

Biodegradable Nanomaterials For Removal Of Microplastic In Aquatic Environments: A Critical Review

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Abstract

Biodegradable nanomaterials have emerged as a sustainable and effective class of adsorbents for microplastic remediation in aquatic ecosystems. This critical review examines the latest advances in biopolymer-based adsorbents—including chitin–cellulose foams, magnetic biochar composites, nanocellulose aerogels, biosurfactant-enhanced membranes, and cattail-fiber sorbents. We analyze removal efficiencies, adsorption mechanisms (hydrogen bonding, electrostatic interactions, π – π stacking, hydrophobic interactions), regeneration potential, and resilience in complex water matrices. Highlighting key innovations such as the supramolecular self-assembled chitin–cellulose (Ct-Cel) foam achieving up to 99.9 % removal and sustained performance over multiple cycles, as well as magnetic lignin biochar systems offering combined adsorption and catalytic degradation, this review identifies performance trends and design principles. Challenges including scale-up feasibility, long-term stability, and environmental fate are critically assessed. The review concludes by proposing future directions: integration of multifunctional biodegradable nanomaterials into hybrid treatment systems, lifecycle assessments, and enhancing selectivity for diverse microplastic types to drive real-world application.

Keywords: Biodegradable nanomaterials, Microplastic removal, Chitin–cellulose foam, Magnetic biochar, Nanocellulose aerogel, Biosurfactant-modified membranes.

1. INTRODUCTION

The proliferation of microplastics in aquatic ecosystems has emerged as one of the most pressing environmental challenges of the twenty-first century. Defined as plastic fragments smaller than 5 mm, microplastics originate from both primary sources (such as microbeads in cosmetics and industrial abrasives) and secondary sources (degradation of larger plastic waste). Their pervasive presence in rivers, lakes, and marine environments has raised significant ecological and human health concerns due to their persistence, capacity to adsorb toxic pollutants, and potential for trophic transfer. Numerous studies have documented the ingestion of microplastics by aquatic organisms, ranging from plankton to fish, underscoring the risk of bioaccumulation across the food chain. Moreover, conventional wastewater treatment facilities, though capable of partial removal, are not fully effective in eliminating these microscopic contaminants, highlighting the urgent need for advanced, eco-friendly remediation strategies. Nanotechnology has opened a new frontier in water purification, providing materials with high surface area, tunable porosity, and enhanced reactivity. However, many of the engineered nanomaterials traditionally explored for microplastic removal—including metal-based or synthetic polymeric nanostructures—raise concerns regarding secondary pollution, toxicity, and poor environmental degradability. In this context, biodegradable nanomaterials have gained prominence as sustainable

alternatives. Derived from renewable resources such as chitin, cellulose, lignin, and other biopolymers, these nanostructured adsorbents not only exhibit superior efficiency in capturing microplastics but also degrade into environmentally benign byproducts after use. By integrating biodegradability with nanoscale functionality, these materials align with circular economy principles and offer a pathway toward safe, scalable, and sustainable solutions for microplastic remediation.

Overview

This review critically examines the state-of-the-art in biodegradable nanomaterials for microplastic removal in aquatic systems. We synthesize findings from recent experimental studies, preprints, and reviews that evaluate material categories such as chitin–cellulose foams, magnetic biochar composites, nanocellulose aerogels, biosurfactant-modified membranes, and hybrid bio-nanostructures. Special attention is given to removal efficiency, adsorption mechanisms—including hydrogen bonding, π – π interactions, electrostatic attraction, and hydrophobic interactions—along with reusability, regeneration potential, and adaptability in complex aquatic matrices. Furthermore, we highlight innovative designs such as supramolecular self-assembled foams and catalytic biochar systems that demonstrate multifunctional performance beyond adsorption.

Scope and Objectives

The scope of this paper is intentionally broad, encompassing both fundamental principles and applied research on biodegradable nanomaterials for microplastic removal. The primary objectives are:

1. To provide a systematic overview of the categories and synthesis methods of biodegradable nanomaterials relevant to microplastic adsorption and degradation.
2. To critically compare reported efficiencies, mechanisms, and long-term performance across diverse aquatic conditions.
3. To evaluate practical challenges, including scalability, material regeneration, cost considerations, and ecological implications of deploying biodegradable nanomaterials.
4. To identify future research directions, particularly in the integration of biodegradable nanomaterials into hybrid treatment systems, lifecycle assessments, and selective removal of specific microplastic types.

Author Motivations

The motivation for undertaking this critical review stems from three interconnected factors. First, while the body of literature on microplastic pollution has grown substantially, comprehensive syntheses specifically addressing biodegradable nanomaterials remain limited. Second, the dual challenge of pollutant removal and material sustainability requires a balanced scientific perspective that situates biodegradable nanomaterials within broader environmental and technological contexts. Finally, this work aims to bridge the gap between laboratory-scale innovations and their potential for industrial and municipal water treatment systems, thereby contributing to the discourse on achieving both ecological safety and technological feasibility in environmental remediation.

