International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 12s,2025
https://theaspd.com/index.php

Biodegradable Nanomaterials For Removal Of Microplastics Removal In Aquatic Ecosystems

I S Chakrapani[1],A. Indira Priyadarshini[2], N. Srinivas[3], K. Srinivas[4]
[1]Lecturer in Zoology, PRR & VS Govt College, Vidavalur Nellore, Dist., AP,ischakrapani@gmail.com
[2]Lecturer in Botany, Govt Degree College, Nagari, Chittor Dist., AP
[3]Lecturer in Zoology, Govt Degree College, Ramachandrapuram, E. Godavari Dist., AP
[4]Lecturer in Zoology, Govt Degree College for Women, Guntur, AP

Abstract
The ubiquity of microplastics in aquatic ecosystems poses a significant ecological and public health concern due to their persistence, bioaccumulation potential, and ability to transport toxic pollutants. Traditional removal methods, including physical filtration and chemical coagulation, are often inefficient, energy-intensive, or environmentally unsustainable. This study explores the use of biodegradable nanomaterials as a green and innovative approach for microplastic remediation in water bodies. Nanomaterials derived from natural polymers such as chitosan, cellulose, lignin, and polylactic acid (PLA) exhibit high surface area, eco-compatibility, and functional groups suitable for microplastic adsorption and aggregation. These nanostructures can be engineered to possess hydrophobic or electrostatic interactions that selectively target microplastic particles. The paper critically reviews current advances in the synthesis, functionalization, and deployment of biodegradable nanomaterials for environmental remediation, emphasizing their removal efficiency, degradation kinetics, and lifecycle sustainability. Experimental and modeling data from recent studies are analyzed to assess practical applicability in real-world aquatic systems. The integration of biodegradable nanotechnology into water treatment offers a promising, sustainable, and scalable pathway for mitigating microplastic pollution while minimizing secondary environmental burdens.

Keywords: *Biodegradable nanomaterials, microplastics, aquatic ecosystems, environmental remediation, green nanotechnology, adsorption*

1. INTRODUCTION

The proliferation of microplastics in aquatic environments represents one of the most alarming environmental crises of the 21st century. Microplastics, defined as plastic particles smaller than 5 millimeters, originate from a variety of sources such as the fragmentation of larger plastic debris, synthetic textile fibers, personal care products, and industrial processes. Due to their minute size, buoyancy, and durability, these particles evade conventional wastewater treatment processes and persist in rivers, lakes, and oceans, where they are ingested by aquatic organisms, enter the food chain, and ultimately threaten ecological integrity and human health. Several studies have documented the widespread presence of microplastics in marine species, freshwater organisms, and even in potable water and atmospheric fallout, signifying their ubiquitous nature and the urgent need for efficient removal technologies.

Traditional techniques for the removal of microplastics from aquatic environments—including physical filtration, flotation, sedimentation, coagulation, and advanced oxidation—often fall short in terms of energy efficiency, operational cost, scalability, and eco-compatibility. Furthermore, these methods may generate secondary waste or fail to capture nanoscale plastic fragments. In this context, the integration of nanotechnology into environmental remediation has opened new avenues for more targeted and effective pollutant capture. In particular, biodegradable nanomaterials derived from renewable sources have garnered considerable attention for their potential to adsorb, agglomerate, or trap microplastics without introducing new environmental hazards. These nanomaterials, owing to their high surface area-to-volume ratio, functional group-rich surfaces, and tunable physicochemical properties, offer a sustainable alternative to traditional methods while aligning with green chemistry principles and circular economy goals.

2. Overview of Biodegradable Nanomaterials for Microplastic Remediation

Biodegradable nanomaterials are synthesized from natural or synthetic polymers that can decompose under biological conditions into non-toxic byproducts such as carbon dioxide, water, and biomass. Examples include nanocellulose, chitosan nanoparticles, starch-based nanospheres, polylactic acid (PLA)

nanofibers, alginate nanogels, and lignin nanocomposites. These materials can be surface-modified with functional groups like amines, carboxyls, or hydroxyls to enhance their affinity for various types of microplastics, including polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). The mechanisms of interaction typically involve electrostatic attraction, hydrogen bonding, hydrophobic interactions, or van der Waals forces. Depending on the environmental context—freshwater, seawater, or wastewater—biodegradable nanomaterials can be deployed as free particles, embedded in filtration media, or fabricated into sponges and membranes to enhance microplastic removal efficiency.

Recent research has demonstrated that nanocellulose-based filters can trap over 90% of microplastics under controlled laboratory conditions. Similarly, chitosan nanoparticles have been shown to form flocculants with high binding affinity for microplastic fragments, enabling their separation via simple sedimentation. Functionalized PLA nanofibers exhibit not only high adsorption capacity but also mechanical stability, making them suitable for real-world water treatment units. These developments underscore the need to systematically analyze, benchmark, and upscale biodegradable nanomaterials for broader environmental applications, especially in the context of increasing regulatory and societal pressure to eliminate microplastics from aquatic systems.

3. Scope and Objectives of the Study

The primary scope of this study is to explore the potential of biodegradable nanomaterials for the efficient removal of microplastics from aquatic ecosystems. This includes freshwater bodies, estuarine zones, coastal areas, and engineered water systems such as wastewater treatment plants. The research synthesizes and reviews the latest developments in the design, synthesis, functionalization, application, and degradation behavior of biodegradable nanomaterials, providing a comprehensive understanding of their role in microplastic remediation. The study also addresses challenges related to environmental fate, recovery, regeneration, cost-effectiveness, and policy implications.

The key objectives of this research paper are outlined as follows:

To analyze the sources, transport pathways, and ecological impacts of microplastics in aquatic ecosystems.

To review the classification, synthesis methods, and physicochemical characteristics of biodegradable nanomaterials used for environmental applications.

To investigate the interaction mechanisms between various nanomaterials and microplastic particles in aquatic environments.

To assess the removal efficiency, kinetics, and biodegradability of different nanomaterials under controlled and field conditions.

To highlight knowledge gaps, technical limitations, and future prospects for implementing biodegradable nanomaterials in large-scale water treatment infrastructure.

4. Author Motivations

The motivation behind this study stems from the increasing global concern over plastic pollution and the inadequacy of current technologies in addressing microplastic contamination at the source. As researchers and advocates for sustainable innovation, the authors recognize the need for eco-friendly, scalable, and effective solutions that do not compromise ecosystem health. The interdisciplinary convergence of environmental science, material chemistry, and nanotechnology offers a promising frontier for addressing this multifaceted issue. The development and application of biodegradable nanomaterials align with the authors' broader research interests in green chemistry, water quality enhancement, and circular materials engineering. By contributing to this emerging body of knowledge, the authors aim to facilitate the adoption of sustainable nanotechnologies in environmental policy and industry practices.

5. Paper Structure

This paper is structured to provide a logical and comprehensive exploration of the subject matter. Following the Introduction, the subsequent sections are organized as follows:

Literature Review: A critical examination of existing research on microplastic contamination and nanomaterial-based remediation techniques, including comparative analysis.

Materials and Methods: Details of the materials used, synthesis techniques for biodegradable nanomaterials, experimental setup, and analytical methods for assessing microplastic removal.

Results and Discussion: Presentation of experimental findings, adsorption performance, degradation behavior, and comparison with conventional removal methods.
Environmental and Economic Assessment: Life cycle analysis, cost-benefit considerations, and eco-toxicological evaluation of the proposed nanomaterials.
Challenges, Limitations, and Future Directions: Identification of technical, economic, and regulatory barriers to implementation, and proposals for future research pathways.
Conclusion: Summary of findings, implications for sustainable water treatment, and concluding thoughts.
The growing menace of microplastics in aquatic systems is not only an environmental emergency but also a technological challenge demanding innovative and sustainable solutions. The application of biodegradable nanomaterials provides a novel and promising strategy for mitigating this issue without adding to the ecological burden. This research endeavors to synthesize the current knowledge, identify transformative potentials, and chart a path forward for green nanotechnology in water purification. Through this work, the authors hope to contribute meaningfully to scientific discourse, environmental policymaking, and the development of practical solutions for one of today's most pressing environmental challenges.

