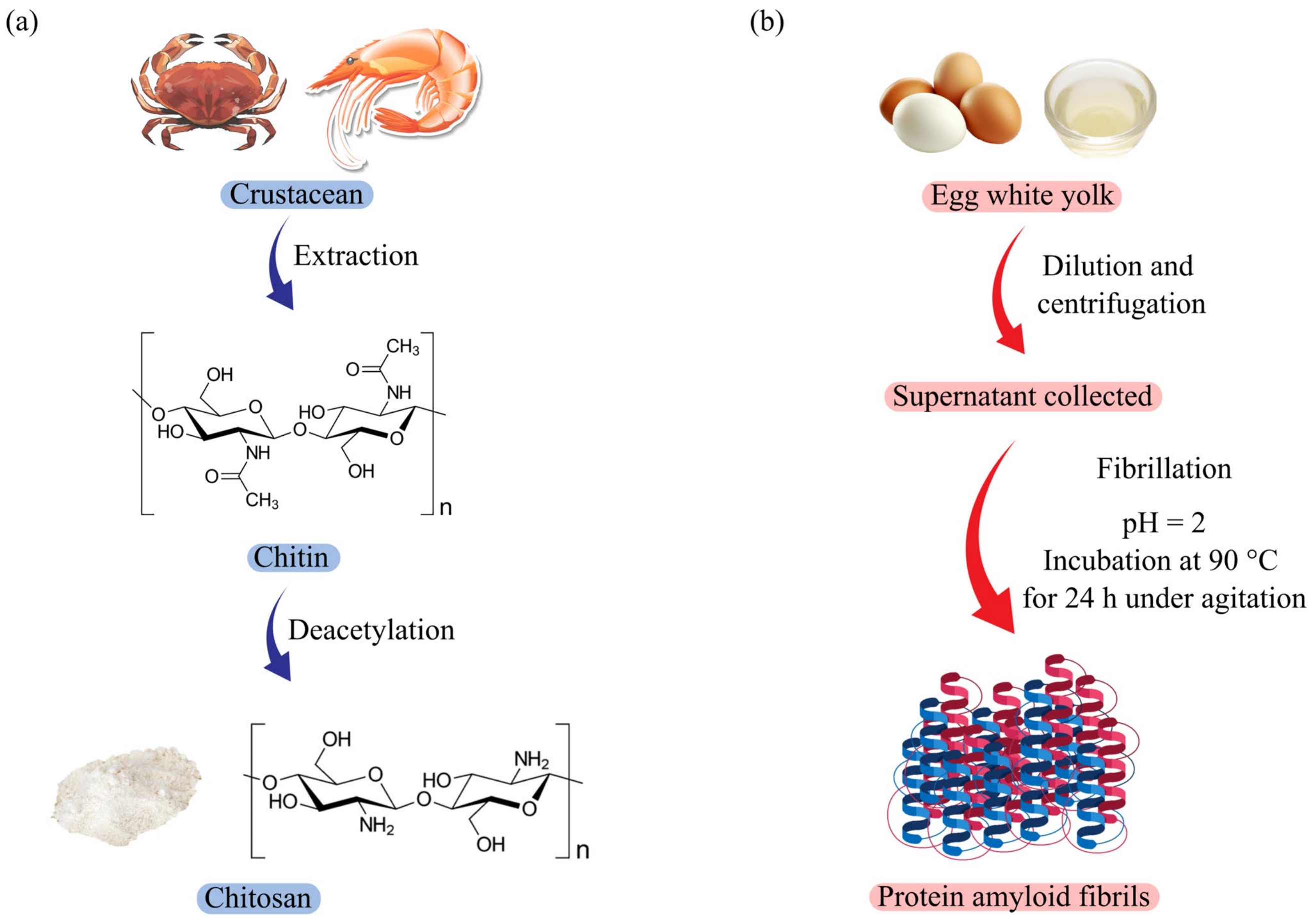


Fig. 3 Animal-based materials utilized for coagulative MPs and NPs removal **a** chitosan and **b** protein amyloid fibrils

its removal performance is highly dependent on the properties of the targeted MPs and NPs. For instance, Facchino et al. (2025) found that using chitosan in combination with iron chloride facilitated the removal of PS and PE MPs but was ineffective for PET removal. Similarly, Huang et al. (2023) reported that chitosan combined with PAC attained higher removal efficiencies for MPs particles in the intermediate size range (100–300 µm) across four of five types of MPs studied, with > 80% removal observed only for PET and PVC. Although chitosan shows considerable potential for MPs and NPs removal via the CFS method, its performance improves significantly when used as a coagulant aid in conjunction with conventional materials. Conversely, protein amyloid fibrils have shown promising removal efficiency as a substitute for conventional coagulants; however, as they have been used in only one study, further investigations are necessary to assess their applicability across different treatment systems.

Microbial-derived

Microorganisms, including bacteria, algae, and yeast, play essential roles in various ecosystems and have been increasingly explored for their potential in environmental remediation. In the context of MPs and NPs removal, several microbes have been specifically used for the coagulative removal of MPs and NPs. Table 5 summarizes the types of microbial-derived materials reported in MPs and NPs removal via the CFS method, along with the types of MPs and NPs studied and the highest removal efficiencies achieved. Where the microbes were employed as coagulant aids, the conventional coagulants used in combination with the material are indicated in italics for clarity.

Microbial-derived coagulants/flocculants have primarily been utilized either on their own, as substitutes for conventional coagulants or as coagulant aids, because chemical modification of microbes may significantly affect their functional properties or even compromise their viability. Among these, *Chlorella vulgaris* algae has been successfully applied in the treatment of various aquatic pollutants, including dyes and heavy metals (Wibowo et al. 2023) and stands out as