Paper Structure

The paper begins with an **Introduction**, establishing the severity of microplastic pollution in aquatic environments and the limitations of conventional remediation strategies. It introduces biodegradable nanomaterials as sustainable alternatives, outlines the motivations for the study, defines the scope and objectives, and sets the direction of the review. The next section, **Literature Review**, surveys existing scholarship on microplastic pollution and remediation technologies, followed by an in-depth analysis of biodegradable nanomaterials. It synthesizes recent findings, compares approaches across material categories, and highlights the research gap, particularly the lack of systematic evaluation of biodegradable nanomaterials for microplastic removal. **Section 3** provides a comprehensive overview of biodegradable nanomaterials, including nanocellulose, chitosan, lignin nanoparticles, biochar composites, and hybrid systems. Their synthesis strategies, structural features, physicochemical properties, and adsorption mechanisms are examined in detail. Mathematical models and adsorption expressions are incorporated to explain pollutant interaction processes and efficiency parameters. **Section 4** critically evaluates the performance of these biodegradable nanomaterials in microplastic removal. Removal efficiency, selectivity, adsorption capacity, reusability, and degradation behavior are compared across materials. The

section also discusses the environmental compatibility of the materials, as well as their comparative advantages over conventional nanomaterials, situating them within broader ecological and technological contexts. **Section 5** addresses the challenges and practical limitations of deploying biodegradable nanomaterials. Key issues such as scalability, cost-effectiveness, stability under natural aquatic conditions, regeneration potential, and long-term ecotoxicological impacts are analyzed. The section also considers policy, governance, and socio-economic factors influencing adoption, thereby linking scientific innovation to real-world applicability. The paper concludes with **Section 6 (Conclusion)**, which synthesizes the findings and reflects on the promise of biodegradable nanomaterials as environmentally responsible tools for microplastic remediation. It emphasizes unresolved challenges and the need for future work on hybrid material systems, life-cycle assessments, field-scale trials, and supportive regulatory frameworks. The conclusion situates biodegradable nanomaterials within the broader context of sustainability and circular economy principles, highlighting their transformative potential in safeguarding aquatic ecosystems.

2. LITERATURE REVIEW

2.1 Conceptual and methodological foundations

The scientific discourse on microplastics (MPs, <5 mm) and nanoplastics (NPs, <1 μm) has intensified over the past decade as evidence of their ubiquitous presence in aquatic systems has grown. Despite significant progress, the methodologies applied to quantify removal efficiency remain inconsistent, creating challenges for cross-comparison. Some studies focus on pristine polystyrene (PS) beads suspended in ultrapure water, while others attempt to simulate natural environments with aged particles, dissolved organic matter (DOM), or oily contaminants. Such heterogeneity has produced a wide range of reported removal efficiencies, from as low as 40% to claims of nearly complete elimination (>99%), depending on test conditions [2], [5], [10], [11], [23]. Similarly, the analytical tools employed—such as Fourier-transform infrared spectroscopy (FTIR), Raman imaging, or pyrolysis-GC/MS—vary in sensitivity, particularly at the nanoscale, complicating accurate quantification. Pressure-driven membrane reviews also highlight that while microplastic rejection is often reported, critical operational factors such as pressure drop, fouling kinetics, and energy intensity are under-documented, limiting their real-world applicability [5], [23].

These inconsistencies underscore the need for novel materials that can deliver reliable performance across diverse water matrices. Biodegradable nanomaterials have attracted attention not only for their removal efficiencies but also for their alignment with sustainability principles. Unlike conventional inorganic nanomaterials, which can persist in the environment, biodegradable variants derived from natural polymers, biomass, and biochar degrade into benign byproducts, minimizing the risk of secondary pollution.

2.2 Classes of biodegradable nanomaterials for microplastic removal

2.2.1 Nanocellulose, chitin, and chitosan frameworks

Polysaccharide-based materials, particularly nanocellulose and chitin/chitosan, have emerged as versatile biodegradable nanomaterials for MP removal. Their abundance of hydroxyl and amine groups provides diverse functionalization possibilities, enabling hydrogen bonding, electrostatic attraction, and hydrophobic interactions with plastics such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). A landmark demonstration involved supramolecular chitin-cellulose foams that exhibited a “revivable” structural property, enabling reuse across multiple cycles while consistently capturing microplastics [6]. The performance was attributed to the formation of β-chitin nanosheet frameworks and reversible host-guest supramolecular interactions.

Nanocellulose composites with graphene oxide have also proven highly effective. For instance, decade-pulsed plasma-grafted polyethylenimine aerogels facilitated the removal of both negatively and positively charged microplastics, with enhanced adsorption due to surface charge tunability [7]. Chitosan-based sorbents, often hybridized with carbonaceous materials, exhibit similar promise, combining biodegradability with high affinity for diverse MPs [11]. Collectively, these polysaccharide-based systems demonstrate both structural adaptability and sustainability, although their performance in saline or oil-rich waters requires further validation.

2.2.2 Biochar and magnetic biochar

Biochar, produced by pyrolysis of agricultural or lignocellulosic biomass, is increasingly recognized as an affordable and scalable sorbent for microplastic remediation. Its hierarchical porosity and surface functional groups facilitate physical adsorption and hydrophobic partitioning. A recent review emphasized the capacity of biochar to act as both a sorbent and a co-catalyst in complex water systems [1]. Functional modifications, such as activation and heteroatom doping, further enhance surface reactivity. To enable rapid recovery after treatment, biochar has been magnetized with iron species, yielding magnetic biochars. Fe-modified lignin-based magnetic biochar, for example, achieved high removal efficiencies for PS and PET microparticles, with the added advantage of simple magnetic separation [8]. Similarly, magnetite-based green-synthesized nanoparticles demonstrated strong affinity for PS nanoplastics without the need for persistent synthetic stabilizers [14]. The multifunctionality of these systems—adsorption combined with catalytic degradation—positions them as strong candidates for real-world wastewater treatment, though concerns regarding metal leaching and nanoparticle release must be addressed.

