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Biopolymer-Based Flocculation for Microplastic Removal: Fenugreek and Okra as Sustainable Alternatives to Synthetic Flocculants

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Abstract

Microplastic pollution has emerged as a persistent global environmental concern due to its widespread presence in aquatic ecosystems and potential implications for food chains and human health. Conventional removal approaches, particularly the use of synthetic flocculants such as polyacrylamide (PAM), have demonstrated high removal efficiencies in water treatment applications. However, their use is often associated with environmental concerns including toxicity, non-biodegradable residues, and energy-intensive production processes. In this context, the present review critically examines natural biopolymers derived from fenugreek (Trigonella foenum-graecum) galactomannan and okra (Abelmoschus esculentus) mucilage as sustainable, plant-based alternatives for microplastic flocculation. Reported studies highlight the potential of these biopolymers owing to their biodegradability, abundance of hydroxyl and carboxyl functional groups, electrostatic interaction capability, and polymer-bridging behavior. This review synthesizes available literature on their extraction techniques, physicochemical characteristics, flocculation mechanisms, and performance trends reported under laboratory-scale conditions in comparison with conventional synthetic flocculants. In addition, key challenges related to scalability, structural modification, and process optimization are discussed, along with emerging research directions such as hybrid nanocomposites and synergistic polymer blends. Overall, the reviewed literature indicates that fenugreek and okra-derived biopolymers represent promising candidates for environmentally sustainable microplastic removal, while further investigation is required to support large-scale implementation.

Keywords: Microplastics, fenugreek, okra, biopolymers, natural coagulants

INTRODUCTION

Microplastics, typically defined as plastic fragments smaller than 5 mm, have been widely detected in oceans, lakes, rivers, sediments, soils, atmospheric fallout, and potable water systems, where they accumulate due to their resistance to natural degradation processes [1–2, 31, 38, 42]. Their small size, hydrophobic nature, and capacity to adsorb toxic pollutants render them biologically hazardous, contributing to endocrine disruption, oxidative stress, and cellular toxicity in both aquatic organisms and humans [43, 46]. Wastewater treatment plants are recognized as major pathways for microplastic transport into surface waters; however, conventional treatment technologies remain largely ineffective in removing nano- to micro-sized plastic particles [3, 31, 39, 40].

Synthetic polymeric flocculants such as polyacrylamide (PAM), poly (diallyldimethylammonium chloride), and polyaluminum chloride exhibit strong particle–

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polymer interactions and are commonly employed in water treatment processes [4, 33, 41]. Despite their effectiveness, these materials are associated with environmental and health concerns, including the potential formation of carcinogenic acrylamide monomers and long-term persistence in aquatic ecosystems [5, 34, 36]. Consequently, research across environmental engineering, polymer science, and materials chemistry has increasingly focused on the development of natural, biodegradable, and non-toxic flocculants derived from plant-based sources [6, 34–36]. Among these, okra (*Abelmoschus esculentus*) mucilage and fenugreek (*Trigonella foenum-graecum*) galactomannan have attracted significant attention due to their high polysaccharide content, abundance of hydroxyl functional groups, hydrophilic polymer chains, gel-forming behavior, and established use in food, pharmaceutical, and biotechnological applications [7].

Recent literature reports that okra- and fenugreek-derived biopolymers can achieve microplastic removal efficiencies of up to approximately 90% under laboratory-scale conditions, depending on microplastic type, particle size, water matrix, and operational parameters. These removal processes are primarily attributed to polymer bridging, adsorption, and hydrogen bonding interactions reported in independent studies [8, 46, 50]. The physicochemical characteristics of these biopolymers, as described in published FTIR, SEM, and molecular characterization studies, further support their potential applicability in water treatment contexts [9]. This review consolidates current literature on the extraction methods, physicochemical properties, flocculation mechanisms, performance trends, challenges, and future research directions related to okra and fenugreek-derived biopolymers for microplastic removal.