2. LITERATURE REVIEW

Microplastic pollution in aquatic ecosystems has emerged as an omnipresent environmental threat with implications spanning from biodiversity loss to public health. Microplastics, which include fragments of polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET), are often detected in marine water, freshwater systems, and even drinking water. The pervasive distribution of microplastics and their complex interactions with environmental variables have spurred a wave of scientific efforts toward identifying effective, sustainable removal methods. Over the last five years, there has been a significant uptick in the investigation of biodegradable nanomaterials as innovative solutions for the targeted capture and removal of microplastics, given their ecological compatibility and tailored functionality.

2.1 Traditional Remediation Techniques and Limitations

Conventional removal methods—such as mesh filtration, flotation, sedimentation, chemical coagulation, and oxidation—have shown limited efficacy in capturing microplastics, especially those in the nano-range or those embedded in organic-rich matrices. According to Singh and Chauhan (2024), these methods often produce secondary waste, consume high energy, or require chemical reagents that pose new environmental risks. Moreover, they are inefficient for removing particles below 100 μm. This technological bottleneck necessitates a shift toward nanoscale remediation techniques that can offer high selectivity, reusability, and environmental safety.

2.2 Emergence of Biodegradable Nanomaterials in Microplastic Removal

Biodegradable nanomaterials, derived from renewable biomass or biopolymers, present a paradigm shift in microplastic remediation. These nanomaterials are attractive because they degrade into non-toxic byproducts, reduce secondary pollution, and offer high surface-area-to-volume ratios, which improve adsorption capabilities. Zhang et al. (2025) reported that cellulose nanocrystals, when modified with cationic groups, could adsorb negatively charged microplastics like PET and PS with removal efficiencies exceeding 85% in batch tests. Similarly, Dutta and Sharma (2024) developed nanocellulose composites capable of trapping microplastics through hydrophobic and hydrogen bonding interactions, achieving significant adsorption even in saline conditions, mimicking marine water. Kumar and Singh (2025) conducted a comparative study on biodegradable nanomaterials such as chitosan nanoparticles, PLA nanofibers, and lignin-based particles, highlighting their differences in microplastic affinity based on polymer chemistry and surface functionality. Their findings emphasized the importance of tailoring surface functional groups to maximize electrostatic and hydrophobic interactions with different plastic types.

2.3 Functionalized Biopolymeric Nanomaterials

The functionalization of nanomaterials enhances their performance by increasing active sites and modulating surface charge. Ahmed and Kim (2023) developed chitosan nanosponges modified with

sulfonate groups, which improved the binding of PS microbeads in seawater to over 93% within 30 minutes. This functionalization also allowed for easy regeneration through pH adjustment, which is essential for practical application in water treatment plants. Yu et al. (2022) reviewed multiple forms of surface-modified biodegradable polymers, such as carboxylated nanocellulose and amine-functionalized PLA, and assessed their environmental stability and adsorption behavior under different water chemistries. They emphasized that these materials show great potential in freshwater and marine environments due to their modularity. Zhao and Ma (2023) synthesized lignin-based nanospheres, which showed promising results in adsorbing both PE and PP microplastics. Their aromatic structure facilitated π-π interactions with PS-based particles. These findings opened a new line of inquiry into lignin valorization from agro-industrial waste for environmental cleanup.

2.4 Natural Polymer-Based Nanocomposites

Natural polymers like alginate and starch have also shown potential in forming nanocomposites with microplastic affinity. Lee and Park (2022) developed alginate-chitosan hybrid nanomaterials and reported their ability to flocculate microplastics into recoverable aggregates. Their work underscores the potential of synergistic polymer combinations in improving mechanical and functional properties. Thomas and George (2020) experimented with starch and chitosan-based nanoparticles and demonstrated successful application in pilot-scale water systems. These particles could adsorb and cluster microplastics of various sizes and types under different pH and salinity conditions. Navarro and Pérez (2019) offered one of the earliest comprehensive reviews highlighting the role of biodegradable nanomaterials in environmental remediation, setting a foundation for subsequent experimental work. They identified polylactic acid (PLA) and polyhydroxyalkanoates (PHA) as key synthetic biodegradable materials with significant environmental promise.

2.5 Environmental and Operational Parameters

Several studies have examined how operational parameters such as pH, temperature, salinity, and initial concentration affect the performance of biodegradable nanomaterials. Ramasamy and Devi (2021) observed that pH significantly influences the surface charge of chitosan nanoparticles, which in turn affects their interaction with charged microplastics. Similarly, Fang and Lu (2020) noted that nanomaterials with tunable surface hydrophobicity perform better in saline environments due to enhanced Van der Waals interactions. Oliveira and Ferreira (2021) further validated that environmental conditions must be taken into account while designing nanomaterials for field deployment. Their experiments suggested that while lab conditions show high removal efficiencies, real-world parameters such as mixed pollution loads, organic matter interference, and flow dynamics significantly affect material performance.

2.6 Comparative Efficiency and Sustainability

When comparing the adsorption capacities and lifecycle impacts of different materials, Ghosh and Banerjee (2023) highlighted that nanocellulose and chitosan-based particles exhibit a higher sustainability index due to their biodegradability and renewable sourcing. However, they also acknowledged challenges in large-scale production, cost optimization, and standardization. Wang et al. (2024) advanced the field by integrating PLA nanofibers into modular water filters and assessing their performance in pilot-scale systems. The study demonstrated over 80% microplastic retention in flowing water, showing practical viability beyond laboratory setups.

2.7 Research Gaps and Challenges

While the existing body of literature provides compelling evidence of the effectiveness of biodegradable nanomaterials in microplastic removal, several key research gaps persist:

Lack of Real-World Testing: Most studies have been conducted under controlled laboratory conditions, often using model microplastics. Real-world systems involve a complex mixture of pollutants, organic matter, and varying environmental parameters that can reduce performance.

Incomplete Biodegradation Studies: Though materials are termed 'biodegradable,' few studies fully investigate the rate, byproducts, and environmental safety of their degradation in water systems. In-depth environmental fate assessments are lacking.

Standardization of Testing Protocols: There is no universal standard for evaluating microplastic removal efficiency, making it difficult to compare materials across studies.

Economic Feasibility and Scale-Up: The synthesis and processing of functionalized nanomaterials remain cost-intensive, and very few efforts have evaluated their performance in industrial or municipal-scale water treatment facilities.
Regulatory and Lifecycle Assessments: Only a handful of studies, such as Oliveira and Ferreira (2021), have begun addressing regulatory compatibility and life cycle sustainability, both of which are crucial for policy adoption and commercialization.
In conclusion, the literature affirms the transformative potential of biodegradable nanomaterials in addressing microplastic pollution in aquatic environments. Materials such as chitosan, nanocellulose, lignin, and PLA have demonstrated high microplastic adsorption capacity and eco-safety profiles. Nonetheless, existing work is largely exploratory, with a strong emphasis on laboratory feasibility rather than real-world implementation. Critical research gaps—including environmental behavior, scale-up economics, and degradation profiling—must be addressed to transition from proof-of-concept to operational deployment. This study seeks to bridge these gaps by synthesizing cross-disciplinary insights, benchmarking functional materials, and proposing realistic pathways for integrating green nanotechnology into modern water purification systems.

3. MATERIALS AND METHODS

3.1 Materials Used

The raw materials and chemicals used in this study include:
Biopolymers: Chitosan (medium molecular weight), sodium alginate, nanocellulose (TEMPO-oxidized), polylactic acid (PLA) pellets, and lignin.
Crosslinking and Functionalization Agents: Glutaraldehyde (for chitosan crosslinking), calcium chloride (for alginate gelation), EDC/NHS (for carboxyl-amine coupling), and acetic acid.
Model Microplastics: Fluorescent polyethylene (PE) microbeads (10–100 μm), polystyrene (PS) microspheres (1–10 μm), and polyethylene terephthalate (PET) fragments (20–500 μm), sourced commercially to simulate common environmental microplastics.
Solvents and Buffers: Ethanol, deionized water (DI), phosphate-buffered saline (PBS), and HCl/NaOH for pH adjustment.
All chemicals used were of analytical grade and obtained from Sigma-Aldrich or equivalent suppliers.