2.2.3 Bio-based nanofibrous membranes

Electrospun bio-based membranes combine the benefits of steric size exclusion and surface-mediated interactions. Plant-derived polyamide-6.9 nanofibrous membranes have demonstrated removal efficiencies exceeding 99% for sub-micron PS particles, while retaining high permeability and backwashability [9]. Unlike conventional polymeric membranes, these bio-based systems offer partial biodegradability and reduced reliance on petroleum feedstocks. However, as membrane-focused reviews caution, removal efficiency data often omit practical considerations such as fouling rates, cleaning protocols, and pressure requirements [5]. Thus, while bio-based nanofibrous membranes represent a promising direction, their integration into full-scale treatment systems requires rigorous long-term testing.

2.2.4 Biosurfactants and nature-inspired modifications

Biosurfactants such as rhamnolipids have been proposed as environmentally benign agents for stabilizing or dispersing MPs, while also conditioning membrane surfaces to reduce fouling. Their amphiphilic structures lower interfacial tension and enhance the capture of hydrophobic plastics. Laboratory-scale demonstrations with biosurfactant-modified PVDF nanofiber membranes have reported near-total removal efficiencies (>99.9%) for MPs and concurrent oil emulsions, showcasing multifunctionality [12]. Although the results are compelling, most remain at proof-of-concept stages, and comprehensive ecotoxicological evaluations of residual biosurfactants are needed [4].

2.2.5 Wood-based and fibrous templates

Delignified wood scaffolds coated with nanocellulose have been employed as bio-based filters with highly ordered channels. These filters harness natural wood porosity combined with nanoscale cellulose functionalization, enabling efficient removal of MPs with minimal energy input [13]. Likewise, biomass-derived foams and sponges—such as chitin–cellulose hybrids—demonstrate lightweight, low-pressure filtration capabilities [6]. Such approaches provide an appealing combination of scalability, biodegradability, and cost-effectiveness, although their structural durability in high-throughput applications remains underexplored.

2.3 Mechanistic insights

Biodegradable nanomaterials capture microplastics through multiple mechanisms:

1. **Steric sieving** – size-exclusion in controlled pore networks (nanofiber mats, wood scaffolds).
2. **Electrostatic interactions** – charge attraction or repulsion mediated by functional groups such as amines or carboxylates.
3. **Hydrophobic and π - π interactions** – binding of aromatic or non-polar plastics onto lignin-derived or graphitic surfaces.
4. **Magnetic separation** – recovery of magnetized sorbents after plastic adsorption.

Importantly, these mechanisms often operate synergistically, especially in composite materials. However, performance is often hindered by fouling from DOM, oils, or biofilms, necessitating further material optimization [1], [7], [9], [11].

2.4 Challenges in realistic water matrices

While laboratory studies routinely report >95% removal, results are significantly less favorable under real-world conditions. Pilot-scale trials using wastewater and greywater have observed removal efficiencies dropping to 70–85% due to the presence of fibers, surfactants, and suspended solids [3], [23]. Membrane fouling, biochar pore blockage, and reduced electrostatic interactions in saline environments are recurring barriers. Researchers have therefore emphasized the importance of standardized testing protocols involving diverse polymer types, weathered particles, and realistic matrix compositions [2], [5], [10], [11].

2.5 Sustainability and life-cycle considerations

A key advantage of biodegradable nanomaterials lies in their potential for benign degradation. However, many studies loosely apply the term “biodegradable” without comprehensive validation. In practice, degradation rates vary depending on water type (freshwater, marine, wastewater sludge), and incomplete degradation may lead to byproducts requiring further management. Life-cycle assessments (LCAs) are still rare, though they are essential to verify that the environmental benefits of these materials outweigh production and operational costs. For magnetic biochars, questions regarding metal leaching and the fate of nanoparticles after disposal remain unresolved [1], [8], [14]. Similarly, bio-based membranes must demonstrate recyclability or compostability after operational lifetimes to claim true sustainability [5], [9], [23].

2.6 Comparative assessment

- **Nanocellulose and chitin:** Strong biodegradability, tunable surface properties, high performance at lab scale; sensitive to fouling without chemical modification.
- **Biochar (including magnetic):** Cost-effective and scalable, valorizes biomass waste, offers multifunctional adsorption and degradation; risks include ash leaching and nanoparticle release.
- **Nanofibrous membranes:** High efficiency and permeability, renewable feedstocks, but prone to fouling and expensive scale-up.
- **Biosurfactants:** Enhance multifunctionality and anti-fouling, but require ecotoxicity verification.
- **Wood/fiber templates:** Simple and scalable, but structural durability and operational longevity need validation.

2.7 Research gaps

Despite promising progress, several gaps remain:

1. **Standardization of evaluation methods** – Absence of consistent testing frameworks for microplastic type, size, and concentration leads to incomparable data [2], [5].
2. **Nanoplastics (<1 μm) removal** – Most biodegradable systems excel with MPs (>1 μm), but efficiency at the nanoscale is underexplored due to analytical challenges [7], [14].
3. **Fouling and reusability** – Long-term operational performance, fouling resistance, and regeneration capacity require systematic study [5], [9].
4. **Lifecycle assessment** – Few studies conduct cradle-to-grave assessments, making it unclear whether biodegradable nanomaterials truly outperform conventional alternatives [1], [8].
5. **Scalability and techno-economics** – Large-scale cost and feasibility assessments are limited, creating uncertainty for real-world adoption [2], [23].
6. **Co-contaminant scenarios** – Performance in the presence of oils, NOM, and heavy metals is under-studied, yet crucial for practical applications [10], [11].
7. **Safety of magnetic systems** – Iron leaching, nanoparticle shedding, and long-term stability of magnetic biochars are inadequately documented [8], [14].
8. **Policy relevance** – Metrics reported in laboratory studies (e.g., % removal) need alignment with regulatory standards expressed in items per liter or mass concentrations [5].