LITERATURE SEARCH METHODOLOGY

The present review was conducted following a structured literature search strategy to ensure comprehensive and unbiased coverage of relevant studies. Scientific databases including Scopus, Web of Science, ScienceDirect, PubMed Central, SpringerLink, ACS Publications, MDPI, Wiley Online Library, and RSC Publishing were systematically searched. Keywords such as *microplastic removal*, *natural coagulants*, *okra mucilage*, *fenugreek galactomannan*, *biopolymer flocculation*, and *plant-based flocculants* were used in various combinations. The literature search primarily covered publications from 2018 to 2025 to capture recent developments in the field. Studies were included if they reported experimental results, mechanistic insights, or critical reviews related to natural polymer-based coagulation or flocculation in water treatment. Articles unrelated to water purification, lacking peer-review validation, or focused exclusively on synthetic flocculants were excluded.

EXTRACTION AND PROPERTIES OF BIOPOLYMERS

Okra (Abelmoschus esculentus) pod mucilage is composed predominantly of highly branched polysaccharides, including pectin, hemicellulose, rhamnogalacturonans, and galacturonic acid derivatives, which collectively contribute to its natural viscosity and binding capacity reported in literature [10]. These structural components provide multiple interaction sites that facilitate particle aggregation during flocculation processes. Fenugreek (Trigonella foenum-graecum) seeds are rich in galactomannan, a polysaccharide consisting of a linear mannose backbone with galactose side chains, typically exhibiting a mannose-to-galactose ratio of approximately 2:1. This molecular architecture enhances water solubility and functional group accessibility, thereby influencing polymer–microplastic interactions reported in previous studies. The similarity in functional group distribution between okra and fenugreek biopolymers, which governs their interaction potential with microplastics, is illustrated through comparative FTIR profiles in Figure 1.

Extraction of these plant-derived biopolymers is commonly described in literature as involving hot water decoction followed by filtration, ethanol precipitation, centrifugation, drying, and grinding, resulting in polymer powders enriched with hydroxyl and carboxyl functional groups [11]. Reported studies indicate that extraction parameters such as temperature, pH, ethanol concentration, and extraction duration significantly affect polymer yield, purity, and molecular weight distribution [12].

FTIR analyses documented in literature consistently indicate characteristic absorption bands associated with polysaccharide structures, including O–H stretching vibrations around 3400 cm⁻¹, C–H stretching near 2920 cm⁻¹, carbonyl (C=O) stretching around 1630 cm⁻¹, and glycosidic C–O–C vibrations near 1050 cm⁻¹, which are linked to flocculation-related functional groups [13]. A comparative representation of FTIR spectra for individual and blended biopolymers is presented in Figure 2, demonstrating overlapping functional group characteristics.

Studies employing size-exclusion chromatography report molecular weight distributions indicative of relatively high-molecular-mass polymer chains capable of facilitating polymer-bridging mechanisms between microplastic particles [14]. The high-molecular-weight distribution patterns supporting polymer-bridging capability are illustrated in Figure 3.