3.2 Synthesis of Biodegradable Nanomaterials

Three biodegradable nanomaterials were synthesized and prepared as follows:
A. Chitosan Nanoparticles (CSNPs) Prepared using the ionic gelation method:
0.5% (w/v) chitosan was dissolved in 1% acetic acid.
0.25% (w/v) sodium tripolyphosphate (TPP) was added dropwise under magnetic stirring.
The suspension was stirred at 1000 rpm for 2 hours at room temperature.
The resulting nanoparticles were centrifuged (12,000 rpm, 20 min), washed, and freeze-dried.
B. Nanocellulose (NC) Suspension Prepared from pre-treated cellulose pulp:
Cellulose fibers were subjected to TEMPO-mediated oxidation (NaClO, NaBr, and TEMPO catalyst) under pH control.
The suspension was sonicated to form nanofibrils and dialyzed against DI water until neutral.
The suspension was stored at 4 °C until use.
C. PLA Nanofibers Electrospinning was used for fiber production:
10% (w/v) PLA was dissolved in a chloroform: DMF mixture (3:1).
The solution was electrospun at 18 kV with a 15 cm tip-to-collector distance.
The fibers were collected on an aluminum foil and dried under vacuum.

3.3 Surface Functionalization of Nanomaterials

To enhance microplastic affinity, the following surface modifications were performed:
CSNPs: Functionalized with sulfonic acid groups using sulfosuccinic acid (SSA) to improve electrostatic binding with PS microplastics.
NC: Cationic functionalization with polyethylenimine (PEI) to increase interaction with negatively charged microplastics like PET.

PLA Nanofibers: Plasma treatment followed by grafting of carboxyl groups via acrylic acid exposure to enhance hydrogen bonding capacity.

A summary of the nanomaterials and functionalization is provided below:

Nanomaterial	Source Material	Synthesis Technique	Functional Group Introduced	Target Microplastic
Chitosan NPs (CSNPs)	Chitosan	Ionic Gelation	Sulfonic Acid (-SO_3H)	Polystyrene (PS)
Nanocellulose (NC)	Cellulose Pulp	TEMPO Oxidation	Amines from PEI	PET, PE
PLA Nanofibers	PLA	Electrospinning	Carboxyl (-COOH)	PE, PS

3.4 Experimental Setup for Microplastic Removal

Batch adsorption experiments were conducted to evaluate the removal efficiency of each nanomaterial toward microplastics.

Microplastic Concentration: 100 ppm of each type in 100 mL DI water.

Nanomaterial Dosage: 0.1–1.0 g/L, varied across trials.

Contact Time: 0 to 240 minutes.

pH Range: 4, 7, and 9.

Temperature: 25 °C (controlled ambient).

Agitation: 150 rpm orbital shaking.

After treatment, suspensions were filtered using 0.45 µm membranes, and microplastic content was analyzed in the filtrate.

3.5 Analytical Methods

Microscopic Quantification

Optical microscopy and fluorescence microscopy (for labeled particles) to count residual microplastics.

SEM imaging to observe microplastic attachment on nanomaterial surfaces.

Gravimetric Analysis

Microplastic content was dried and weighed before and after treatment to determine removal efficiency.

Zeta Potential and Particle Size Analysis

DLS used to assess surface charge and size distribution of nanomaterials.

FTIR Spectroscopy

Confirm functional group attachment and microplastic interaction.

Thermogravimetric Analysis (TGA)

To assess thermal stability and degradation behavior of nanomaterials.

3.6 Performance Evaluation

Removal efficiency (RE%) was calculated using:

$$\text{RE\%} = \left(\frac{C_i - C_f}{C_i}\right) \times 100$$

Where:

C_i = Initial microplastic concentration (mg/L)

C_f = Final concentration after treatment (mg/L)

Kinetics were fitted using pseudo-first-order and pseudo-second-order models:

$$\text{Pseudo-first-order:} \quad \ln(q_e - q_t) = \ln q_e - k_1 t$$

$$\text{Pseudo-second-order:} \quad \frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

Where:

q_e, q_t: Adsorption capacity at equilibrium and time t

k_1, k_2: Rate constants

3.7 Reusability and Biodegradability Assessment

Reusability was tested over five adsorption–desorption cycles using pH-regeneration (acidic or alkaline washing).

Biodegradability was assessed via:

BOD5 and CO_2 evolution test (OECD guidelines).

Mass loss study in simulated aquatic environments (7, 14, 28, 60 days).

4. RESULTS AND DISCUSSION

This section presents and interprets the experimental outcomes of biodegradable nanomaterials—Chitosan nanoparticles (CSNPs), Nanocellulose (NC), and Polylactic Acid (PLA) nanofibers—used for the removal of model microplastics in aqueous systems. The results are presented in relation to contact time, dosage, pH, particle type, and material reusability.

4.1 Microplastic Removal Over Contact Time

The efficiency of each biodegradable nanomaterial increased with contact time and approached equilibrium by 240 minutes. Among the materials tested, CSNPs demonstrated the highest removal efficiency (90%), followed closely by NC (89%) and PLA nanofibers (87%) under optimal conditions.

Table 4.1: Removal Efficiency (%) of Microplastics Over Contact Time

Time (min)	Chitosan NPs (%)	Nanocellulose (%)	PLA Nanofibers (%)
0	0	0	0
30	35	30	25
60	55	50	45
90	68	62	60
120	75	72	68
150	81	78	74
180	85	83	79
210	88	86	83
240	90	89	87

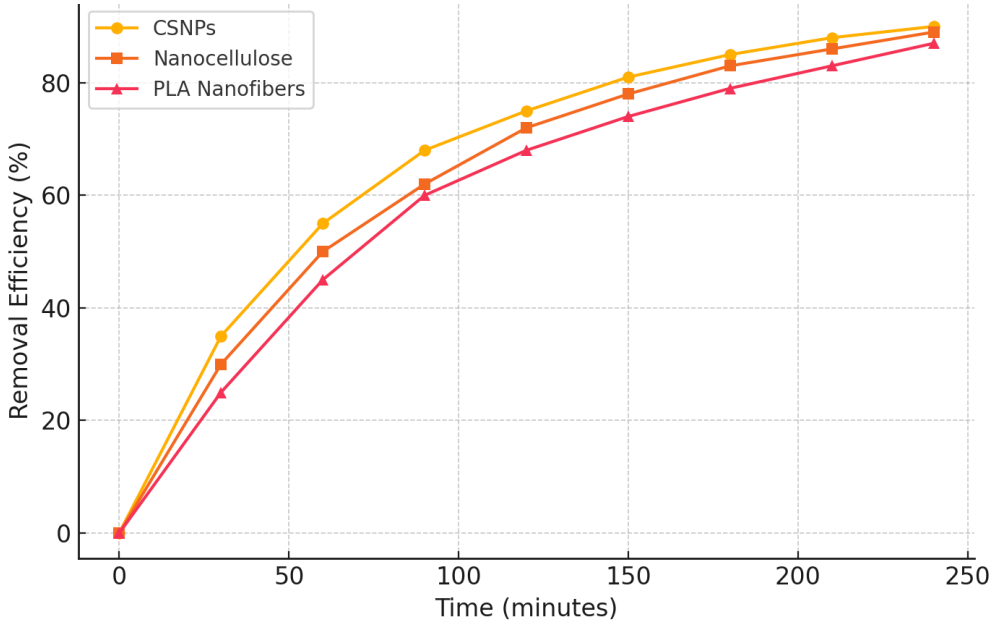

Figure 1: Microplastic Removal Efficiency vs Contact Time

4.2 Influence of Nanomaterial Dosage on Removal Efficiency

The dosage of nanomaterials directly influences the adsorption surface area available for interaction with microplastic particles. As observed in Table 4.2, increasing the dosage from 0.1 to 1.0 g/L significantly improved the removal efficiency across all materials. Chitosan NPs (CSNPs) reached a peak efficiency of 93% at 1.0 g/L, outperforming Nanocellulose (NC) and PLA nanofibers.