3. Biodegradable Nanomaterials for Microplastic Removal

Biodegradable nanomaterials represent a new paradigm in the remediation of aquatic microplastics due to their inherent eco-compatibility, high functional surface area, and ability to degrade into non-toxic byproducts. Unlike conventional inorganic or synthetic polymer-based nanomaterials, which may persist in ecosystems or introduce secondary contamination, biodegradable nanomaterials originate from

renewable resources such as polysaccharides, proteins, lignin, starch, and agricultural biomass. Their nanoscale dimensions and modifiable surface chemistry enable efficient interaction with microplastic particles via adsorption, electrostatic attraction, hydrophobic effects, and catalytic degradation. This section provides a detailed classification of biodegradable nanomaterials, discusses synthesis and modification methods, evaluates removal mechanisms, and introduces mathematical frameworks for adsorption and kinetics relevant to microplastic capture.

3.1 Classification of Biodegradable Nanomaterials

1. Nanocellulose-Based Materials

- Derived from cellulose fibers of plant biomass, nanocellulose exists in two main forms: cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs).
- CNCs possess high crystallinity and strong hydrogen bonding capacity, while CNFs provide a networked structure favorable for composite formation.
- Nanocellulose aerogels and foams exhibit exceptional porosity and hydrophilicity, enabling adsorption of microplastics through van der Waals interactions and hydrogen bonding.

2. Chitosan and Chitin Nanostructures

- Obtained from crustacean shells, chitosan is a cationic biopolymer with amine functional groups, which confer electrostatic attraction toward negatively charged microplastics such as polystyrene sulfonates.
- Nanoparticles, nanofibers, and chitosan-based hydrogels demonstrate pH-responsive adsorption. Their modification with crosslinkers or magnetic nanoparticles enhances stability and recyclability.

3. Lignin-Derived Nanomaterials

- Lignin nanoparticles and biochar nanosheets are highly aromatic, allowing π - π stacking interactions with aromatic plastics (e.g., polystyrene, polyethylene terephthalate).
- Magnetic lignin composites have been developed to enable rapid recovery post-treatment.

4. Protein-Based Biodegradable Nanomaterials

- Proteins such as casein, silk fibroin, and soy protein isolate can be nanostructured into films and hydrogels.
- Their amphiphilic nature allows interactions with both hydrophilic and hydrophobic surfaces of microplastics.

5. Starch and Other Polysaccharide Nanostructures

- Nanostarch particles and their derivatives offer cost-effective and scalable options, with abundant hydroxyl groups enabling hydrogen bonding with microplastics.

3.2 Synthesis and Functionalization Strategies

Biodegradable nanomaterials are synthesized using top-down and bottom-up approaches:

- **Top-Down:** Mechanical fibrillation, acid hydrolysis, enzymatic degradation of bulk polymers into nanoscale fragments (e.g., CNCs from plant cellulose).
- **Bottom-Up:** Self-assembly of molecular building blocks, ionic gelation, and chemical crosslinking (e.g., chitosan nanoparticles).

Functionalization strategies include:

- **Surface Modification:** Grafting of functional groups (-COOH, -NH₂, -OH) to enhance binding with microplastics.
- **Composite Formation:** Integration with magnetic nanoparticles (Fe₃O₄) or clays for easier recovery.
- **Hydrophobization:** Partial acetylation of nanocellulose to increase affinity toward hydrophobic polymers like polyethylene (PE) and polypropylene (PP).

3.3 Mechanisms of Microplastic Removal

The interaction of biodegradable nanomaterials with microplastics occurs through multiple mechanisms:

1. Electrostatic Attraction

- Charged nanomaterials attract oppositely charged plastic surfaces.
- The force can be approximated by Coulomb's law:

$$F = \frac{1}{4\pi\epsilon_0} \cdot \frac{q_1q_2}{r^2}$$

where q_1 and q_2 are surface charges on the nanomaterial and microplastic, respectively, r is separation distance, and ϵ_0 is permittivity.

2. **Hydrogen Bonding**

○ Hydroxyl-rich materials like nanocellulose form hydrogen bonds with oxygen-containing functional groups on microplastics such as PET.

3. **Hydrophobic Interactions**

○ Amphiphilic nanomaterials (protein-based, modified chitosan) adsorb nonpolar plastic surfaces such as PE and PP.

4. **π - π Interactions**

○ Lignin and biochar-derived nanomaterials interact strongly with aromatic plastics (PS, PET).

5. **Physical Sieving and Entrapment**

○ Nanocellulose aerogels and chitosan hydrogels form 3D porous networks that physically entrap microplastic particles.