Table 4 MPs and NPs removal via the CFS method using animal-derived materials

Coagulants/Flocculants	Dosage (mg/L)	MPs or NPs type	MPs or NPs concentration (g/L)	Treatment time	Removal (%)	References
Unmodified, complete substitutes for conventional coagulants						
Chitosan	25–250	PE (34–50 µm)	0.2	RS = 250 rpm, 2 min SS = 60 rpm, 30 min SE = 60 min	81.5	Prasetyo et al. (2025)
Chitosan	0.25–5	PS (1 µm)	0.025	RS = 400 rpm, 1 min SS = 0–200 rpm, 15 min SE = 10–40 min	21.4	Raj et al. (2024)
Protein amyloid fibrils	0.1–62	PS (500 nm)	0.05	RS = 300 rpm, 5–10 min SS = 50 rpm, 15–20 min SE = 30 min	98.2	Peydayesh et al. (2021)
Chemically modified, complete substitutes for conventional coagulants						
Quaternized chitosan	0.125–2	PS (25 µm)	15–60	RS = 800 rpm, 2 min SS = 200 rpm, 20 min SE = 30 min	65	Yu et al. (2024)
Hydrophobic chitosan	5–30	PET (10 µm), pristine and aged	0–0.15	RS = 400 rpm, 1 min SS = 50 rpm, 15 min SE = 30 min	89.65	He et al. (2024)
Coagulant aids						
Chitosan + *$FeCl_3$*	0.2–2	PS (40 µm), PE & PET (20–500 µm)	0.3	RS = 500 rpm, 1 min SS = 90 rpm, 15 min SE = 30 min	PS = 85.08 PE = 85.65 PET = Low removal	Facchino et al. (2025)
Chitosan + *alum*	1–4	PE (0.09–1 mm)	0.04	RS = 150 rpm, 3 min SS = 40 rpm, 20 min SE = 30 min	92.13	Eamrat et al. (2024)
Chitosan + *$FeCl_3$*	0.5–0.9	PS (1 µm)	0.025	RS = 400 rpm, 1 min SS = 0–200 rpm, 15 min SE = 10–40 min	99.8	Raj et al. (2024)
Chitosan + *PAC*	0–100	PET, PE, PVC, PS, PP (< 100–500 µm)	0.1 g (d.w)	RS = 300 rpm, 0.5 min SS = 50 rpm, 10 min SE = 30 min	~ 30–90	Huang et al. (2023)
Chemically modified coagulant aids						
Hydrophobic chitosan + *PAC*	5–30	PET (10 µm), pristine and aged	0–0.15	RS = 400 rpm, 1 min SS = 50 rpm, 15 min SE = 30 min	99.9	He et al. (2024)

RS rapid stirring, *SS* slow stirring, *SE* settling, *d.w.* dry weight

the only microorganism investigated across multiple studies for MPs and NPs coagulative removal (Esmaeili Nasrabadi et al. 2023a; Lotfigolsefidi et al. 2025), demonstrating removal efficiencies of 74.62% and 84% of PS and PE MPs (both < 425 µm), respectively. The highest MPs removal efficiency was achieved with *Saccharomyces cerevisiae* yeast, with 98.81% removal of PS MPs (100 µm) (Zahmatkesh Anbarani et al. 2023). In the context of coagulant aids, Sönmez et al. (2025) reported the utilization of rhamnolipid extracted from *Pseudomonas aeruginosa* in combination with alum as the conventional coagulant. However, the removal performance achieved was weaker than that of other microbial-derived materials used without conventional coagulants, although the targeted MPs types differed. Among the three groups of natural-based coagulants and flocculants, microbial-derived materials demonstrate the strongest capability to remove MPs and NPs particles without the need for conventional coagulants. Nonetheless, these microbes require complex preparation methods, e.g., isolation, cultivation, identification, storage, etc., which complicate their application on a larger scale. Therefore, a comprehensive techno-economic analysis is essential before advancing their

Table 5 MPs and NPs removal via the CFS method using microbial-derived materials

Coagulants/Flocculants	Dosage (mg/L)	MPs or NPs type	MPs or NPs concentration (g/L)	Treatment time	Removal (%)	Reference
Unmodified, complete substitutes for conventional coagulants						
Chlorella vulgaris algae	50–400	PS (< 425 µm)	0.1–0.9	RS = 110 rpm, 2 min SS = 110 rpm, 0.5–8 min SE = 10–180 s	74.62	Lotfigolsefidi et al. (2025)
Bacterial cellulose *Komagataeibacter saccharivorans*	5:1–100:1 (w.w./d.w.)	PAN (20–50 µm)	1	SMS = 60–300 rpm, 5–30 min SE = 5–120 min	89.3	Rodrigues et al. (2024)
Spirulina platensis microalgae	50–250	PS (< 425 µm)	0.1–0.9	RS = 400 rpm, 1 min SS = 100 rpm, 15 min SE = 30 min	81	Eydi Gabrabad et al. (2024b)
Brucella intermedia ZL-06	0–250	Nylon 6–6 (10 µm), pristine and aged	0.025–0.2	SMS = 150 rpm, 30 min SE = 70 min	> 90	Zhao et al. (2024)
Chlorella vulgaris algae	50–200	PE (< 425 µm)	0.5	RS = 400 rpm, 1 min SS = 100 rpm, 15 min SE = 30 min	84	Esmaeili Nasrabadi et al. (2023a)
Saccharomyces cerevisiae yeast	100–300	PS (100 µm)	0.2–0.9	RS = 400 rpm, 1 min SS = 100 rpm, 15 min SE = 30 min	98.81	Zahmatkesh Anbarani et al. (2023)
Coagulant aids						
Rhamnolipid from *Pseudomonas aeruginosa + alum*	1–100	PVC (45 µm)	5	RS = 100 rpm, 1 min SS = 40 rpm, 30 min SE = 120 min	73.95	Sönmez et al. (2025)

RS rapid stirring, *SS* slow stirring, *SMS* single mixing stage, *SE* settling, *w.w.* wet weight, *d.w.* dry weight

employment as a conventional coagulant substitute in practical applications.

Comparison of conventional and natural-based coagulants/flocculants

A comparative assessment of MPs and NPs removal using conventional and natural-based coagulants/flocculants provides a foundation for evaluating recent advancements and challenges that influence their practical application in water and wastewater treatment. Conventional coagulants, e.g., alum, ferric salts, and synthetic polymers, are widely acknowledged for their high and predictable removal efficiency, frequently reported in the range of 80–99% under optimized conditions (Khan et al. 2023; Wiśniowska et al. 2024), enabling their widespread application in full-scale water treatment plants. In contrast, natural-based coagulants/flocculants, as discussed in the preceding sections, have demonstrated good removal performance comparable to conventional coagulants, in some cases exceeding 70–98%, particularly in controlled or simplified water matrices. However, their effectiveness remains highly dependent on material compositions, extraction methods, and experimental conditions. Table 6 summarizes the comparison between conventional and natural-based coagulants, highlighting both their performance and key operational conditions (Badawi et al. 2023; Diver et al. 2023).