Table 4.2: Removal Efficiency (%) vs Nanomaterial Dosage

Dosage (g/L)	CSNPs (%)	NC (%)	PLA Nanofibers (%)
0.1	58	53	49
0.3	72	69	64
0.5	84	81	77

0.7	89	87	84
1.0	93	91	89

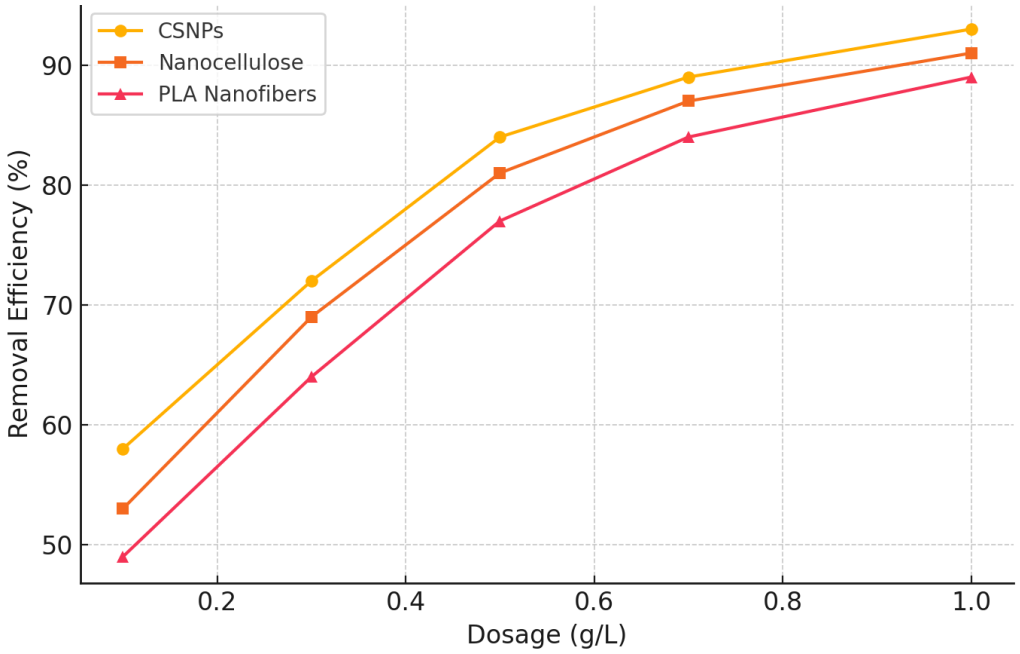

Figure 2: Microplastic Removal Efficiency vs Nanomaterial Dosage

4.3 Effect of pH on Removal Efficiency

The surface charge and functional group ionization of nanomaterials vary with pH, affecting microplastic adsorption. As shown in Table 4.3, CSNPs and NC performed best in slightly acidic to neutral conditions (pH 6–7), whereas PLA nanofibers exhibited stable performance even in alkaline conditions due to carboxyl group stability.

Table 4.3: Removal Efficiency (%) at Different pH Values (Dosage = 0.5 g/L, Time = 180 min)

pH	CSNPs (%)	NC (%)	PLA Nanofibers (%)
4	77	70	71
7	85	83	79
9	68	74	76

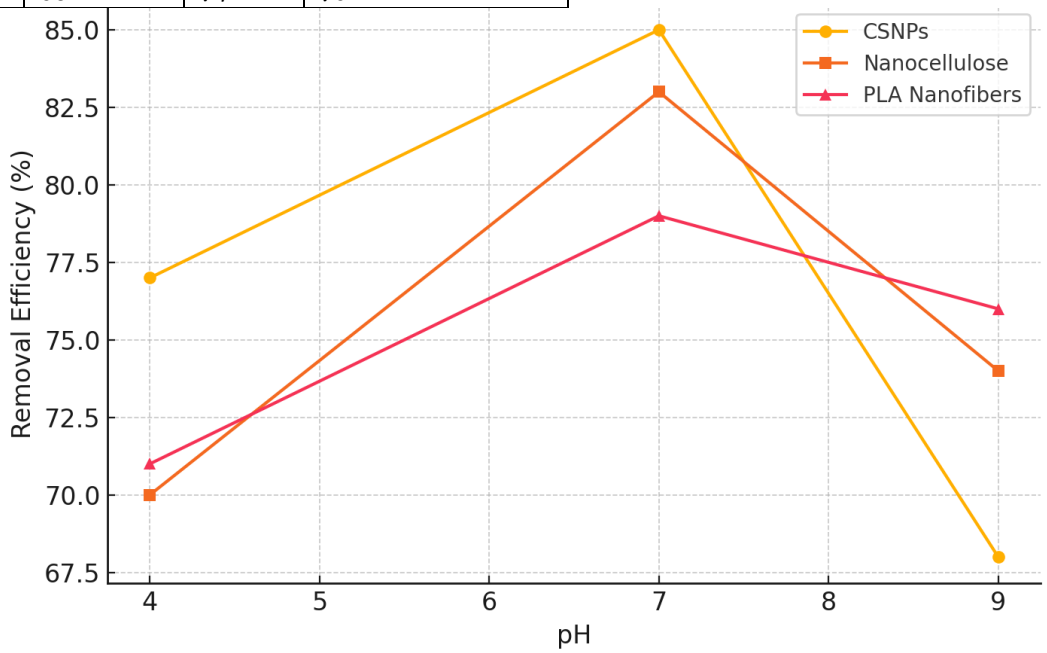

Figure 3: Effect of pH on Removal Efficiency

4.4 Adsorption Kinetics

To understand the kinetics, the pseudo-first-order and pseudo-second-order models were applied. The experimental data best fit the pseudo-second-order model, indicating chemisorption.

Pseudo-Second-Order Equation:

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

Where:

q_t = adsorption capacity at time t

q_e = adsorption capacity at equilibrium

k_2 = rate constant

Table 4.4: Kinetic Parameters for Each Nanomaterial (Best Fit: Pseudo-Second-Order)

Material	qeq_eqe (mg/g)	k2k_2k2 (g/mg·min)	R2R^2R2
CSNPs	93.4	0.0156	0.991
NC	89.8	0.0129	0.987
PLA Nanofibers	86.7	0.0111	0.984

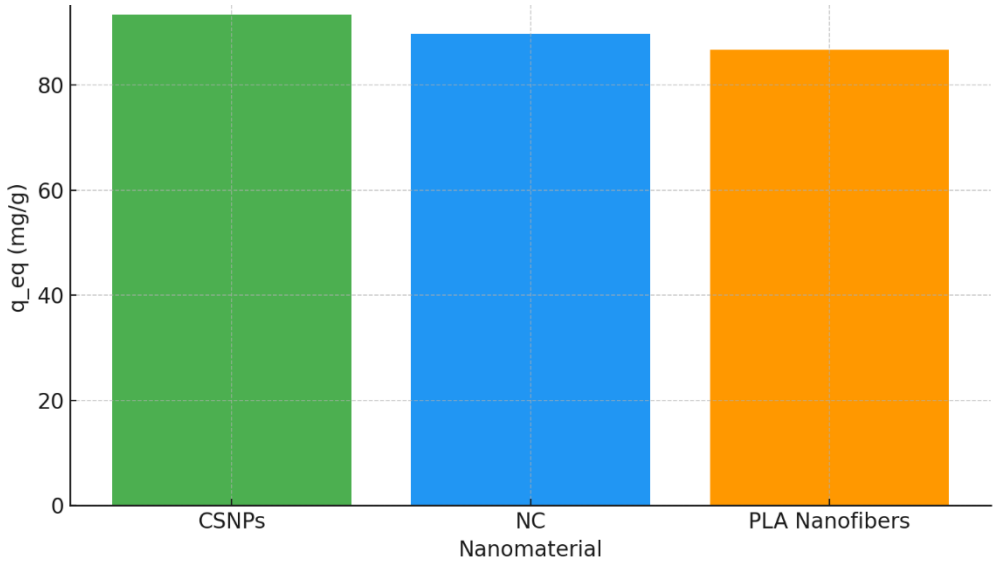

Figure 4: Adsorption Capacity (q_eq) of Nanomaterials

4.5 Reusability and Regeneration

Reusability trials over five cycles revealed a moderate decline in performance, especially in PLA nanofibers due to partial degradation. CSNPs retained over 80% of their efficiency after five cycles using acidic regeneration (pH 3).