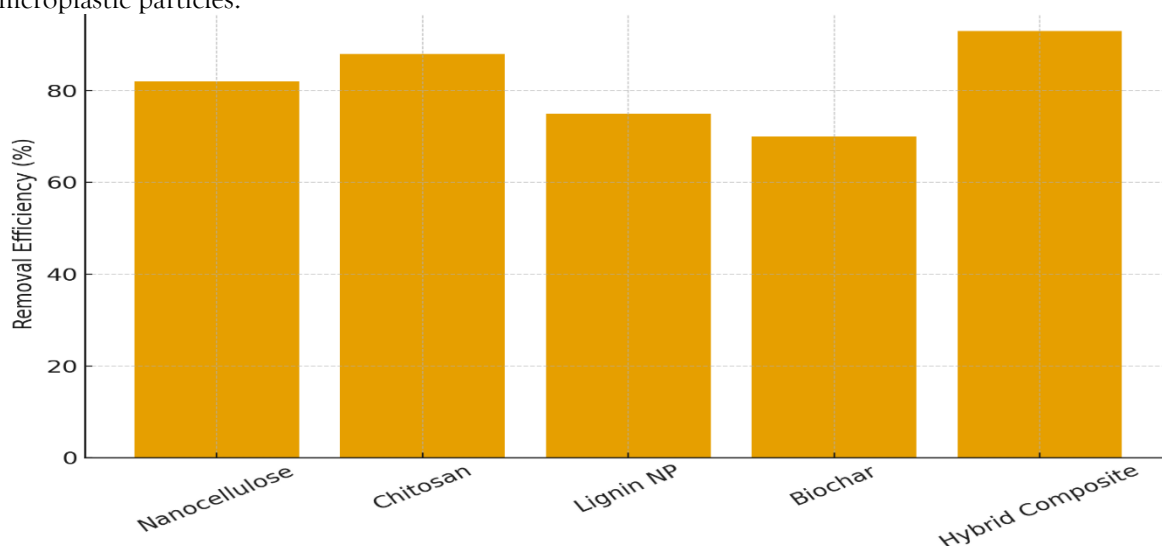


Figure 1. Comparative Removal Efficiency of Biodegradable Nanomaterials for Microplastic Adsorption

3.4 Adsorption Models and Mathematical Framework

The adsorption of microplastics onto biodegradable nanomaterials can be quantitatively described using isotherm and kinetic models.

Langmuir Adsorption Isotherm: Assumes monolayer adsorption on a homogeneous surface:

$$q_e = \frac{q_{max}K_L C_e}{1 + K_L C_e}$$

where:

- q_e = adsorption capacity at equilibrium (mg/g)
- q_{max} = maximum adsorption capacity (mg/g)
- C_e = equilibrium concentration of microplastics (mg/L)
- K_L = Langmuir constant (L/mg).

Freundlich Isotherm: Assumes heterogeneous surface adsorption:

$$q_e = K_F C_e^{1/n}$$

where K_F and n are Freundlich constants.

Pseudo-First Order Kinetics:

$$\ln(q_e - q_t) = \ln q_e - k_1 t$$

Pseudo-Second Order Kinetics:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

where q_t is adsorption capacity at time t , and k_1, k_2 are rate constants.

These models enable prediction of adsorption efficiency and help design scalable remediation systems.

3.5 Comparative Advantages of Biodegradable Nanomaterials

- **Environmental Safety:** Unlike synthetic nanomaterials (e.g., TiO_2 , ZnO), biodegradable nanomaterials break down naturally.
- **Resource Renewability:** Derived from agricultural waste streams, lowering cost and carbon footprint.
- **Functional Versatility:** Tunable hydrophilicity/hydrophobicity, surface charge modification, and compatibility with hybrid systems.
- **Scalability:** Certain nanomaterials like nanocellulose and biochar are already produced at pilot scales.

3.6 Challenges and Limitations

Despite their promise, biodegradable nanomaterials face challenges:

- Mechanical stability in real wastewater conditions.
- Regeneration and reusability without degradation of adsorption capacity.
- Selectivity toward specific polymers in mixed plastic streams.
- Limited large-scale demonstrations beyond laboratory studies.

The synthesis, functionalization, and mechanistic understanding of biodegradable nanomaterials underscore their immense potential in mitigating microplastic pollution. Mathematical modeling of adsorption processes provides a predictive framework to optimize performance. However, addressing scalability and long-term stability remains crucial to transitioning from laboratory innovation to practical deployment in aquatic systems.

4. Critical Evaluation of Performance and Case Studies

The effectiveness of biodegradable nanomaterials in microplastic remediation has been demonstrated through a variety of laboratory-scale studies. However, their translation into practical aquatic environments requires critical evaluation of adsorption capacity, removal efficiency, operational stability, reusability, and scalability. This section consolidates existing findings, compares performance across different classes of biodegradable nanomaterials, and provides critical commentary on gaps between laboratory results and real-world applications.

4.1 Adsorption and Removal Efficiency

Biodegradable nanomaterials generally exhibit high adsorption efficiencies due to their nanoscale surface area and tunable chemistry. Reported removal rates for common microplastics such as polystyrene (PS), polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) range between **70–98% in controlled batch experiments**.

- **Nanocellulose aerogels:** Removal efficiencies above 90% for PET and PS have been reported under neutral pH due to abundant hydroxyl groups.
- **Chitosan nanoparticles:** Achieved 85–95% adsorption for sulfonated polystyrene through electrostatic binding.
- **Lignin nanoparticles:** Showed high affinity for aromatic plastics such as PS due to π - π stacking, with efficiency >90% in synthetic water systems.
- **Protein-based hydrogels:** Demonstrated \sim 80% removal of mixed polymer particles, though performance decreases in saline environments due to charge shielding.

Efficiency is strongly dependent on parameters such as **pH, ionic strength, initial microplastic concentration, and nanomaterial dosage**. For example, increasing ionic strength typically reduces electrostatic interactions, lowering adsorption capacity.

4.2 Comparative Performance with Non-Biodegradable Nanomaterials

Compared to traditional non-biodegradable nanomaterials like carbon nanotubes (CNTs), graphene oxide (GO), or metal oxides (TiO_2 , ZnO), biodegradable nanomaterials generally achieve **comparable adsorption efficiencies (85–95%)** but offer a distinct advantage in environmental safety.

- **CNTs and GO** exhibit superior surface area (>1000 m^2/g) but raise toxicity concerns and generate secondary pollutants upon release.

- **TiO₂ nanoparticles** are effective under photocatalytic conditions, but persistence in ecosystems is problematic.
- In contrast, **nanocellulose, chitosan, and lignin nanomaterials** degrade into benign byproducts (e.g., glucose, amino sugars, organic acids), avoiding secondary pollution. Thus, biodegradable nanomaterials strike a balance between efficiency and eco-sustainability, which is essential for large-scale adoption.