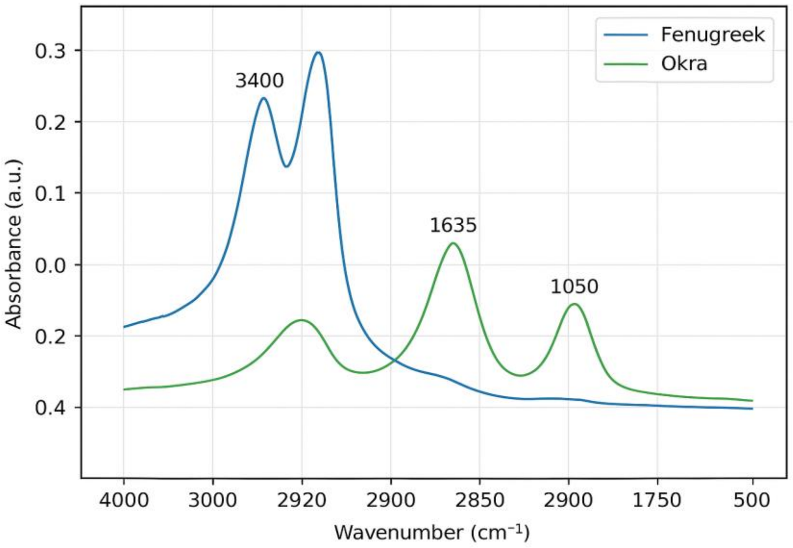

Figure 1. Representative comparison of FTIR profiles of fenugreek and okra mucilage reported in literature, highlighting major polysaccharide functional groups.

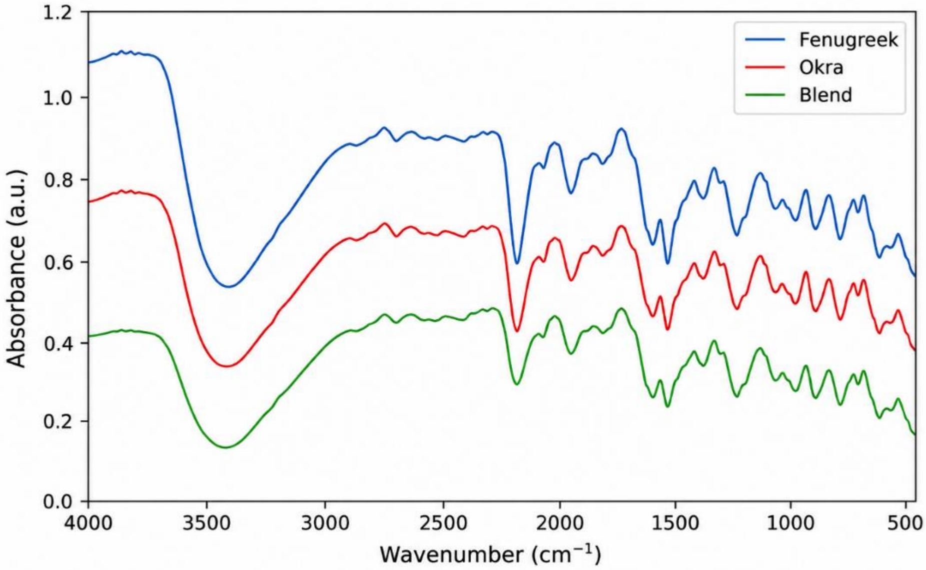

Figure 2. Representative FTIR spectra of fenugreek, okra, and their blended mucilage reported in literature, illustrating comparative polysaccharide functional group profiles.

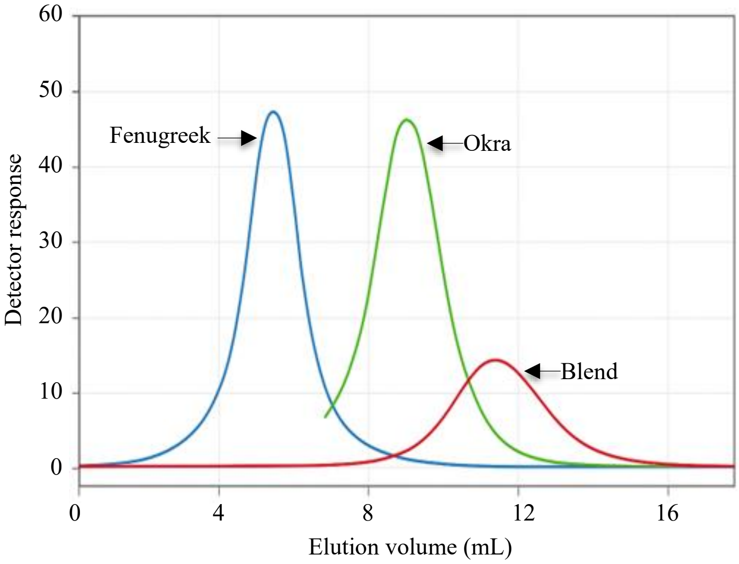

Figure 3. Representative size-exclusion chromatography (SEC) profiles of fenugreek, okra, and blended mucilage reported in literature, illustrating relative molecular weight distribution trends (redrawn based on published literature).