A key advantage of natural-based alternatives is their tendency to generate lower volumes of biodegradable and less toxic sludge, which reduces concerns about metal-rich residues commonly associated with conventional coagulants (Ali et al. 2025). Moreover, natural coagulants often exhibit broader pH tolerance and, in certain cases, reduced sensitivity to pH adjustment compared to metal salts, although performance variability remains a challenge (Badawi et al. 2023). From an economic perspective, natural-based coagulants/flocculants can be cost-effective when derived from locally available biomass; however, challenges associated with standardization of extraction methods and scalability to industrial applications continue to constrain their consistent performance under real-world conditions (Koul et al. 2022). It should be noted that most studies used synthetic water matrices spiked with MPs and/or NPs particles, which may overestimate removal efficiencies compared to environmentally derived samples due to reduced matrix complexity. Therefore, future studies should prioritize evaluations

Table 6 Comparison between conventional and natural-based coagulants

Aspect	Conventional coagulants	Natural-based coagulants
Example	Alum, ferric salts, synthetic polymers	Chitosan, *Moringa oleifera* etc
Performance consistency	High and predictable across water types	Good performance, varied depending on source, extraction and water matrix
Sludge characteristics	Higher volume of metal-rich sludge, requires regulated disposal	Lower volume, biodegradable, lower toxicity
Toxicity and residuals	Possible metal (Al/Fe) and polymer monomer residuals	Low chemical toxicity, may introduce organic load
pH sensitivity	Strongly pH-dependent, often requiring pH adjustment	Some possess broader pH tolerance
Cost and availability	Low cost, widely available, industrially standardized	Low cost using biomass requires supply and standardization
Scalability	Fully established for large-scale use	Mostly lab- and pilot-scale, limited regulatory acceptance

under environmentally relevant conditions to better predict field-scale performance. Nonetheless, the comparison presented herein highlights both the potential and the current limitations of natural-based coagulants, emphasizing the need for deeper mechanistic understanding and standardized evaluation frameworks to facilitate their transition from laboratory-scale studies to practical water treatment applications.

Removal mechanism

The removal mechanisms of MPs and NPs using natural-based materials via the CFS method are similar to those observed with conventional inorganic metal-based coagulants, comprising charge neutralization, electrostatic patching, adsorption bridging, sweep flocculation and netting-bridging. A schematic illustration of these mechanisms is shown in Fig. 4 and further elaborated in the following subsections.

Charge neutralization and electrostatic patching

The removal of MPs and NPs particles in the CFS process mainly relies on electrostatic interactions between the plastic particles and the coagulants/flocculants employed. Two key removal mechanisms governed by electrostatic interactions are charge neutralization and electrostatic patching. These interactions are possible as the MPs and NPs particles are typically negatively charged, including PS, PE, PP, PA, PVC, PMMA, and PAN (Gao et al. 2023; Hu et al. 2023; Avazpour and Noshadi 2024; Rodrigues et al. 2024), while the coagulants/flocculants commonly carry a positive charge, as evidenced by zeta potential measurements (Li et al. 2024; Sönmez et al. 2025). In the charge neutralization mechanism, positively charged coagulants/flocculants neutralize the negative surface charges on MPs and NPs particles, leading to electrostatic destabilization and allowing the particles to aggregate through the van der Waals forces, forming flocs with an overall charge approaching zero (Avazpour and Noshadi 2024). On the other hand, the electrostatic patching mechanism occurs when coagulants are adsorbed non-uniformly onto the plastic particles, forming an anisotropic distribution of surface charges (Hu et al. 2022). The flocculation process occurs as positively and negatively charged surface patches on different particles attract each other at their local microregions, promoting aggregation and efficient removal. Unlike charge neutralization, complete surface charge neutralization is not achieved during electrostatic patching, as the particles retain a partial net charge (Hu et al. 2023).

Most studies in this review indicated that charge neutralization plays a predominant role in the removal of MPs and NPs by natural-based coagulants/flocculants. For unmodified natural-based materials applied as direct substitutes for conventional coagulants, such as okra seed, *Moringa oleifera*, and protein amyloid fibrils, complete neutralization of the negative surface charge on MPs and NPs particles has been reported (Peydayesh et al. 2021; Avazpour and Noshadi 2024; Eydi Gabrabad et al. 2024a). In the case of chemically modified natural-based coagulants/flocculants, such as modified cellulose, starch, and chitosan, the removal process was predominantly characterized by electrostatic patching (Hu et al. 2022; He et al. 2024; Magalhães et al. 2024). These findings suggest that natural-based materials, whether unmodified or chemically modified, exhibit a charge neutralization capacity comparable to conventional coagulants, e.g., alum, PAC, $FeCl_3$, etc., although with varying degrees of effectiveness. In both cases, the materials contribute to the compression of the electrical double layer surrounding MPs and NPs particles, thereby reducing electrostatic repulsion and promoting particle destabilization, aggregation, and subsequent sedimentation (Huang et al. 2023).

The use of conventional coagulants enables efficient removal of MPs and NPs particles, primarily due to the cationic strength of hydrolysates produced by inorganic metal coagulants. Natural-based materials acting as coagulants facilitate removal through two different pathways. First, coagulant aids such as chitosan and sodium alginate, which