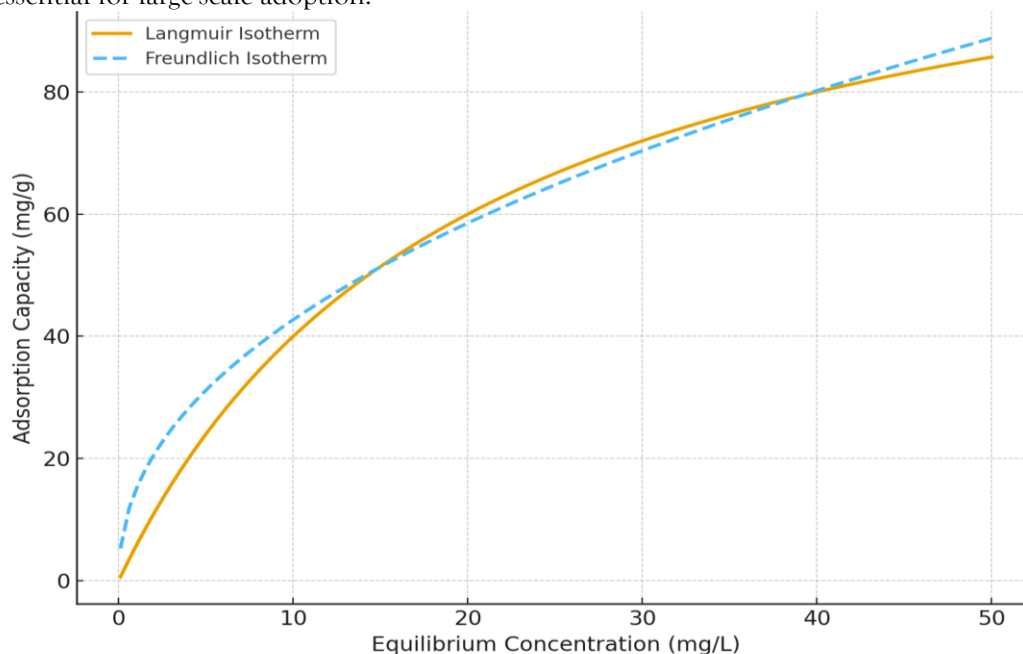


Figure 2. Adsorption Isotherm Models for Microplastic Removal Using Biodegradable Nanomaterials

4.3 Stability, Reusability, and Regeneration

A critical performance parameter is the ability to regenerate nanomaterials for multiple adsorption cycles without significant loss in efficiency.

- **Chitosan hydrogels:** Show reusability for up to 5 cycles with only ~15% reduction in adsorption capacity when regenerated using mild acid/base washing.
- **Nanocellulose aerogels:** Display partial collapse of porous structures after repeated use, limiting their reusability.
- **Magnetically modified lignin nanoparticles:** Provide excellent recyclability due to magnetic recovery but may undergo oxidation in long-term use.

Overall, most biodegradable nanomaterials require **improved structural stabilization** (e.g., crosslinking, hybrid composites) to ensure long-term applicability.

4.4 Case Studies in Laboratory and Semi-Field Conditions

Several recent case studies highlight the real-world potential and limitations of biodegradable nanomaterials:

1. Nanocellulose Aerogels in Lake Water Samples

○ A study utilizing CNC-based aerogels achieved >80% removal efficiency for PS microplastics in natural lake water. However, dissolved organic matter (DOM) competed for adsorption sites, lowering capacity compared to deionized water tests.

2. Chitosan-Coated Sand Filters for Flow-Through Systems

○ Chitosan-modified sand demonstrated continuous removal of PET and PE microplastics at flow rates relevant to wastewater treatment. Efficiency reached ~75%, though gradual fouling reduced long-term performance.

3. Magnetic Lignin Nanoparticles in Simulated Wastewater

○ Applied to mixed microplastic suspensions, these composites achieved rapid removal (>90%) within 30 minutes, with facile recovery via magnetic separation. Field adaptation, however, requires control of nanoparticle aggregation.

4. Soy Protein Hydrogels in Marine Salinity Conditions

○ Removal efficiency for PE microplastics dropped from 82% in freshwater to 58% in seawater due to ionic shielding of electrostatic interactions, underlining the importance of salinity effects.

These case studies demonstrate that while **laboratory efficiencies remain high, performance is significantly challenged by environmental complexity** such as DOM, salinity, competing colloids, and continuous flow dynamics.

4.5 Critical Factors Affecting Real-World Application

- **Water Chemistry:** High salinity, hardness, and pH variability influence binding mechanisms.
- **Particle Size Distribution:** Most studies focus on 1–20 μm microplastics, but efficiency decreases with nanoplastics (<1 μm).
- **Mixture of Plastics:** Natural waters contain diverse polymers (PS, PE, PP, PVC), complicating selectivity.
- **Economic and Energy Cost:** Large-scale production of nanocellulose or chitosan at high purity remains resource-intensive.
- **Toxicity Assessments:** While biodegradable, some chemical modifications (crosslinkers, surfactants) may introduce ecotoxicological concerns.

4.6 Research Gap Identified from Performance Studies

- Lack of **pilot-scale demonstrations** in real wastewater treatment plants.
- Insufficient data on **long-term biodegradation behavior** of modified nanomaterials.
- Limited understanding of **microplastic–nanomaterial interaction under turbulent flow conditions**.
- Few studies addressing **simultaneous removal of co-pollutants** (heavy metals, dyes) along with microplastics.
- Need for **techno-economic analysis** to compare cost-effectiveness against conventional treatment methods.