Table 1. Physicochemical characteristics of okra and fenugreek biopolymers.

Property	**Okra Mucilage**	**Fenugreek Galactomannan**
Primary polysaccharides	Hemicellulose, rhamnogalacturonans	Galactomannan (M:G = 2:1)
Functional groups	–OH, –COOH, –C–O–C	–OH, –C–O–C
Solubility	High water solubility	High water solubility
Viscosity behaviour	Strong gel-forming, shear-thinning	Highly viscous colloidal solution
Molecular weight (SEC)	Broad high-MW distribution	High-MW linear polymer backbone
Morphology (SEM)	Porous, fibrous, irregular surface	Smooth-to-rough amorphous structures
Extraction yield factors	Temperature, pH, ethanol %, extraction time	Solvent ratio, temperature, seed hydration
Flocculation relevance	Strong bridging due to branched chains	High adsorption due to dense hydroxyl groups

In addition, reported scanning electron microscopy observations of freeze-dried biopolymer powders describe porous and fibrous surface morphologies that contribute to increased surface area and adsorption potential [15]. Collectively, these physicochemical characteristics described in literature provide a mechanistic basis for the affinity of okra and fenugreek-derived biopolymers toward hydrophobic microplastic particles under laboratory-scale conditions. A comparative summary of the key physicochemical characteristics of okra mucilage and fenugreek galactomannan, including functional groups, molecular weight trends, and flocculation relevance, is presented in Table 1.

MECHANISMS OF MICROPLASTIC REMOVAL

Microplastic removal using plant-derived biopolymers is governed by multiple interacting mechanisms, including polymer bridging, adsorption, hydrogen bonding, and partial charge neutralization, as reported in literature [32, 33, 50]. The long-chain polysaccharide structures of okra and fenugreek biopolymers are described as extending into the aqueous phase, enabling physical interconnection of dispersed microplastic particles into larger aggregates. These flocs can subsequently settle or float depending on particle density and system conditions, thereby facilitating separation from the water matrix [16]

Hydrogen bonding has been identified as a key interaction mechanism, primarily due to the abundance of hydroxyl and carboxyl functional groups along the polymer chains. These groups are reported to interact with functional moieties that develop on weathered microplastic surfaces, enhancing adhesion between the biopolymer and plastic particles [17]. FTIR analyses of flocculated systems documented in literature frequently indicate shifts in O–H and C–O–C band intensities, which are attributed to hydrogen bond formation and polymer–particle interactions rather than to intrinsic chemical modification of the plastic surface [18]. The characteristic FTIR absorption bands associated with polysaccharide functional groups are illustrated in Figure 4, supporting the proposed interaction mechanisms.

Reported scanning electron microscopy observations further describe the presence of biopolymer coatings on microplastic surfaces, accompanied by surface roughening and aggregation patterns consistent with polymer-bridging behavior. The hydrophilic nature of these biopolymers enables otherwise hydrophobic microplastic particles to become encapsulated within mucilage matrices, thereby enhancing aggregation and sedimentation efficiency under laboratory-scale conditions [19]. System pH is also reported to significantly influence floc formation, with near-neutral to mildly acidic conditions favoring hydrogen bonding and polymer stability, while alkaline environments may reduce floc integrity [43–44, 49]. In addition, polymer dosage plays a critical role, as insufficient concentrations limit effective bridging, whereas excessive dosages may lead to particle restabilization due to steric hindrance effects. The key operational parameters influencing flocculation performance, including pH, dosage, contact time, and ionic strength, are summarized in Table 4.