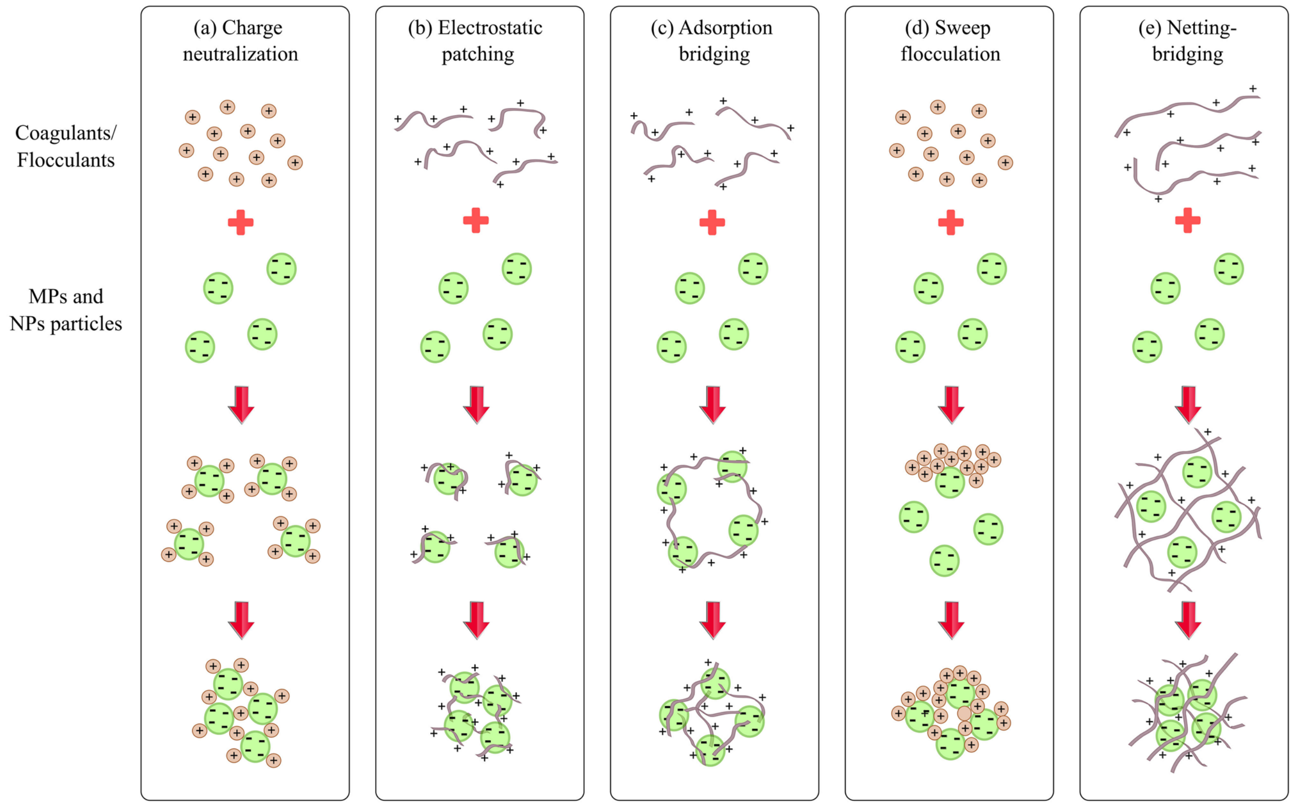


Fig. 4 MPs and NPs removal mechanism via the CFS method

carry a positive charge, assist metal-based coagulants in neutralizing the negatively charged MPs and NPs particles, following the mechanisms previously described (Eamrat et al. 2024; Facchino et al. 2025). Second, in cases where conventional coagulants result in the formation of partially positively charged flocs, the introduction of natural-based coagulant aids, e.g., laminarin, can further adjust the zeta potential towards neutrality, thereby achieving nearly complete neutralization (Chen et al. 2024a, b).

It should be emphasized that although charge neutralization and electrostatic patching are widely recognized as the primary removal mechanisms governing MPs and NPs removal by natural-based coagulants/flocculants, they are not the sole pathways influencing removal efficiency. Other mechanisms should also be carefully considered, as multiple factors may concurrently contribute to the overall removal efficiency. Additionally, some articles have misinterpreted the dominant removal mechanism, incorrectly attributing charge neutralization as the primary mechanism when the electrostatic patching mechanism would better explain the observed results. This misclassification often arises when researchers observe a decrease in the magnitude of the zeta potential measured between the MPs and NPs particles before treatment and in the flocs formed after the CFS removal process, despite the final zeta potential not reaching an absolute or near-zero value, which indicates charge neutralization. Nonetheless, both mechanisms play an effective role in coagulation studies, and it is imperative that future studies properly determine the appropriate mechanism based on the coagulant type and charge density of the materials utilized to ensure an understanding of the removal processes involved.

Adsorption bridging

Adsorption bridging is a key mechanism of MPs and NPs removal via the CFS method, in which natural-based coagulants/flocculants establish intermolecular interactions with plastic surfaces, acting as physical bridges that link particles and induce aggregation. This mechanism is commonly reported for hydrophobic polymers such as PE and PP and aromatic polymers such as PS (Gao et al. 2023; Huang et al. 2023), which occurs through the extension and adsorption of polymeric chains or functional groups on the coagulants/flocculants molecules onto MPs and NPs surfaces. Natural-based materials rich in polysaccharides, proteins, or other coagulative compounds typically carry functional groups such as hydroxyl (–OH), carboxyl (–COOH), and amine (–NH_2), which enable interaction with MPs and NPs particles primarily through hydrogen bonding (Zahmatkesh

Anbarani et al. 2023; Zhao et al. 2024). Additionally, adsorption may also occur via van der Waals forces and hydrophobic interactions, facilitated by the non-polar segments of natural-based compounds and the inherently hydrophobic nature of plastic particles (Hu et al. 2023; Avazpour and Noshadi 2024; Eamrat et al. 2024; Magalhães et al. 2025). In the case of weathered MPs and NPs, although the aging process often increases particle hydrophilicity and thus significantly weakens hydrophobic interactions, the formation of cracks, grooves, etc., on the surface of MPs and NPs particles substantially increases the specific surface area available for adsorption, enhancing aggregation (Chen et al. 2024a; Eydi Gabrabad et al. 2024a). It should be emphasized that the strength and efficiency of adsorption bridging are highly dependent on the specific natural-based material employed, as the nature and density of functional groups and polymeric substances influence interactions with MPs and NPs particles.

From the studies included in this review, the occurrence of the adsorption bridging mechanism can be identified and verified through three key analytical techniques: (1) scanning electron microscopy (SEM), (2) Fourier transform infrared spectroscopy (FTIR), and (3) X-ray photoelectron spectroscopy (XPS). In SEM analysis, adsorption bridging is evidenced by the formation of molecular bridges linking MPs and NPs particles or by the deposition of small coagulant particles on the surfaces of MPs and NPs, as demonstrated in surface micrographs across multiple studies (Raj et al. 2024; Zhang et al. 2024). FTIR analysis, which characterizes functional groups on material surfaces, can reveal adsorption bridging by comparing the spectra of MPs and NPs particles before and after the CFS process. The appearance of new peaks in the post-treatment spectra indicates the formation of new bonds between the coagulant and plastic surfaces, exemplified by Raj et al. (2024), who observed a new C–O–C bond formation in PS MPs-containing flocs, suggesting crosslinking between chitosan and the plastic particles. Conversely, the absence of a new peak, as reported by Facchino et al. (2025) for PS and PET MPs treated with $FeCl_3$ assisted by chitosan and sodium alginate, indicates that adsorption did not occur and that other mechanisms likely governed the removal. XPS provides further evidence of adsorption bridging, detecting characteristic elemental peaks, shifts in the binding energies of specific functional groups, and the appearance of new elements on the surface of treated plastics (Li et al. 2024; Zhao et al. 2024). These complementary techniques are essential in elucidating the underlying removal mechanisms in CFS-based MPs and NPs remediation studies.