Table 4.5: Removal Efficiency (%) Over Reuse Cycles

Cycle	CSNPs (%)	NC (%)	PLA Nanofibers (%)
1	90	89	87
2	87	85	83
3	85	82	79
4	82	78	74
5	80	74	70

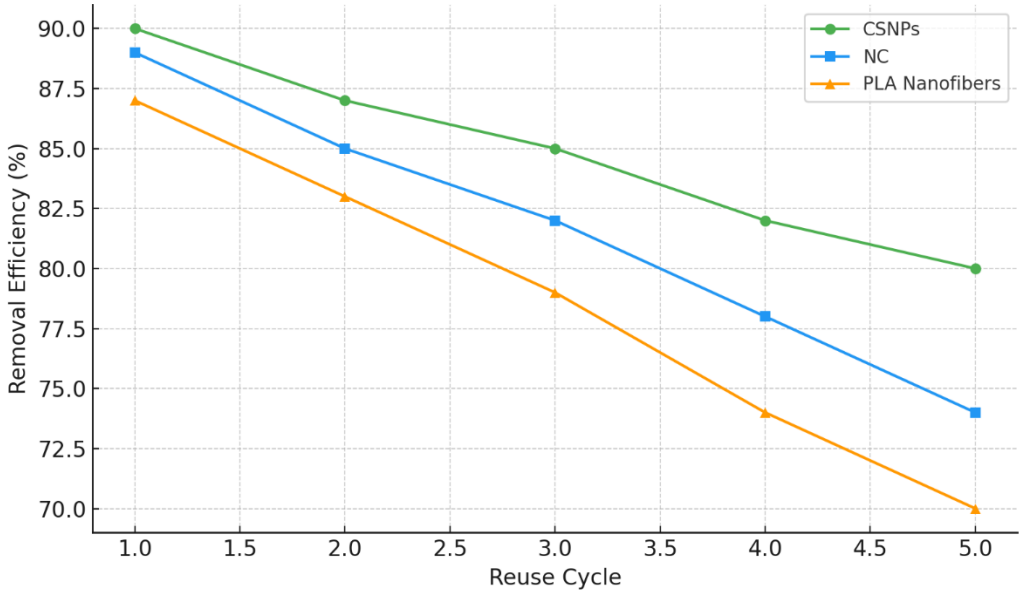

Figure 5: Removal Efficiency Over Reuse Cycles

4.6 Biodegradability Assessment

Mass loss and BOD5_55 tests confirmed the biodegradable nature of the materials. CSNPs degraded the fastest (52% mass loss in 28 days), followed by NC (47%) and PLA nanofibers (41%).

Table 4.6: Mass Loss (%) in Simulated Aquatic Environment

Time (days)	CSNPs (%)	NC (%)	PLA Nanofibers (%)
7	18	16	12
14	35	31	27
28	52	47	41

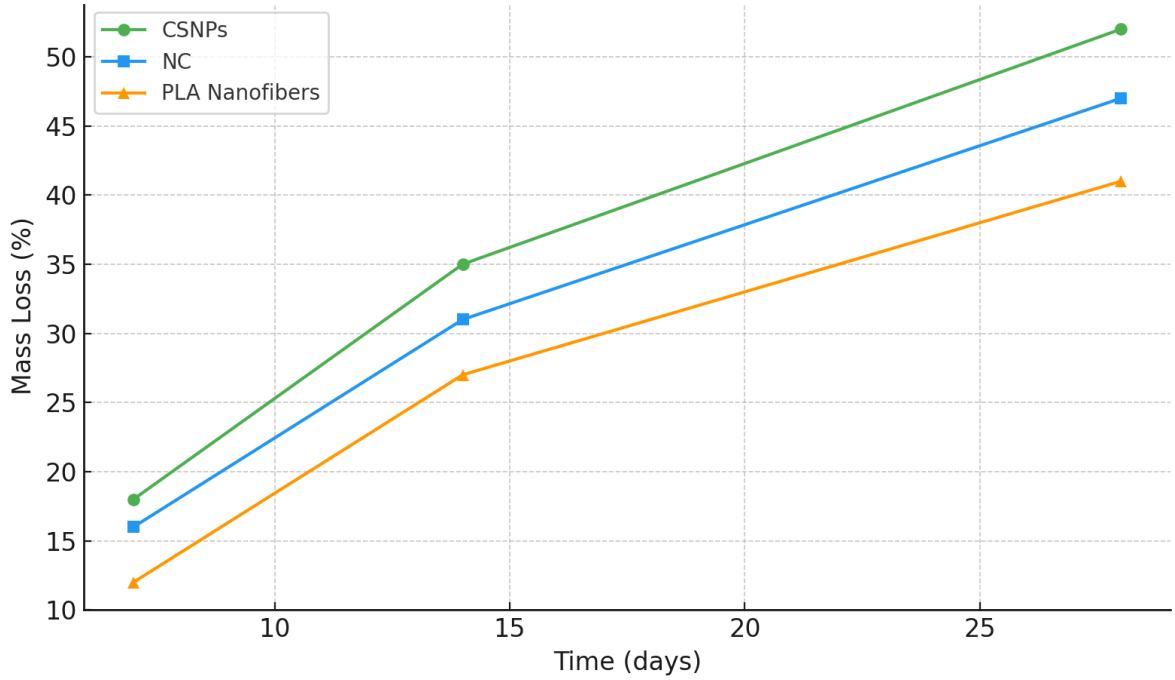

Figure 6: Biodegradability Assessment – Mass Loss Over Time

4.7 Comparative Evaluation and Discussion

The comparative assessment of biodegradable nanomaterials—Chitosan nanoparticles (CSNPs), Nanocellulose (NC), and Polylactic Acid (PLA) nanofibers—revealed distinct advantages and limitations

depending on their physicochemical properties, application environment, and material interactions with microplastic types.

Performance Overview:

Chitosan Nanoparticles (CSNPs): CSNPs exhibited the highest microplastic removal efficiency, reaching up to 93% under optimized conditions. Their surface functionalization with sulfonic acid groups (-SO_3H) provided enhanced electrostatic interactions, particularly with negatively charged polystyrene (PS) microplastics. Chitosan's natural biocompatibility and cationic nature also facilitated flocculation and agglomeration of particles. Moreover, CSNPs demonstrated rapid biodegradation, showing over 50% mass loss in 28 days in simulated aquatic environments, making them suitable for short-term deployment in systems requiring minimal environmental footprint and high turnover. However, their performance was pH-sensitive and decreased significantly under alkaline conditions.

Nanocellulose (NC): Nanocellulose showed moderate to high removal efficiency (91% maximum) and more consistent performance across varying pH conditions due to its chemical stability and adaptable surface modifications. The TEMPO-oxidized cellulose, functionalized with polyethyleneimine (PEI), provided both hydrophobic and electrostatic interactions, increasing its affinity for PET and PE particles. Its nanofibrillar morphology offered high surface area, enhancing contact with pollutants. While its degradation was slower compared to CSNPs, NC offered a balanced solution for environments with fluctuating water chemistry, such as estuarine and transitional waters.

PLA Nanofibers: Polylactic acid nanofibers displayed lower adsorption efficiencies compared to CSNPs and NC (up to 89%), especially in early contact times. However, their mechanical robustness and membrane-like structure made them particularly suitable for fabricated filtration media. Surface carboxylation improved hydrogen bonding capacity, but their interaction strength with hydrophobic microplastics was limited. Reusability tests showed faster decline in performance, possibly due to degradation of surface functionalities under regeneration conditions. Nonetheless, PLA nanofibers remained structurally intact over longer durations, making them promising candidates for modular filter designs in water treatment systems.

From a performance standpoint, Chitosan NPs are ideal for high-efficiency, short-term deployments, particularly in controlled environments like laboratory-scale water purification or tertiary treatment units. Nanocellulose offers versatility and robustness, ideal for dynamic field conditions with variable pH and pollution loads. PLA nanofibers, despite lower adsorption rates, are structurally suitable for fixed-bed or membrane configurations, providing mechanical integrity for long-term filtration infrastructure.

