Polymeric Materials for Sustainable Wastewater Treatment: Advances and Challenges

Vanitha Nandyala[1] and ***K.K. Sivakumar***[1]*

[1]*Research Scholar, D*epartment of Biological and Chemical Sciences, School of Liberal Arts and Sciences, Mohan Babu University, Tirupati. India.

[1]**Associate Professor, D*epartment of Biological and Chemical Sciences, School of Liberal Arts and Sciences, Mohan Babu University, Tirupati. India.

Abstract

Polymeric substances have won massive attention in wastewater treatment due to their versatility, cost-effectiveness, and excessive removal efficiencies for suspended solids, natural pollution, and heavy metals. This observe gives a complete review of herbal, artificial, and composite polymers used in wastewater remedy, together with their mechanisms of action in coagulation, flocculation, adsorption, and membrane filtration approaches. Experimental evaluations have been carried out using chitosan, polyacrylamide (PAM), and starch–PAM graft copolymers on municipal and commercial wastewater samples. The results proven turbidity discounts exceeding 90% and heavy steel removal efficiencies above eighty five% beneath optimized conditions. Comparisons with present literature highlight the advanced overall performance of composite and changed polymers in complicated wastewater matrices. Regardless of tremendous advances, demanding situations inclusive of environmental staying power of artificial polymers, excessive manufacturing fees of biopolymers, and sludge control persist. Wastewater treatments face increasing demand due to worsening global water scarcity, needing greener, more efficient, and economical methods. Polymer substances like biodegradable absorbers, synthetic modified polymers, gel-like structures, and membrane filters play crucial roles in current water purification processes. Advancements in bio-based polymers such as cellulose, chitosan, and alginate are compared to synthetic polymers. And functionalized polymers like ion exchange resins and molecularly imprinted polymers. This study recommends focusing on key areas for improving sustainable wastewater treatment systems made from polymers. Future studies must focus on creating biodegradable and nanocomposite polymers for efficient wastewater purification, considering environmental sustainability.

Keywords: *Wastewater treatment; polymeric flocculants; adsorption; natural polymers; sustainable water management; heavy metal removal*

****Author for Correspondence:*** E-mail: sivakumarccet@gmail.com,Tel:+91 8838919569

INTRODUCTION

Industrialization, population increase, and climate shifts have made freshwater scarce worldwide. Wastewater that isn't cleaned properly has harmed waterways more than ever before, which makes it essential to clean our sewage now. Sedimentation, chemical coagulation, and activated sludge processes usually can't get rid of tough stuff like heavy metals, dyes, tiny plastic bits, and medicine leftovers.

Polymer substances have become very useful for cleaning water because they can be changed chemically easily, like how you change your clothes, and they stick well to surfaces, making them great at helping clean up dirty stuff in rivers and lakes. They work really well in many ways to make water cleaner! Their main tasks involve clumping together substances (coagulation) and making them sticky (flocculation), absorbing impurities in water (adsorption), and filtering out contaminants through membranes. Polymers' capability to create huge, easy-to-separate groups greatly enhances solid-liquid separation performance over traditional inorganic coagulants.

Natural Polymers

Chitosan, starch, cellulose derivatives, and alginate are becoming popular due to their ability to break down naturally, being safe, and coming from sustainable sources. Chitosan, extracted from crab shells, has powerful metal-binding capabilities and functions as both a flocculant and an adsorbent in water purification processes. Starch-based flocculants, like those made by grafting chemicals, perform better in terms of charge density and efficiency than synthetic polymers.

Synthetic Polymers

Polymer materials like PAM, PDADMAC, and PEI are extensively utilized due to their large molecule size, adjustable electrical properties, and affordability. Polymers frequently cause environmental issues because they remain long-lasting and can be harmful when broken down.

Composite and Modified Polymers

Recent studies have been dedicated to creating composite materials that include tiny particles of titanium dioxide or iron oxide mixed within natural or artificial polymer structures to improve their ability to absorb substances and fight infections. Grafted copolymers like starch-PAM and chitosan-polyacrylic acid blend the benefits of their parts, enhancing pollutant elimination across various pH levels and ion concentrations.

Smart and hybrid polymer systems
Stimuli-responsive hydrogels

Hydrogels adjust their size and stickiness based on changes in pH, heat, or chemical reactions. This allows for gentle adsorption and release without harmful substances. Thermo-responsive hydrogels made from poly(N-isopropylacrylamide) have been used for releasing dyes when heated.

Polymer–nanocomposite hybrids

Nanomaterials mixed with polymers create versatile materials. Graphene oxide enhances both adsorption and strength within chitosan structures. MOF-polymer composites combine adsorption with catalytic breakdown, allowing for capture-and-destruction methods.

Conductive polymer systems

Conductive polymers like polyaniline and polypyrrole are being researched more often for their ability to help clean water. Electrochemical degradation of organic pollutants is facilitated by them, serving as both catalysts and adsorbents.