Sweep flocculation

Sweep flocculation is a removal mechanism in the CFS process in which coagulants/flocculants form precipitates or polymeric matrices that physically entrap MPs and NPs particles, leading to their settling and removal from the solution. In conventional metal-based coagulants/flocculants, sweep flocculation occurs by forming metal hydroxide precipitates, which result from the hydrolysis of metal salts during coagulation (Huang et al. 2023). In contrast, natural-based coagulants/flocculants induce sweep flocculation primarily through their polymeric structure or gel-forming capabilities. These materials, rich in polysaccharides, proteins, and other biopolymers, can form dense, viscous, or gel-like matrices in aqueous environments. These matrices can physically entrap MPs and NPs particles within a bulk phase, effectively mimicking the sweeping action of metal-based hydrolysates and facilitating particle aggregation and removal (Li et al. 2024). Sweep flocculation is less sensitive to polymer type and instead depends on coagulant dosage and floc matrix formation, which enable the enmeshment of diverse MPs and NPs, including PS, PE, and PET, in the flocs (Chen et al. 2024b; Facchino et al. 2025; Lotfigolsefidi et al. 2025). Among the studies included in this review, a majority reported that the use of natural-based materials, particularly when employed as coagulant aids, increases the size of the flocs produced, contributing to sweep flocculation (Chen et al. 2024b; Eamrat et al. 2024). Furthermore, the formation of smaller precipitates or gel-like structures during coagulation can contribute to the sweeping process, merging into larger flocs and enhancing the probability of MPs and NPs entrapment (He et al. 2024; Lotfigolsefidi et al. 2025). The formation of larger aggregates generates denser flocs, significantly reducing the settling time and improving overall removal efficiency (Eydi Gabrabad et al. 2024b).

Netting-bridging

Netting-bridging is an important removal mechanism in the CFS process, particularly when high molecular weight polymers or fibrous natural-based coagulants/flocculants are employed. In contrast to the adsorption-bridging mechanism, which depends on specific adsorption sites, netting-bridging occurs when large polymer molecules or fibrous materials form a net that physically entraps MPs and NPs particles through passive interactions such as hydrogen bonding. Although the process shares similarities with sweep flocculation, the netting-bridging mechanism requires the polymer or fibers to form passive interparticle interactions with the plastic particles rather than bulk entrapment by sweep flocculation. Among the studies reviewed, this mechanism was consistently reported by one research group across four different studies (Lapointe et al. 2022, 2023; Alioua and

Lapointe 2023; Mebarki et al. 2025) focusing on the removal of PE and PES MPs along with PS NPs using alum and PAM and aided by multiple cellulosic fibers. In these studies, fibrous materials acted as bridging agents, significantly enlarging the floc size and promoting the efficient entrapment of plastic particles within a network of fiber bridges. This enlargement of flocs resulted in faster settling, higher removal efficiencies, reduced coagulation dosages, and even the potential replacement of traditional sedimentation with simple screening methods due to the significantly large floc size. Similarly, Hu et al. (2023) reported the occurrence of netting-bridging in the removal of different NPs types using a starch-based coagulant aided by PSA. In this system, the starch-based coagulant facilitated charge neutralization, while the silanol groups of PSA formed compact, dense flocs with MPs and NPs via netting-bridging, further enhancing the overall removal process.

Factors affecting removal performance

pH

The pH of the solution is a major factor governing the performance of MPs and NPs removal via natural-based coagulation, as it affects coagulant hydrolysis, floc stability and key mechanistic interactions, such as charge neutralization. The majority of studies included in this systematic review reported that optimal removal performance can be achieved under slightly acidic to slightly alkaline conditions (pH 6.3–10) (Chen et al. 2024b; Zhang et al. 2024). MPs and NPs particles typically exhibit a negative surface charge (Hu et al. 2022; Sönmez et al. 2025), while many natural-based coagulants/flocculants, including proteins and polysaccharides, are positively charged (Karnena and Saritha 2022; Kurniawan et al. 2022). These charge differences promote electrostatic interactions, with charge neutralization and bridging enhanced at neutral or slightly alkaline pH (Esmaeili Nasrabadi et al. 2023b). Under these pH conditions, zeta potential values approach zero, leading to minimized interparticle repulsion, effective destabilization, enhanced aggregation, and improved settling of MPs and NPs particles (Huang et al. 2023). Nevertheless, some studies have demonstrated that acidic conditions (pH 2–5.37) are more favorable for MPs and NPs removal (Peydayesh et al. 2021; Rodrigues et al. 2024), attributed to increased protonation of functional groups on both plastic particles and coagulant surfaces, enhancing electrostatic attraction and promoting aggregation. Therefore, it should be emphasized that the optimal pH for MPs and NPs removal is highly dependent on the polymer type of the plastic particles and the specific coagulants used, as variations in surface charge behavior across different pH levels significantly influence coagulation efficiency and floc formation dynamics.

Flocs derived from natural-based coagulants/flocculants at an optimum pH exhibit high stability and resistance to shear forces, enabling the flocs to remain intact and settle efficiently (Magalhães et al. 2025). On the other hand, flocs could be weakened and broken at inappropriate pH values due to polymer denaturation or electrostatic repulsion, leading to fragmentation and resuspension, thereby reducing removal efficiency (Magalhães et al. 2025). In the case of microbial-based coagulants/flocculants, coagulation efficiency highly depends on the production of extracellular polymeric substances (EPS), which facilitate MPs and NPs aggregation. An increase in pH is linked to the enhancement of EPS secretion, promoting the formation of dense aggregates that improve removal efficiency. Lotfigolsefidi et al. (2025) demonstrated that raising the pH from 4 to the optimum value of 7.5 significantly increased EPS production by *Chlorella vulgaris* algae, resulting in the formation of denser aggregates with increased gravitational settling of PS MPs. Due to the variability of coagulation–flocculation systems, pH optimization is critical, and case-specific adjustments are necessary to achieve high removal of MPs and NPs.

Coagulants/flocculants dosage

The dosage of coagulants/flocculants plays a critical role in governing MPs and NPs removal efficiency, influencing the probability of collision between plastic particles and the coagulants/flocculants. All studies included in this systematic review consistently reported that an intermediate dosage of coagulants/flocculants yields the highest removal performance. At low dosages, the available surface area for particle interactions is insufficient (Tabinda et al. 2025), limiting charge neutralization and bridging mechanisms, which in turn reduce aggregation and allow MPs and NPs particles to remain stable and suspended. Increasing the dosage of coagulants/flocculants enhances the available surface area, promoting greater interaction with plastic particles (He et al. 2024). This improves charge neutralization, bridging, and sweep flocculation, resulting in higher removal efficiency. However, excessive dosages can lead to floc breakage, which ruptures the formation of large and stable flocs (Prasetyo et al. 2025). In addition, overdose leads to charge reversal, in which excessive coagulants/flocculants restabilize MPs and NPs particles due to electrostatic repulsion (Mebarki et al. 2025), reducing aggregation and eventually decreasing removal performance.