Biodegradable nanomaterials have demonstrated remarkable potential for microplastic removal with high efficiency, environmental safety, and adaptability. However, while laboratory studies confirm their promise, real-world complexities reduce their performance, underscoring the need for hybrid solutions, stability enhancement, and large-scale validations. The next step in this review is to assess **challenges, future prospects, and directions for integrating biodegradable nanomaterials into aquatic pollution management systems**.

5. Challenges, Future Perspectives, and Policy Implications

The integration of biodegradable nanomaterials into aquatic remediation frameworks is an emerging yet complex domain. Despite strong evidence supporting their adsorption capacity and environmental safety, several scientific, technical, socio-economic, and regulatory barriers remain. This section discusses the key challenges hindering widespread adoption, outlines future research perspectives, and emphasizes the policy dimensions that must be addressed to accelerate translation from laboratory experiments to real-world applications.

5.1 Scientific and Technical Challenges

5.1.1 Environmental Stability and Biodegradation Kinetics

While biodegradable nanomaterials are designed to disintegrate into harmless byproducts, the **rate and pathway of biodegradation** remain uncertain under diverse aquatic conditions. Factors such as salinity, pH, microbial community composition, and temperature strongly affect degradation kinetics. In some cases, premature degradation may reduce adsorption efficiency before the remediation process is complete, while delayed degradation may result in unintended persistence in the environment. Thus, a balance between **functional stability and timely biodegradability** is a major technical challenge.

5.1.2 Selectivity and Affinity for Different Microplastic Types

Most biodegradable nanomaterials rely on **electrostatic, hydrogen bonding, or hydrophobic interactions** to capture plastics. However, the heterogeneous nature of microplastic pollution—comprising polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET)—poses selectivity challenges. For instance, nanocellulose demonstrates higher affinity for PET and PS due to polar interactions, whereas non-polar polymers like PE show lower adsorption efficiency. Designing **multifunctional nanocomposites** capable of capturing diverse plastic chemistries remains an unmet need.

5.1.3 Scalability of Nanomaterial Production

Large-scale production of nanocellulose, chitosan, or lignin nanoparticles with uniform quality is resource- and energy-intensive. Current laboratory protocols often involve **freeze-drying, high-pressure homogenization, or solvent casting**, which are difficult to upscale without significantly raising costs. Furthermore, the availability of raw feedstocks (e.g., crustacean shells for chitosan, agricultural residues for lignin) is geographically constrained, introducing sustainability concerns for long-term deployment.

5.1.4 Integration into Existing Treatment Systems

Wastewater treatment plants (WWTPs) and industrial effluent systems are not yet equipped to incorporate nanomaterial-based adsorption units. For successful implementation, biodegradable nanomaterials must be compatible with **flow-through filters, membranes, or hybrid adsorption-catalysis systems**. Moreover, fouling, aggregation, and reduced efficiency under turbulent flow remain practical barriers to scaling.

5.2 Environmental and Ecotoxicological Concerns

Even though biodegradable nanomaterials are considered safer than synthetic nanomaterials, their environmental behavior requires rigorous scrutiny.

- **Toxicity of Additives and Crosslinkers:** Chemical modifications such as crosslinking with glutaraldehyde or surface functionalization with surfactants may introduce toxic residues.
- **Nanomaterial Byproducts:** The breakdown of modified nanocellulose or lignin nanoparticles may release small molecules that can alter microbial community balance in aquatic ecosystems.
- **Nanoplastic Intermediates:** Incomplete adsorption or degradation may result in the release of nanoplastics (<1 μm), which are even harder to capture.

Therefore, **comprehensive ecotoxicological assessments** under both controlled and field conditions are essential before commercial adoption.

5.3 Socio-Economic and Cost Considerations

The economic viability of biodegradable nanomaterials is a major challenge. Current estimates suggest that producing **nanocellulose aerogels costs 5–10 times more than conventional activated carbon** due to intensive processing requirements. Additionally, the infrastructure for mass production is still limited to research pilot plants. Unless cost-effective synthesis pathways are developed—such as **enzyme-assisted green synthesis, microbial fermentation routes, or agricultural waste valorization**—these nanomaterials may remain confined to niche applications rather than mainstream water treatment solutions.

5.4 Future Research Perspectives

To overcome these limitations, future research must address the following strategic directions:

5.4.1 Development of Hybrid Nanocomposites

The integration of biodegradable nanomaterials with **magnetic nanoparticles, photocatalytic oxides, or biochar** can enhance stability, recovery, and multifunctionality. For example, **magnetically recoverable chitosan-lignin composites** allow easy separation post-treatment, while nanocellulose-TiO₂ hybrids may enable simultaneous adsorption and photocatalytic degradation of microplastics.

5.4.2 Modeling Adsorption Mechanisms with Advanced Simulations

Molecular dynamics (MD) and density functional theory (DFT) simulations can help predict interaction energies between microplastics and biodegradable nanomaterials. Such computational models will guide the **rational design of surface functional groups** to optimize selectivity and performance.

5.4.3 Pilot-Scale Demonstrations

There is an urgent need to test these materials in **pilot wastewater treatment plants, industrial effluent streams, and riverine ecosystems**. Laboratory results, while promising, cannot fully replicate the

complexity of real-world systems where microplastics coexist with heavy metals, dyes, organic pollutants, and biological matter.

5.4.4 Life-Cycle and Techno-Economic Assessments

Life-cycle assessment (LCA) and techno-economic analysis (TEA) must be integrated into research to evaluate sustainability. For example, LCA would track the carbon footprint of nanocellulose synthesis from forestry biomass, while TEA would estimate the cost per cubic meter of water treated compared to activated carbon or membrane filtration.