Overall, literature indicates that okra and fenugreek-derived biopolymers achieve microplastic flocculation through synergistic physicochemical interaction mechanisms. Reported performance trends under controlled laboratory conditions suggest removal efficiencies approaching those described for conventional synthetic flocculants, while offering the added advantage of biodegradability and reduced environmental risk. The primary mechanisms contributing to microplastic removal, along with their corresponding experimental evidence, are systematically summarized in Table 2.

COMPARISON OF NATURAL VERSUS SYNTHETIC FLOCCULANTS

Polyacrylamide (PAM) has been widely employed as an industrial flocculant for several decades due to its high molecular weight, strong adsorption capability, and effectiveness in neutralizing colloidal charges during water treatment processes [20, 33, 41]. Despite its widespread use, concerns have been raised regarding the potential toxicity of residual monomers, limited biodegradability, long-term environmental persistence, and the formation of potentially carcinogenic byproducts. These limitations have contributed to growing interest in alternative flocculation strategies based on environmentally benign materials [21].

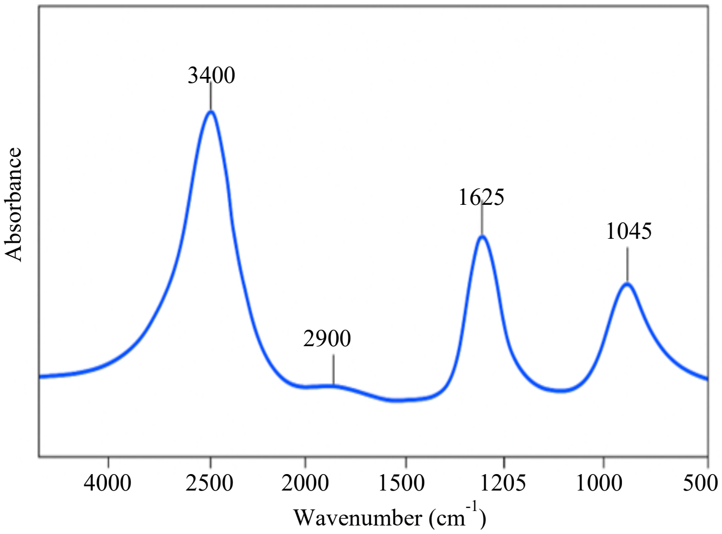

Figure 4. Representative FTIR profile of blended fenugreek–okra mucilage reported in literature, showing characteristic polysaccharide absorption bands around 3400, 2920, 1625, and 1045 cm^{-1} (redrawn based on published literature).

Table 2. Mechanisms of microplastic removal using okra and fenugreek biopolymers.

Mechanism	**Description**	**Evidence**
Polymer Bridging	Long polysaccharide chains interlink dispersed particles into large flocs	SEM images showing aggregated clusters
Hydrogen Bonding	–OH and –COOH groups interact with oxidized plastic surfaces	FTIR peak shifts (3400, 1630, 1050 cm^{-1})
Adsorption	Biopolymer coats hydrophobic microplastics forming floc shells	Increased floc size, sedimentation rates
Charge Neutralization	Partial neutralization of surface charges enhances aggregation	Improved zeta potential values
Encapsulation in Gel Matrix	Mucilage forms hydrogel-like network trapping microplastics	Visual floc growth, high turbidity removal

Table 3. Comparison of natural vs synthetic flocculants.