Optimization of dosage needs to be determined on a case-by-case basis, as natural-based coagulants/flocculants differ significantly in their coagulative compound content, while MPs and NPs vary in polymer type, size and shape. From an application perspective, dosage selection for natural-based coagulants/flocculants should be guided by their intended role in the treatment process. From Tables 3, 4 and

5, materials used as complete substitutes for conventional coagulants generally require higher dosages to provide sufficient charge neutralization and sweep flocculation, whereas natural-based coagulants employed as coagulant aids or flocculants are effective at lower dosages by enhancing bridging and floc strengthening. For natural-based materials serving as complete substitutes for conventional coagulants/flocculants without modification, optimal dosages range from 20 mg/L for PS NPs removal using lysozyme amyloid fibrils (Peydayesh et al. 2021) to 250 mg/L for PS MPs removal using oak powder (Esmaeili Nasrabadi et al. 2023b) and *Spirulina platensis* algae (Eydi Gabrabad et al. 2024b). In contrast, natural-based materials used as coagulant aids or flocculants typically require much lower dosages, between 0.2 and 50 mg/L (Huang et al. 2023; Facchino et al. 2025). Therefore, a stepwise optimization strategy, beginning with jar-test screening and followed by fine-tuning based on MPs and NPs concentration, particle size distribution, and water matrix composition, is recommended. In addition, dosage optimization should balance removal efficiency with potential increases in organic load and sludge production to ensure process sustainability and scalability.

Interfering substances

Real MPs- and NPs-containing wastewater contains various interfering substances, such as anions, cations, and natural organic matter (e.g., humic acid), which can significantly influence the CFS process. Several studies have investigated the effects of common anions, including Cl^-, SO_4^{2-} and CO_3^{2-}, on removal performance, demonstrating that both the type and concentration of anions are critical factors (Zhang et al. 2024). The presence of anions at moderate concentrations initially enhances removal performance by increasing the ionic strength of the solution, which results in electrical double-layer compression, facilitating the aggregation of MPs and NPs particles (Huang et al. 2023). However, at higher anion concentrations, a slight decline in coagulation performance is observed, likely due to increased competition between anions and plastic particles for available adsorption sites on the coagulants/flocculants (He et al. 2024).

Natural organic matter (NOM), particularly humic acid, is another common constituent of wastewater that is often selected as a representative compound in studies on the coagulative removal of MPs and NPs particles. However, the studies in this review reported contradictory findings on its effects, and no clear consensus has been established. Chen et al. (2024b) observed that the presence of humic acid had no significant impact on the removal of PE MPs when laminarin was used as a coagulant aid. In contrast, He et al. (2024) reported that humic acid, particularly at higher concentrations (up to 25 mg/L), improved the removal efficiency of PET MPs when using chitosan-PAC composites, likely by serving as a bridging agent between MPs particles and the flocculant. On the other hand, several other studies have indicated adverse effects of humic acid presence, especially at elevated concentrations, where increased consumption of coagulant by humic acid substances reduced its availability for interaction with plastic particles, thus affecting removal performance (Hu et al. 2022; Gao et al. 2023). These conflicting findings highlight the complexity of NOM interactions in coagulation processes, implying that the removal efficiencies are highly dependent on factors such as the type of coagulant employed, the properties of MPs and NPs particles, and the overall composition of the wastewater matrix.

Some studies have also investigated the influence of additional inorganic (e.g., kaolin) and organic compounds (e.g., surfactant) on the coagulation performance for MPs and NPs removal. The presence of kaolin was found to adversely affect the removal efficiency, similar to humic acid, primarily due to competition for adsorption sites and destabilization of water impurities (Gao et al. 2023). Regarding surfactants, the presence of cetyl trimethylammonium bromide, a cationic surfactant, negatively affected MPs and NPs removal by depositing excessive positive charges on the plastic surface, thereby reducing the effectiveness of charge neutralization. This can be mitigated by introducing anionic surfactants, such as sodium dodecylbenzene sulfonate, which reduce the zeta potential and enhance charge neutralization (He et al. 2024). However, Gao et al. (2023) reported that the utilization of another anionic surfactant, sodium dodecyl sulfate, had no significant impact on the process, while the presence of the non-ionic surfactant Tween 20 improved removal performance. These findings suggest that the influence is compound-specific; thus, accurate characterization of the surface charge of MPs and NPs particles, as well as of any interfering compounds, is essential for optimizing charge neutralization and maximizing coagulation performance.

Given the complexity of water chemistry, several studies utilized real water samples collected from various sources, e.g., tap water, surface water (lakes and rivers), sludge supernatant, municipal wastewater, or synthetically prepared wastewater. These waters were spiked with model MPs and NPs to evaluate the effectiveness of natural-based coagulants/flocculants under more realistic conditions. Most studies incorporating real water reported improved MPs and NPs removal, attributed to the presence of background ions and organic matter that facilitate aggregation (Huang et al. 2023). Additionally, the capture of MPs and NPs particles by sludge biomass was found to enhance particle settling (Eamrat et al. 2024). Nevertheless, the dosage of coagulants/flocculants required to achieve effective removal performance in real water is higher than in deionized water (Hu et al. 2022). These findings highlight the need for future research to prioritize testing under actual, realistic water conditions to better evaluate the practical applicability of natural-based coagulation processes for MPs and NPs removal.

Stirring speed and duration

A typical CFS process comprises three sequential stages: (1) a coagulation stage involving rapid stirring for a very short duration, followed by (2) a flocculation stage characterized by slow stirring over a long period, and (3) a sedimentation or settling phase without stirring, allowing sufficient time for particle settling. Although most reviewed studies did not systematically assess the effects of stirring speed and duration, those that did demonstrate the significant influence of these parameters on MPs and NPs removal efficiency. Increasing stirring speed results in a higher collision frequency between MPs and NPs particles and the coagulants/flocculants, promoting aggregation (Avazpour and Noshadi 2024; Raj et al. 2024). Extending the stirring duration further enhances the performance by providing a longer timeframe for floc formation (Esmaeili Nasrabadi et al. 2023b). However, excessively high stirring speeds or prolonged mixing can introduce shear forces strong enough to disrupt floc integrity, leading to fragmentation (Alioua and Lapointe 2023). During the sedimentation stage, a longer settling duration facilitates more complete interactions between MPs and NPs and coagulants/flocculants (Rodrigues et al. 2024). Nevertheless, extended settling times may delay downstream processes, affecting the overall system throughput and increasing operational costs. Therefore, optimizing the stirring speed, stirring duration, and the choice of coagulant/flocculant is critical, as different coagulants/flocculants exhibit varying resistance to shear forces, which directly impacts floc stability and overall process efficiency.