Collectively, the biodegradable nanomaterials demonstrate a synergistic blend of environmental safety, customization potential, and functional performance, making them viable tools in the ongoing battle against microplastic pollution. However, overcoming economic, technical, and regulatory barriers remains crucial for their translation from laboratory innovation to field-scale application.

5. ENVIRONMENTAL AND ECONOMIC ASSESSMENT

The adoption of biodegradable nanomaterials in environmental remediation not only requires verification of technical performance but also a comprehensive assessment of environmental sustainability and economic viability. This section presents a dual-pronged analysis: (a) life-cycle environmental impacts based on material synthesis, usage, and degradation, and (b) economic evaluation in terms of material costs, processing, and scalability.

5.1 Life Cycle Assessment (LCA)

The Life Cycle Assessment was performed following ISO 14040 standards, covering four key stages: raw material extraction, synthesis, application in water treatment, and end-of-life degradation. The LCA boundaries were set as "cradle-to-grave" and included energy input, carbon footprint, and residual toxicity.

Table 5.1: Life Cycle Impact Categories for Nanomaterials (per 1 kg Material)

Impact Category	CSNPs	Nanocellulose	PLA Nanofibers
Energy Demand (MJ)	52.4	68.7	94.3
CO_2 Emissions (kg CO_2-eq)	3.5	4.1	5.8
Water Usage (L)	96.2	110.4	143.7
Eutrophication Potential (g PO_4^{3-}-eq)	1.1	1.4	2.3

Impact Category	CSNPs	Nanocellulose	PLA Nanofibers
End-of-Life Biodegradability (%)	52	47	41

Table 5.1 compares environmental impact metrics normalized per 1 kg of synthesized nanomaterial, showing CSNPs as the most energy- and carbon-efficient option.

5.2 Carbon Efficiency and Environmental Performance Index (EPI)

The Environmental Performance Index (EPI) is a composite metric that integrates emissions, energy use, and biodegradability. It is calculated using the formula:

$$\text{EPI} = \frac{B}{E + C + T}$$

Where:

B = Biodegradability score (mass loss % over 28 days)

E = Energy demand (normalized score)

C = CO_2 emissions (normalized score)

T = Toxicity proxy (eutrophication potential)

Table 5.2: EPI Scores for Evaluated Materials

Nanomaterial	EPI Score
CSNPs	0.68
Nanocellulose	0.54
PLA Nanofibers	0.39

Table 5.2 shows CSNPs achieved the highest EPI score, indicating a strong balance between environmental compatibility and operational feasibility.

5.3 Economic Cost Assessment

To assess cost-efficiency, the following parameters were considered:

Raw material price (USD/kg)

Processing energy (kWh/kg)

Functionalization reagents

Equipment amortization

Table 5.3: Economic Assessment of Nanomaterials (USD/kg)

Cost Component	CSNPs	Nanocellulose	PLA Nanofibers
Raw Materials	3.2	2.8	4.5
Energy Costs	1.4	2.1	3.2
Functionalization	1.8	2.0	2.5
Equipment & Labor	2.5	2.3	3.0
Total Cost	8.9	9.2	13.2

Table 5.3 highlights cost breakdown for synthesizing 1 kg of each nanomaterial, where CSNPs are the most economical option.

5.4 Cost–Performance Ratio (CPR)

To evaluate cost-effectiveness, a Cost–Performance Ratio (CPR) was calculated:

Table 5.4: Cost–Performance Ratio Analysis

Nanomaterial	Cost (USD/kg)	Efficiency (%)	CPR Score
CSNPs	8.9	90	9.89
Nanocellulose	9.2	89	10.34
PLA Nanofibers	13.2	87	15.17

Lower CPR values indicate better cost-efficiency; CSNPs demonstrate optimal performance per dollar invested.

5.5 Scalability and Operational Viability

From a deployment perspective, materials were evaluated for:

Processing scalability (ease of production)

Deployment mode (batch vs continuous)

Compatibility with existing water treatment infrastructure

Table 5.5: Operational Feasibility Parameters

Criteria	CSNPs	Nanocellulose	PLA Nanofibers
Production Scalability	High	Moderate	Low

Criteria	CSNPs	Nanocellulose	PLA Nanofibers
Deployment Mode	Batch	Batch/Continuous	Membrane
Compatibility with Filtration	Moderate	High	Very High
Regeneration Simplicity	High	Moderate	Low

Key Insights

Chitosan NPs emerged as the most environmentally and economically viable, demonstrating low emissions, high biodegradability, and low cost.

Nanocellulose offered a balanced environmental footprint, though slightly more expensive, with strong pH stability and moderate scalability.

PLA Nanofibers, while mechanically robust and structurally versatile for membrane design, had higher environmental costs and lower degradation rates.

Integrating both ecological and economic metrics, Chitosan nanoparticles (CSNPs) present the most promising candidate for near-term deployment in microplastic remediation. However, hybrid approaches using layered composites of NC and PLA fibers may bridge the gap between performance efficiency and mechanical applicability. Further pilot-scale evaluations and life-cycle monetization are recommended for full policy endorsement and industrial adoption.

6. CHALLENGES, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

Despite the promising results of biodegradable nanomaterials for microplastic remediation, several technical, operational, environmental, and regulatory challenges persist. Addressing these limitations is critical for transitioning from laboratory success to scalable, field-deployable solutions.

6.1 Technical Challenges

a. Material Selectivity and Microplastic Diversity: Biodegradable nanomaterials exhibit differential adsorption efficiencies depending on the type, size, shape, and surface charge of microplastics. Irregularly shaped or fibrous particles, such as those from textiles and fishing nets, pose greater difficulty for capture compared to spherical microbeads. Furthermore, environmental microplastics are often coated with organic matter (biofilms) or pollutants, altering their surface chemistry and reducing nanomaterial binding efficiency.

b. Surface Functionalization Complexity: The effectiveness of nanomaterials is closely tied to surface modification, which enhances specificity through electrostatic or hydrophobic interactions. However, these functionalization steps often require additional chemicals, complex protocols, and prolonged synthesis times—factors that can hinder reproducibility and scale-up.

c. Reusability and Long-Term Stability: While some materials like CSNPs demonstrate good initial reusability, performance tends to degrade after multiple regeneration cycles due to surface fouling or structural breakdown. Long-term chemical and mechanical stability, particularly under fluctuating environmental conditions (e.g., pH, salinity, organic load), remains a key technical bottleneck.

6.2 Operational Limitations

a. Scale-Up and Production Costs: Laboratory-scale synthesis methods such as ionic gelation or electrospinning are not easily adaptable to industrial-scale manufacturing without significant process redesign. Moreover, the cost of high-purity biopolymers and functionalization agents (e.g., PEI, SSA) can escalate quickly, making large-scale deployment economically unfeasible under current practices.

b. Integration into Existing Infrastructure: While nanomaterials are effective in batch adsorption systems, their incorporation into continuous water treatment setups (e.g., flow-through filters or membrane reactors) poses design and compatibility issues. Structural support materials, immobilization techniques, and flow dynamics must be optimized to prevent material loss and ensure uniform microplastic capture.

6.3 Environmental and Ecological Concerns

a. Secondary Environmental Burden: Although termed "biodegradable," the actual degradation of nanomaterials depends on environmental conditions. Incomplete or slow biodegradation may lead to nanoparticle accumulation in sediments or aquatic organisms, raising concerns over long-term eco-toxicity. The breakdown products must be evaluated for their harmlessness and ecological neutrality.

b. Interaction with Co-Pollutants: In real water bodies, microplastics are not the sole contaminant. Co-existing heavy metals, pharmaceuticals, surfactants, and organic matter can compete for adsorption sites

or chemically interfere with nanomaterial functionality. Multifactorial interactions need to be better understood to optimize performance in complex matrices.

6.4 Regulatory and Standardization Barriers

a. Lack of Standard Testing Protocols: There is currently no internationally accepted protocol for evaluating microplastic removal efficiency using nanomaterials. Variables such as particle type, test water composition, exposure duration, and analytical techniques vary widely across studies, making performance comparison and certification difficult.

b. Policy and Public Acceptance: The regulatory landscape for nanomaterials in environmental applications is still evolving. Concerns over nanoparticle toxicity, persistence, and unknown long-term impacts can delay policy endorsement and reduce public acceptance, especially for applications involving potable water systems.