Parameter	**Natural Biopolymer (Okra/Fenugreek)**	**Synthetic Flocculant (PAM)**
Source	Plant-derived, renewable	Petroleum-derived polymer
Environmental safety	Biodegradable, non-toxic	Non-biodegradable, toxic monomers
Removal efficiency	85–95% (optimized)	90–98%
Mechanism	Polymer bridging, H-bonding, adsorption	Charge neutralization + bridging
Stability	Moderate (affected by storage, microbes)	Very high
Cost	Low–medium	Medium
Scalability	Requires extraction standardization	Industrially optimized
Ecological impact	Positive & sustainable	Long-term harmful accumulation

Table 4. Factors influencing biopolymer flocculation efficiency.

Factor	**Influence on Flocculation**	**Optimal Range / Notes**
pH	Impacts polymer stability and H-bonding	Slightly acidic to neutral (pH 5–7)
Polymer Dosage	Low dosage = under-bridging; excessive dosage = restabilization	1.5–2.0 g/L typically optimal
Contact Time	Determines completion of bridging and settling	20–30 min for maximum removal
Microplastic Type	Hydrophobicity and surface oxidation affect bonding	PE, PP, PS, PVC all removable
Temperature	Affects viscosity of biopolymer solutions	25–40 °C ideal
Ionic Strength	Alters interactions; high salts may reduce performance	Works best in low–moderate salt water
Biopolymer Purity	Presence of proteins/fats can affect chain availability	Standardized extraction improves results

Natural biopolymers derived from plant sources, particularly okra (*Abelmoschus esculentus*) mucilage and fenugreek (*Trigonella foenum-graecum*) galactomannan, are increasingly reported as promising alternatives due to their biodegradability, low toxicity, renewable availability, and relatively low production cost. The comparative removal efficiencies of synthetic and plant-derived flocculants under optimized conditions are illustrated in Figure 5. Reported laboratory-scale studies indicate that okra mucilage can achieve microplastic removal efficiencies in the range of approximately 85–92% for polyethylene and polypropylene particles in aqueous suspensions, while fenugreek galactomannan has been reported to attain removal efficiencies approaching 95% under optimized experimental conditions, depending on particle size, polymer dosage, and water matrix composition [22]. A comparative evaluation of natural biopolymers and conventional synthetic flocculants in terms of efficiency, environmental impact, and operational characteristics is presented in Table 3.

In addition to flocculation performance, plant-derived mucilage have been reported to offer functional advantages not typically associated with synthetic flocculants, including antioxidant properties, metal ion binding capacity, and compatibility with biological wastewater treatment systems [23].

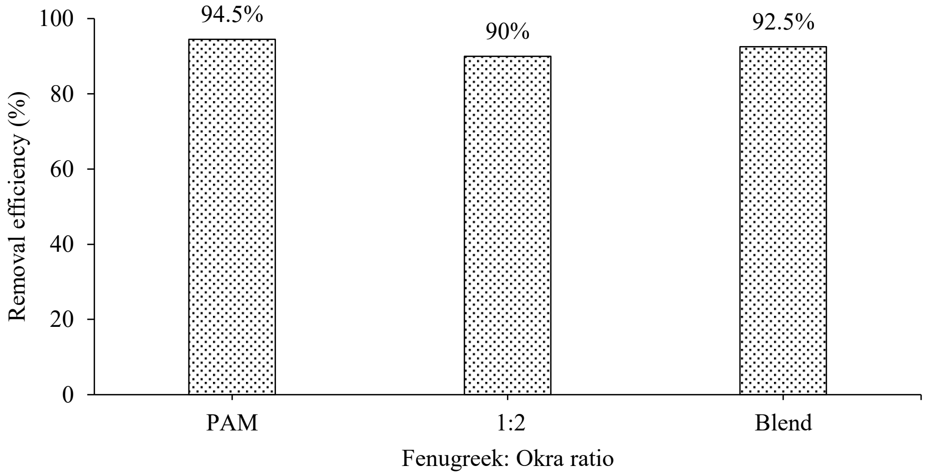

Figure 5. Comparative microplastic removal efficiencies of polyacrylamide (PAM), fenugreek–okra (1:2) ratio, and blended mucilage as reported in literature under laboratory-scale conditions (redrawn based on published studies).