MPs and NPs properties

The removal performance of MPs and NPs particles via CFS processes is strongly governed by the intrinsic characteristics of the plastic particles, including polymer type, concentration, size, and physical condition. Self-sedimentation of MPs and NPs may occur without requiring coagulants/flocculants if the polymer has a density greater than water (Gao et al. 2023). In terms of concentration, better removal is generally achieved for lower MPs and NPs initial concentrations; however, given the anticipated escalation of plastic pollution in the near future, studies based solely on low plastic concentrations may not accurately represent real-world conditions. Higher MPs and NPs concentrations increase the probability of collisions between plastic particles and coagulants/flocculants, thus promoting aggregate formation (Esmaeili Nasrabadi et al. 2023b). Nonetheless, beyond an optimal concentration threshold, removal efficiency declines due to the saturation of available coagulant binding sites and the intensification of electrostatic repulsive forces, adversely affecting aggregation.

CFS removal efficiency by natural-based coagulants/flocculants is also influenced by the particle size of MPs and NPs. Higher removal efficiency is often associated with smaller particles due to enhanced collision between the particles and natural-based coagulants/flocculants (Khan et al. 2023). Additionally, smaller MPs and NPs possess a larger specific surface area and a higher density of surface functional groups, which contribute to a higher negative charge and promote ionic adsorption (Abdul Rahman et al. 2024). Nonetheless, high removal may still be maintained for larger particles, albeit at a slightly lower efficiency, as reported by Ramakrishnan and Sathiyamoorthy (2025) particularly when sufficient coagulant dosage and floc growth are achieved to enable effective sweep flocculation. Long MPs, particularly fibrous forms, can be easily aggregated due to greater contact surface area and increased probability of collision with coagulants/flocculants (Huang et al. 2023; Avazpour and Noshadi 2024). However, excessively large particles may compromise the adsorption and bridging mechanisms, ultimately reducing removal efficiency (Huang et al. 2023). These findings collectively suggest that MPs and NPs size exerts a non-linear influence on removal performance, and particle size should be evaluated alongside morphology and surface chemistry when assessing the performance of natural-based coagulants for MPs and NPs removal.

The effectiveness of natural-based coagulants is also affected by the type of MPs and NPs particles evaluated. Most of the included studies spiked primary MPs and NPs particles, which are commercially produced in these sizes, into synthetic wastewater. However, the exclusive use of primary MPs and NPs particles does not fully represent real MPs and NPs, which also comprises secondary MPs and NPs formed through degradation processes. Differences in size, shape, surface chemistry, and surface charge affect interactions with coagulants and flocculants, resulting in different removal efficiencies for primary versus secondary MPs and NPs (Khan et al. 2023). Comparative studies have reported inconsistent findings: some demonstrate higher removal efficiencies for aged particles (Gao et al. 2023; Li et al. 2024; Zhao et al. 2024), while others reported superior removal of pristine particles (He et al. 2024; Panigrahi et al. 2024). Higher removal of aged particles has been attributed to increased surface roughness, reduced hydrophobicity, and the formation of oxidized functional groups, all of which promote coagulation (Zhao et al. 2024). Importantly, removal performance is also influenced by the aging pathway. Nakazawa et al. (2021), reported enhanced removal of photochemically aged particles, whereas mechanically aged particles exhibited reduced removal efficiency due to changes in zeta potential and particle stability. These contrasting outcomes highlight the need for systematic investigation into the effects of particle aging by incorporating both primary and secondary MPs and NPs, employing realistic aging mechanisms and complex water matrices. Such approaches are essential to better represent environmental conditions and to enable more accurate evaluation of coagulation-based removal performance.

Temperature

Although the effect of temperature on the coagulative removal of MPs and NPs particles using natural-based materials is often overlooked, it does play a critical role in determining removal performance. Only three studies in this systematic review have examined the influence of temperature on MPs and NPs removal: (1) PET MPs removal using chitosan-polyaluminum chloride between 10 and 30 °C (He et al. 2024); (2) PAN MPs removal using *Komagataeibacter saccharivorans* bacterial cellulose between 15 and 30 °C (Rodrigues et al. 2024); and (3) Nylon 6–6 MPs removal by *Brucella intermedia* ZL-06 bacteria between 20 and 50 °C (Zhao et al. 2024). Temperature affects the chemical kinetics of the coagulation process, where increasing temperature enhances Brownian motion (He et al. 2024), thereby promoting more frequent collisions between MPs particles and coagulative compounds and improving removal performance. However, excessive temperature increases may damage the microstructure of coagulants/flocculants and destabilize or fragment the formed flocs due to increased thermal movement, causing a reduction in removal efficiency (Zhao et al. 2024). The combined effects of temperature and Brownian motion demonstrate the necessity to optimize coagulation conditions. Based on the reviewed studies, the optimal temperature for maximizing MPs and NPs removal typically ranges from 25 to 30 °C. As the thermal stabilities and coagulative efficiencies of different natural-based coagulants/flocculants are significantly distinctive, selecting an optimal operational temperature range is essential to ensure effective MPs and NPs removal.

Key challenges

Although all findings reported in this study highlight the promising potential of natural-based coagulants/flocculants for the removal of MPs and NPs particles from aquatic environments, several key challenges must be addressed prior to their practical implementation in real-world applications. One of the primary concerns is the inherent variability associated with natural-based materials. Derived from diverse biological sources, such as plants and microorganisms, natural-based coagulants and flocculants exhibit considerable inconsistencies in their chemical composition, resulting in significant variability in removal performance (Kurniawan et al. 2022). These inconsistencies stem from factors such as raw material origin, seasonal variations, and differences in extraction methodologies across batches, posing a major challenge to achieving reliable and reproducible removal performance across different water treatment contexts (Badawi et al. 2023; Leiviskä and Santos 2023). Moreover, the lack of harmonization or standardization in extraction and preparation methods further complicates quality control efforts, making comparisons between studies difficult and impeding the establishment of universally applicable protocols.

The utilization of plant-based materials as coagulants/flocculants also poses challenges related to their availability, as certain plant species are geographically restricted, limiting their applicability in different regions of the world (Iwuozor et al. 2023). For instance, among the plant-based coagulants and flocculants discussed in this study, *Moringa oleifera* and okra are predominantly cultivated in tropical and subtropical areas, while oak trees are primarily found across the Northern Hemisphere (Elkhalifa et al. 2021; Morales 2021; Pareek et al. 2023). Such regional limitations necessitate importing these materials into areas where they are not naturally available, consequently increasing operational costs. Furthermore, natural-based materials often face temporal availability issues, as seasonal variations may limit year-round access, thus raising concerns about their ability to meet the consistent supply demands required for large-scale applications (Iber et al. 2021). In the absence of importation, identifying and validating locally available alternatives suitable for diverse climates is required, further complicating the research and development process.