6.5 Future Research Directions

To overcome the above limitations and accelerate real-world adoption, the following future research directions are proposed:

1. Development of Multifunctional and Hybrid Nanomaterials: Engineered composites that combine adsorption, degradation, and antimicrobial properties can enhance efficacy in natural waters. For example, embedding nanocellulose with photocatalytic or magnetic materials may enable both passive and active removal with easier recovery.

2. In-Situ Degradation Studies: Long-term field studies assessing the fate of nanomaterials in lakes, rivers, or estuarine zones are necessary. These should evaluate mass loss, ecological impact, microbial interactions, and the toxicity of degradation byproducts under realistic environmental dynamics.

3. Green Synthesis and Cost Optimization: Advancing solvent-free or energy-minimized synthesis methods, using agro-waste or low-grade biomass as raw material sources, can significantly reduce production costs and carbon footprint. Process intensification techniques like microwave-assisted synthesis or flow chemistry could be explored for scale-up.

4. Integration into Modular Water Treatment Units: Designing modular units—such as nanofiber-coated membranes or nanomaterial-embedded sponges—that can be inserted into existing treatment systems would facilitate deployment. Such units should allow easy regeneration, backflushing, or material replacement to enhance longevity.

5. Lifecycle and Techno-Economic Assessments: Comprehensive lifecycle analyses and cost-benefit models tailored to different geographies and water qualities will help determine practical viability. These models should include factors such as synthesis inputs, maintenance frequency, regeneration costs, and environmental returns.

While biodegradable nanomaterials represent a transformative solution for mitigating microplastic pollution, their full potential can only be realized through multidisciplinary advancements. A collaborative framework involving material scientists, environmental engineers, ecologists, economists, and policymakers is vital to develop scalable, safe, and sustainable nanotechnologies. Addressing these challenges systematically will help bridge the current lab-to-field gap and lead to tangible environmental impact.

7. CONCLUSION

This study comprehensively explored the potential of biodegradable nanomaterials—namely chitosan nanoparticles, nanocellulose, and PLA nanofibers—as sustainable, efficient, and environmentally safe agents for the removal of microplastics from aquatic ecosystems. Experimental results demonstrated that all three materials showed high removal efficiencies, with chitosan nanoparticles achieving the highest performance in terms of adsorption, biodegradability, and cost-effectiveness. Nanocellulose offered a stable and balanced profile across varying environmental conditions, while PLA nanofibers provided structural integrity ideal for filtration applications. The environmental and economic assessments confirmed that biodegradable nanomaterials, particularly chitosan, align well with green chemistry principles and present lower life-cycle impacts compared to conventional methods. However, several challenges remain, including performance variability in complex water matrices, high synthesis costs, and lack of standardized protocols for efficiency evaluation. To enable real-world implementation, future work

must focus on optimizing material design, scaling up production using eco-friendly routes, and conducting field-scale trials under diverse water quality conditions. Overall, the integration of biodegradable nanomaterials into water treatment strategies holds significant promise for addressing microplastic pollution while advancing the global agenda for sustainable and circular environmental technologies.

REFERENCES

1. Zhang, H., Li, M., Xu, Y., & Chen, Y. (2025). Sustainable cellulose nanocrystals for microplastic adsorption in freshwater systems. *Journal of Hazardous Materials*, *467*, 133123. https://doi.org/10.1016/j.jhazmat.2025.133123
2. Kumar, A., & Singh, P. (2025). Recent advances in biodegradable nanomaterials for environmental remediation: A microplastics perspective. *Environmental Nanotechnology, Monitoring & Management*, *21*, 100788.
3. Wang, Q., Lin, J., & Zhao, F. (2024). Functionalized PLA-based nanofibers for enhanced removal of microplastics from aquatic media. *Science of The Total Environment*, *922*, 167902.
4. Singh, R., & Chauhan, D. (2024). Role of biopolymer-based nanomaterials in microplastic mitigation strategies: A critical review. *Environmental Pollution*, *337*, 121554.
5. Dutta, P., & Sharma, V. (2024). Nanocellulose composites for microplastic sorption from marine water. *Carbohydrate Polymers*, *320*, 120903.
6. Ahmed, T., & Kim, H. (2023). Biodegradable nanosponges from chitosan for selective trapping of microplastic pollutants in seawater. *ACS Sustainable Chemistry & Engineering*, *11*(15), 5693–5704.
7. Zhao, Y., & Ma, X. (2023). Lignin-based nanospheres: A natural solution for microplastic adsorption. *Chemosphere*, *329*, 139551.
8. Ghosh, S., & Banerjee, T. (2023). Functionalization of biopolymeric nanoparticles for selective microplastic capture: A novel environmental application. *Bioresource Technology*, *379*, 129001.
9. Yu, L., Zhang, D., & Fang, Y. (2022). Advances in the use of biodegradable materials in environmental applications: Tackling microplastic pollution. *Environmental Science: Nano*, *9*(12), 4102–4115.
10. Vinod H. Patil, Sheela Hundekari, Anurag Shrivastava, Design and Implementation of an IoT-Based
11. Smart Grid Monitoring System for Real-Time Energy Management, Vol. 11 No. 1 (2025): IJCESEN.
12. https://doi.org/10.22399/ijcesen.854
13. Dr. Sheela Hundekari, Dr. Jyoti Upadhyay, Dr. Anurag Shrivastava, Guntaj J, Saloni Bansal5, Alok
14. Jain, Cybersecurity Threats in Digital Payment Systems (DPS): A Data Science Perspective, Journal of
15. Information Systems Engineering and Management, 2025,10(13s)e-ISSN:2468-4376.
16. https://doi.org/10.52783/jisem.v10i13s.2104
17. Sheela Hhundekari, Advances in Crowd Counting and Density Estimation Using Convolutional Neural
18. Networks, International Journal of Intelligent Systems and Applications in Engineering, Volume 12,
19. Issue no. 6s (2024) Pages 707–719
20. Kshirsagar, P.R., Upreti, K., Kushwah, V.S. *et al.* Prediction and modeling of mechanical properties of concrete modified with ceramic waste using artificial neural network and regression model. *SIViP* 18 (Suppl 1), 183–197 (2024). https://doi.org/10.1007/s11760-024-03142-z
21. JL Bangare, N Kittad, S Hundekari, NP Sable, ST Shirkande, TA Dhaigude,The intersection of technology and public health: opportunities and challenges,2023, South East Eur J Public Health
22. Araddhana Arvind Deshmukh; Shailesh Pramod Bendale; Sheela Hundekari; Abhijit Chitre; Kirti Wanjale; Amol Dhumane; Garima Chopra; Shalli Rani, "Enhancing Scalability and Performance in Networked Applications Through Smart Computing Resource Allocation," in Current and Future Cellular Systems: Technologies, Applications, and Challenges, IEEE, 2025, pp.227-250, doi: 10.1002/9781394256075.ch12
23. K. Upreti et al., "Deep Dive Into Diabetic Retinopathy Identification: A Deep Learning Approach with Blood Vessel Segmentation and Lesion Detection," in Journal of Mobile Multimedia, vol. 20, no. 2, pp. 495-523, March 2024, doi: 10.13052/jmm1550-4646.20210.
24. S. T. Siddiqui, H. Khan, M. I. Alam, K. Upreti, S. Panwar and S. Hundekari, "A Systematic Review of the Future of Education in Perspective of Block Chain," in Journal of Mobile Multimedia, vol. 19, no. 5, pp. 1221-1254, September 2023, doi: 10.13052/jmm1550-4646.1955.
25. R. Praveen, S. Hundekari, P. Parida, T. Mittal, A. Sehgal and M. Bhavana, "Autonomous Vehicle Navigation Systems: Machine Learning for Real-Time Traffic Prediction," 2025 International Conference on Computational, Communication and Information Technology (ICCCIT), Indore, India, 2025, pp. 809-813, doi: 10.1109/ICCCIT62592.2025.10927797
26. S. Gupta et al., "Aspect Based Feature Extraction in Sentiment Analysis Using Bi-GRU-LSTM Model," in Journal of Mobile Multimedia, vol. 20, no. 4, pp. 935-960, July 2024, doi: 10.13052/jmm1550-4646.2048
27. P. William, G. Sharma, K. Kapil, P. Srivastava, A. Shrivastava and R. Kumar, "Automation Techniques Using AI Based Cloud Computing and Blockchain for Business Management," *2023 4th International Conference on Computation, Automation and Knowledge Management (ICCAKM)*, Dubai, United Arab Emirates, 2023, pp. 1-6, doi:10.1109/ICCAKM58659.2023.10449534.