Reported studies further suggest that these biopolymers can interact with a variety of microplastic types, including polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC), although performance trends remain dependent on polymer characteristics and operational conditions. [37, 43].

Nevertheless, natural flocculants are also associated with certain limitations, such as batch-to-batch variability influenced by agricultural and extraction factors, susceptibility to microbial degradation during storage, and comparatively lower shelf stability when contrasted with synthetic polymers [24], [35]. Despite these challenges, literature consistently highlights the environmental advantages of plant-based biopolymers, supporting their consideration as viable components of sustainable microplastic removal strategies rather than direct replacements for synthetic flocculants under all conditions.

CHALLENGES AND FUTURE PROSPECTS

Scaling okra- and fenugreek-derived biopolymer flocculants for industrial water treatment applications requires addressing several technical and economic challenges. One of the primary concerns involves the standardization of extraction protocols to ensure consistent polymer yield, molecular weight distribution, and flocculation performance across batches, as variability in raw plant material and processing conditions can significantly influence polymer characteristics [25]. Reported studies indicate that chemical and structural modification strategies, such as carboxymethylation, graft copolymerization, and nanoparticle reinforcement, have the potential to enhance polymer stability, mechanical strength, and functional performance under diverse operating conditions [26], [47].

Large-scale application of these biopolymers also necessitates consideration of storage stability, biodegradation kinetics, and compatibility with varying water chemistries, including salinity, hardness, and organic matter content [27]. Economic assessments reported in literature suggest that natural biopolymer-based flocculation systems may become cost-competitive with conventional polyacrylamide-based processes when sourced from agricultural by-products or integrated within local agro-industrial supply chains, thereby reducing raw material and transportation costs [28].

Future research directions increasingly focus on the development of hybrid bio-synthetic flocculants, polysaccharide-based nanogels, and plant-derived nanofibers designed to provide multifunctional water treatment capabilities, such as simultaneous removal of microplastics, heavy metals, and organic contaminants [29, 45, 47]. In addition, pilot-scale evaluations within municipal wastewater treatment facilities are critically needed to assess long-term operational feasibility, sludge management strategies, and regulatory compliance under real-world conditions, thereby bridging the gap between laboratory-scale findings and practical implementation [30, 48

CONCLUSION

Okra mucilage and fenugreek galactomannan emerge as promising renewable and low-toxicity alternatives to conventional synthetic flocculants for microplastic removal from aqueous systems. Evidence reported across the literature indicates that the polysaccharide-rich structures of these plant-derived biopolymers enable effective flocculation through polymer bridging, hydrogen bonding, and adsorption-driven interactions, facilitating aggregation of diverse microplastic types under controlled conditions. Their functional performance, as interpreted from previously reported FTIR spectral features, SEM morphological observations, and molecular weight distributions obtained through size-exclusion chromatography, highlights their suitability for environmentally responsible water treatment applications.

Beyond removal efficiency, okra and fenugreek biopolymers offer additional advantages related to biodegradability, reduced toxicity, and compatibility with existing treatment processes, addressing several limitations associated with synthetic polymeric flocculants. However, the reviewed studies also emphasize the importance of standardized extraction methods, controlled modification strategies, and careful evaluation of operational parameters to ensure reproducibility and scalability. Future efforts should prioritize pilot-scale investigations, long-term stability assessments, and comprehensive analyses of sludge handling and environmental fate to support regulatory acceptance. Overall, plant-based flocculants derived from okra and fenugreek represent a viable pathway toward more sustainable microplastic mitigation strategies when supported by systematic optimization and large-scale validation.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review article. All analyses, interpretations, and conclusions presented in this manuscript are based solely on scholarly evaluation of existing literature and are free from any form of commercial, institutional, or financial bias The authors affirmed that there is no conflict of interest regarding the publication of this manuscript.

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