Various studies also raise important sustainability concerns regarding the use of plant-based materials for water treatment, as many of these materials are also food or feed resources. Their large-scale use may therefore create competition with food supplies. For instance, *Moringa oleifera*, one of the most frequently studied coagulants, is rich in proteins and oils, making it a highly valuable nutritional resource (Caspersen and Rasmussen 2024). Although natural-based materials have demonstrated effective MPs and NPs removal, their widespread application could increase demand for edible seeds and plants, inflate market prices, and exert pressure on land use and food security, especially in regions already facing food insecurity (Koul et al. 2022; Diver et al. 2023). Consequently, although this approach may contribute to the achievement of SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water), it may inadvertently undermine SDG 2 (Zero Hunger). Therefore, the responsible development and deployment of natural-based coagulants should extend beyond technical performance to consider socioeconomic and food security impact assessments (Koul et al. 2022). To mitigate these risks, the use of non-edible residues or waste biomass should always be prioritized for scaling up natural-based coagulants, thereby avoiding the diversion of resources from the food system (Tijjani Usman et al. 2023).

In addition to the availability and sustainability concerns, the limited shelf life and instability of natural coagulants/flocculants pose another significant challenge, as such materials tend to degrade over time due to their organic nature. Plant-based materials are susceptible to microbial contamination, particularly under poor storage conditions, as well as biochemical degradation mediated by natural enzymatic activity (Tijjani Usman et al. 2023). Although microorganism-based materials are generally less prone to contamination due to production under controlled fermentation conditions, improper storage can still result in the growth of competing microorganisms, leading to degradation of the desired coagulants/flocculants (Lotfigolsefidi et al. 2025). The resulting change in the chemical composition of the coagulants/flocculants compromises the functional compounds responsible for coagulation/flocculation, ultimately reducing overall performance. Therefore, the development of effective storage strategies and stabilization techniques is essential to maintain the functional integrity of natural-based materials for practical water treatment applications.

The efficiency of a process is also a key consideration in determining the suitability of natural-based coagulants/flocculants against synthetic chemicals. Even though natural-based coagulants are generally more environmentally friendly, several materials have demonstrated lower coagulation efficiencies and often require higher dosages or chemical modifications to achieve removal performance comparable to that of synthetic chemicals (Iber et al. 2021). Unlike conventional coagulants and flocculants, the performance of natural-based materials is often limited to a narrow pH range, limiting their applicability in water bodies with fluctuating physicochemical properties (Diver et al. 2023). Furthermore, the use of natural-based materials may introduce excess organic matter into the water, potentially altering key parameters such as color and odor or even promoting microbial growth and the formation of unwanted biofilms in water treatment facilities (Alazaiza et al. 2022; El Bouaidi et al. 2022). To mitigate these negative impacts, additional pre-treatment to remove undesired contaminants or post-treatment processes may be necessary, thereby increasing the overall operational costs of water treatment (Alnawajha et al. 2022).

A major challenge to the large-scale adoption of natural-based coagulants/flocculants in industrial or environmental applications is ensuring scalability and economic viability. While laboratory-scale studies often report favorable performance and cost-effectiveness, maintaining consistency and quality during scale-up remains a significant hurdle (Diver et al. 2023). Thus, economic feasibility assessments and pilot-scale trials are essential to validate the performance of these materials under industrial conditions while ensuring compliance with stringent environmental regulations (Karnena and Saritha 2022). Adopting natural-based materials may also face poor regulatory and industry acceptance, as their familiarity with and the confidence in the proven efficacy of synthetic coagulants and flocculants may create resistance to adopting newer, less standardized alternatives (El Bouaidi et al. 2022). Overcoming this barrier requires comprehensive data-driven evaluations, robust risk assessments, and clear guidelines to ensure that natural-based materials meet the operational and regulatory standards of the modern water treatment process.

Future perspectives

The use of natural-based coagulants and flocculants for the removal of MPs and NPs particles presents an appealing alternative to synthetic chemicals. Nonetheless, their potential adoption in large-scale applications is constrained by several challenges, including variability in material composition, material availability, degradation during storage, potential secondary pollution and process scalability. Addressing these challenges is essential to enhancing their functionality and facilitating integration into water treatment systems. As coagulation performance is susceptible to the variability of natural-based materials, future research should prioritize the development of standardized preparation, extraction, and purification methods to achieve consistent performance. This can be accomplished by identifying and isolating key active compounds responsible for coagulation efficacy, such as proteins and polysaccharides, thereby enabling more refined and reliable preparation protocols. Additionally, regional availability must be considered, with efforts directed towards identifying and utilizing locally abundant natural coagulants. Storage stability is another critical factor limiting the practical application of natural-based coagulants and flocculants. Enhancing their shelf-life with natural preservatives could mitigate degradation and microbial contamination during storage.

A comprehensive, long-term environmental impact assessment on the utilization of natural-based coagulants and flocculants is required to evaluate their biodegradability, the formation of potentially toxic by-products and their interactions with MPs and NPs particles. Given that natural-based materials may alter water quality parameters, such as color, odor, or microbial population, it is imperative to understand their fate and transformation in aquatic environments to ensure their safe and sustainable applications. Despite promising results reported by various studies, as summarized in this review, the challenges associated with large-scale utilization and economic feasibility persist. Future research efforts should focus on generating comprehensive datasets that include cost-effectiveness analyses, compatibility assessments with existing treatment infrastructure, and rigorous risk evaluations, to facilitate industrial decision-making and advance adoption in the water treatment process.

Conclusion

The utilization of natural-based coagulants and flocculants in the CFS process offers a promising, environmentally sustainable approach for the removal of MPs and NPs particles from aquatic environments. Materials derived from plants, animals, and microorganisms have demonstrated strong potential as alternatives to conventional coagulants, whether applied as substitutes for conventional coagulants in their natural form or chemically modified or as coagulant aids in combination with chemical coagulants. MPs and NPs particles are mainly removed through mechanisms such as charge neutralization, electrostatic patching, adsorption bridging, sweep flocculation and netting-bridging, with various physicochemical and operational parameters significantly influencing the overall performance. Despite these advantages, several challenges persist, including variability in material composition and availability, degradation during storage, the risk of secondary pollution to the environment, and scalability constraints, all of which hinder their large-scale applications. Addressing these challenges requires optimization of process parameters and the integration of comprehensive life-cycle assessments to ensure the practical viability of natural-based coagulants/flocculants. Future research on this topic should focus on enhancing the stability, efficiency, and storage properties of these materials, as well as conducting pilot-scale studies to bridge the gap between laboratory research and real-world applications. Advancement of this technology will position natural-based coagulants and flocculants as viable, eco-friendly alternatives for MPs and NPs removal, contributing to the development of sustainable water treatment solutions.

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Data availability The data supporting this study's findings are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial or non-financial interest in the subject matter or materials discussed in this manuscript.

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