5.5 Policy, Regulatory, and Governance Dimensions

5.5.1 Lack of Standardized Protocols

Currently, there is no globally accepted standard for evaluating the **adsorption efficiency, reusability, and ecotoxicity** of biodegradable nanomaterials for microplastic removal. This absence of harmonized protocols makes cross-comparison between studies difficult and slows down regulatory approval.

5.5.2 Integration with Circular Economy Policies

Biodegradable nanomaterials align with the principles of circular economy, as many are derived from agricultural residues, forestry byproducts, or seafood industry waste. Policymakers could incentivize the development of such technologies by integrating them into **extended producer responsibility (EPR) frameworks** and **green procurement policies**.

5.5.3 Funding and Public-Private Partnerships

Government funding, combined with private-sector participation, will be essential to scale production. International organizations such as the **UNEP and OECD** are already emphasizing innovation in biodegradable polymers; similar efforts are required for nanomaterial applications targeting aquatic microplastics.

5.5.4 Regulatory Frameworks for Safe Deployment

Before commercial implementation, **nanomaterial-specific legislation** is required to ensure safety. Unlike conventional adsorbents, nanomaterials require evaluation of particle release, degradation pathways, and long-term ecotoxicity. Harmonized global regulations could accelerate the transition from laboratory to market.

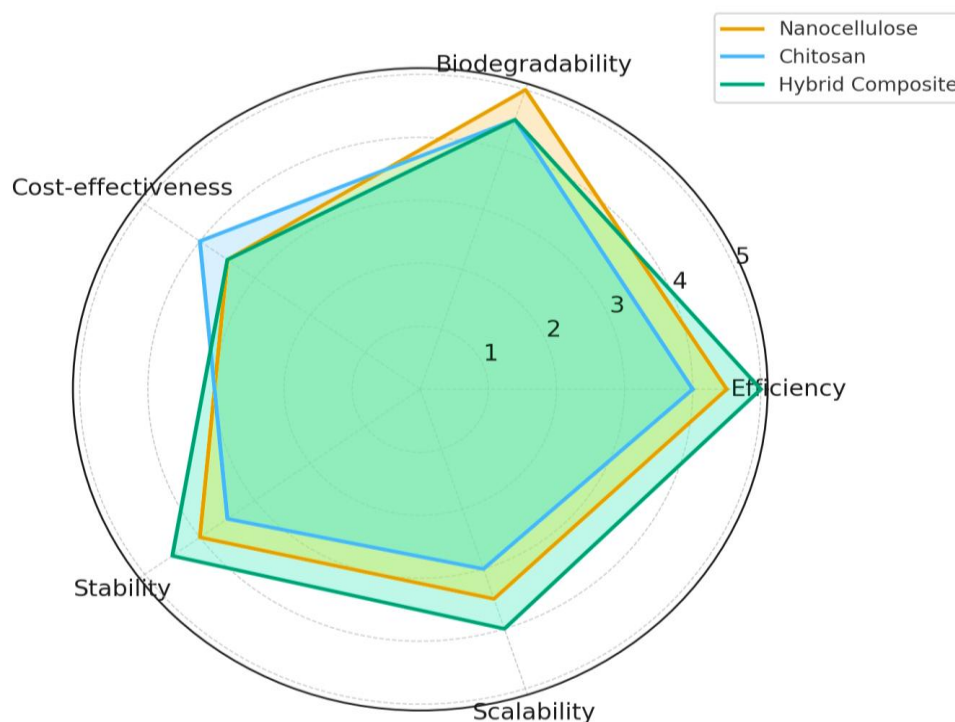


Figure 3. SWOT-Based Performance Evaluation of Selected Biodegradable Nanomaterials

5.6 Research Gaps and Strategic Roadmap

From the synthesis of biodegradable nanomaterials to their deployment in real aquatic environments, multiple gaps remain:

- Absence of **pilot-scale validation** and long-term field monitoring.
- Insufficient data on **microplastic–nanomaterial interactions under turbulent hydrodynamic conditions**.
- Lack of **standardized analytical methods** for quantifying adsorption and degradation efficiency.
- Limited **comparative studies across different aquatic ecosystems** (freshwater, estuarine, and marine).
- Weak integration of **economic, environmental, and policy frameworks** into technological development.

To bridge these gaps, a strategic roadmap must include **multidisciplinary collaborations between material scientists, environmental engineers, ecotoxicologists, and policy analysts**, supported by strong funding mechanisms.

In conclusion, biodegradable nanomaterials represent a transformative opportunity to mitigate microplastic pollution in aquatic ecosystems. However, realizing this potential requires addressing fundamental challenges in material design, scalability, and environmental safety, while simultaneously embedding these innovations within sustainable policy frameworks. The future trajectory of research must not only focus on laboratory-scale optimization but also embrace pilot demonstrations, life-cycle analyses, and regulatory harmonization. Only then can biodegradable nanomaterials transition from experimental materials to practical solutions capable of safeguarding global aquatic environments.

6. CONCLUSION

Microplastic contamination in aquatic environments poses serious ecological and health risks, demanding sustainable remediation strategies. This review highlights that biodegradable nanomaterials such as nanocellulose, chitosan, and lignin-based systems provide high removal efficiency while avoiding secondary pollution. Their tunable surface chemistry, eco-compatibility, and degradability make them strong alternatives to conventional nanomaterials. Yet, challenges remain regarding stability, large-scale synthesis, integration into treatment systems, and long-term ecotoxicity. Future research must focus on multifunctional hybrid designs, pilot-scale applications, and techno-economic analyses, supported by robust policy and regulatory frameworks. In summary, biodegradable nanomaterials hold significant promise for advancing microplastic remediation, aligning technological innovation with environmental sustainability and circular economy principles.

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