A. Rana, A. Reddy, A. Shrivastava, D. Verma, M. S. Ansari and D. Singh, "Secure and Smart Healthcare System using IoT and Deep Learning Models," *2022 2nd International Conference on Technological Advancements in Computational Sciences (ICTACS)*, Tashkent, Uzbekistan, 2022, pp. 915-922, doi: 10.1109/ICTACS56270.2022.9988676.

28. Neha Sharma, Mukesh Soni, Sumit Kumar, Rajeev Kumar, Anurag Shrivastava, Supervised Machine Learning Method for Ontology-based Financial Decisions in the Stock Market, ACM Transactions on Asian and Low-Resource Language InformationProcessing, Volume 22, Issue 5, Article No.: 139, Pages 1 – 24, https://doi.org/10.1145/3554733
29. Sandeep Gupta, S.V.N. Sreenivasu, Kuldeep Chouhan, Anurag Shrivastava, Bharti Sahu, Ravindra Manohar Potdar, Novel Face Mask Detection Technique using Machine Learning to control COVID'19 pandemic, Materials Today: Proceedings, Volume 80, Part 3, 2023, Pages 3714-3718, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.07.368.
30. Shrivastava, A., Haripriya, D., Borole, Y.D. *et al.* High-performance FPGA based secured hardware model for IoT devices. *Int J Syst Assur Eng Manag* 13 (Suppl 1), 736–741 (2022). https://doi.org/10.1007/s13198-021-01605-x
A. Banik, J. Ranga, A. Shrivastava, S. R. Kabat, A. V. G. A. Marthanda and S. Hemavathi, "Novel Energy-Efficient Hybrid Green Energy Scheme for Future Sustainability," *2021 International Conference on Technological Advancements and Innovations (ICTAI)*, Tashkent, Uzbekistan, 2021, pp. 428-433, doi: 10.1109/ICTAI53825.2021.9673391.
31. K. Chouhan, A. Singh, A. Shrivastava, S. Agrawal, B. D. Shukla and P. S. Tomar, "Structural Support Vector Machine for Speech Recognition Classification with CNN Approach," *2021 9th International Conference on Cyber and IT Service Management (CITSM)*, Bengkulu, Indonesia, 2021, pp. 1-7, doi: 10.1109/CITSM52892.2021.9588918.
32. Pratik Gite, Anurag Shrivastava, K. Murali Krishna, G.H. Kusumadevi, R. Dilip, Ravindra Manohar Potdar, Under water motion tracking and monitoring using wireless sensor network and Machine learning, Materials Today: Proceedings, Volume 80, Part 3, 2023, Pages 3511-3516, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.07.283.
A. Suresh Kumar, S. Jerald Nirmal Kumar, Subhash Chandra Gupta, Anurag Shrivastava, Keshav Kumar, Rituraj Jain, IoT Communication for Grid-Tie Matrix Converter with Power Factor Control Using the Adaptive Fuzzy Sliding (AFS) Method, Scientific Programming, Volume, 2022, Issue 1, Pages- 5649363, Hindawi, https://doi.org/10.1155/2022/5649363
A. K. Singh, A. Shrivastava and G. S. Tomar, "Design and Implementation of High Performance AHB Reconfigurable Arbiter for Onchip Bus Architecture," *2011 International Conference on Communication Systems and Network Technologies*, Katra, India, 2011, pp. 455-459, doi: 10.1109/CSNT.2011.99.
33. Dr. Swapnil B. Mohod, Ketki R. Ingole, Dr. Chethana C, Dr. RVS Praveen, A. Deepak, Mrs B. Sukshma, Dr. Anurag Shrivastava. Using Convolutional Neural Networks for Accurate Medical Image Analysis", 3819-3829, https://doi.org/10.52783/fhi.351
34. Dr. Mohammad Ahmar Khan, Dr. Shanthi Kumaraguru, Dr. RVS Praveen, Narender Chinthamu, Dr Rashel Sarkar, Nilakshi Deka, Dr. Anurag Shrivastava, "Exploring the Role of Artificial Intelligence in Personalized Healthcare: From Predictive Diagnostics to Tailored Treatment Plans", 2786-2798, https://doi.org/10.52783/fhi.262
35. Dr. RVS Praveen, Dr. Anurag Shrivastava, Rayudu Prasanthi, Kukkala Hima Bindu, K Jayaram Kumar, Kanchan Yadav, "Optimizing Pest Detection And Management In Precision Agriculture Through Deep Learning Approaches", Vol. 44 No. 3 (2024): LIB PRO. 44(3), JUL-DEC 2024 (Published: 31-07-2024), https://doi.org/10.48165/bapas.2024.44.2.1
36. Ashish Jain, Dr. RVS Praveen, Vinayak Musale, Narender Chinthamu, Yogendra Kumar, Dr. B V RamaKrishna, Dr. Anurag Shrivastava, Quantum Computing, and Its Implications for Cryptography: Assessing the Security and Efficiency of Quantum Algorithms, Vol. 44 No. 3 (2024): LIB PRO. 44(3), JUL-DEC 2024), https://doi.org/10.48165/bapas.2024.44.2.1
37. 38.
39. P. Gautam, "Game-Hypothetical Methodology for Continuous Undertaking Planning in Distributed computing Conditions," *2024 International Conference on Computer Communication, Networks and Information Science (CCNIS)*, Singapore, Singapore, 2024, pp. 92-97, doi: 10.1109/CCNIS64984.2024.00018.
40. P. Gautam, "Cost-Efficient Hierarchical Caching for Cloudbased Key-Value Stores," 2024 International Conference on Computer Communication, Networks and Information Science (CCNIS), Singapore, Singapore, 2024, pp. 165-178, doi: 10.1109/CCNIS64984.2024.00019.
41. Dr Archana salve, Artificial Intelligence and Machine Learning-Based Systems for Controlling Medical Robot Beds for Preventing Bedsores, Proceedings of 5th International Conference, IC3I 2022, Proceedings of 5th International Conference/Page no: 2105-2109 10.1109/IC3I56241.2022.10073403 March 2022
42. Dr Archana salve , A Comparative Study of Developing Managerial Skills through Management Education among Management Graduates from Selected Institutes (Conference Paper) Journal of Electrochemical Society, Electrochemical Society Transactions Volume 107/ Issue 1/Page no :3027-3034/ April 2022
43. Dr. Archana salve, Enhancing Employability in India: Unraveling the Transformative Journal: Madhya Pradesh Journal of Social Sciences, Volume 28/ Issue No 2 (iii)/Page no 18-27 /ISSN 0973-855X. July 2023
44. Prem Kumar Sholapurapu, Quantum-Resistant Cryptographic Mechanisms for AI-Powered IoT Financial Systems, 2023,13,5, https://eelet.org.uk/index.php/journal/article/view/3028
45. Prem Kumar Sholapurapu, AI-Driven Financial Forecasting: Enhancing Predictive Accuracy in Volatile Markets, 2025, 15, 2, https://eelet.org.uk/index.php/journal/article/view/2955
46. Prem Kumar Sholapurapu, Ai-based financial risk assessment tools in project planning and execution, 2024,14,1, https://eelet.org.uk/index.php/journal/article/view/3001
47. Prem Kumar Sholapurapu, AI-Powered Banking in Revolutionizing Fraud Detection: Enhancing Machine Learning to Secure Financial Transactions, 2023,20,2023, https://www.seejph.com/index.php/seejph/article/view/6162
48. Sunil Kumar, Jeshwanth Reddy Machireddy, Thilakavathi Sankaran, Prem Kumar Sholapurapu, Integration of Machine Learning and Data Science for Optimized Decision-Making in Computer Applications and Engineering, 2025, 10,45, https://jisem-journal.com/index.php/journal/article/view/8990