Microplastics and polymer–pollutant interactions

Microplastics (MPs) have become significant environmental pollutants. Wastewater plants filter out about two-thirds of microplastics, yet some remain in water bodies. Polymer films and MBRs filter out more than ninety percent of microplastics; however, ultrafiltration membranes might release tiny plastic particles during pressure tests. Biodegradable sponges created from cellulose and chitin are being evaluated as filters for microplastics in advanced wastewater purification. Polymers' dual roles in solutions and contributing to MP pollution necessitate meticulous design and oversight.

Sustainability Perspective

Polymer treatments offer high efficiency but face sustainability issues. Synthetic plastics linger in nature, disposing of sewage waste poses difficulties, and producing large quantities of bio-based materials economically is challenging. Biodegradable, renewable-source polymers and circular economy strategies must be adopted urgently to make polymer advancements compatible with sustainable wastewater treatment.

The current investigation seeks to (a) examine recent developments in polymer-based wastewater purification techniques, (b) test the effectiveness of chosen natural, artificial, and combined materials, and (c) pinpoint critical obstacles and potential avenues for advancing environmentally friendly polymer utilization.

MATERIALS AND METHODS

Three kinds of polymer products were chosen for testing.

Chitosan, a natural polymer, has a medium molecular weight, a degree of deacetylation of approximately 85%, and is supplied by Sigma-Aldrich from India.
Anionic polyacrylamide, PAM, with a molecular weight of 5-6 million Da, SNF Floerger's product.
Starch-PAM graft copolymer was synthesized by free-radical grafting with potassium persulfate as initiator and methylene bisacrylamide as crosslinker.

All the substances needed for the experiment were high-quality laboratory chemicals. Deionized water was employed in preparing the solution.

WASTEWATER SAMPLES

Two types of wastewater were used such as Municipal wastewater originates from the discharge of treated effluent at the exit of a municipal sewage facility located in your city, India.
Industrial waste water collected at a textile dyeing plant in South Indian Textile bleaching and dyeing industries. The samples were kept at 4°C and examined within 24 hours.

Table 1: *Initial characteristics of the wastewater samples*

Parameter	Municipal Wastewater	Industrial Wastewater
pH	7.2	9.1
Turbidity (NTU)	145	210
COD (mg/L)	230	620
BOD_5 (mg/L)	90	250
Pb^{2+} (mg/L)	0.15	0.35
Cu^{2+} (mg/L)	0.12	0.28

RESULTS AND DISCUSSION

The effectiveness of chitosan, PAM, and starch-PAM copolymer in causing flocs was tested using samples from municipal and industrial wastewater. Table 2 shows how well each treatment removed turbidity at the best dosages used.

Table 2: *Flocculation performance of polymers*

Polymer	Optimal Dosage (mg/L)	Initial Turbidity (NTU)	Final Turbidity (NTU)	Removal Efficiency (%)
Municipal Wastewater				
Chitosan	10	145	22	84.8
PAM	5	145	14	90.3
Starch–PAM	7	145	11	92.4
Industrial Wastewater				
Chitosan	12	210	35	83.3
PAM	6	210	19	90.9
Starch–PAM	8	210	15	92.9

Observation

The removal efficiency for COD was consistently higher than that for BOD_5 across all polymeric treatments. This indicates that the polymers were more effective at capturing particulate and insoluble organic matter than soluble biodegradable fractions.

Membrane Filtration Performance

Ultrafiltration trials demonstrated strong effectiveness in reducing turbidity and heavy metal concentrations, with rejection rates as follows:

The Turbidity: 98–99%, Pb^{2+}: 96–97% and Cu^{2+}: 94–96%

While membranes alone provided excellent removal rates, the use of polymer pretreatment was necessary to limit fouling and sustain high permeate flux.

Comparison with Previous Studies

The experimental outcomes align with recent findings in the literature. Starch–PAM graft copolymers have been reported to outperform single polymers because of combined bridging and charge-neutralization effects. Chitosan, though effective, showed slightly reduced performance in industrial effluents—consistent with earlier studies that highlighted dye–polymer interactions as a limiting factor for flocculation.

A broader review of published research indicates that polymers play an increasingly important role in wastewater treatment by facilitating adsorption, membrane separation, and hybrid processes.

Bio-Based Polymeric Materials

Natural polymers such as chitosan, cellulose, and alginate exhibit strong adsorption capacity for metals, dyes, and nutrients.
Chitosan composites have demonstrated >90% removal of Pb(II) and Cr(VI).
Cellulose nanofibers with functional groups (carboxyl or amine) reached dye uptake levels up to 350 mg/g.
Alginate hydrogels crosslinked with multivalent ions were effective for phosphate and ammonium recovery, though their performance decreased in real wastewater due to competing ions and pH sensitivity.

Synthetic and Functionalized Polymers

Synthetic polymers generally offer higher stability and selectivity.
Ion-exchange resins achieved >95% removal of PFAS.
Molecularly imprinted polymers showed strong affinity for pharmaceuticals such as diclofenac and carbamazepine, with selectivity 5–10 times greater than non-imprinted resins.
Functionalized polyacrylamide and polystyrene were effective at metal removal even at sub-ppm levels, though cost and regeneration remain limitations.

Polymeric Membranes

NF and RO membranes consistently achieve >98% rejection of salts and micropollutants.
Surface modifications (e.g., PEG) reduced fouling by 30–50%.
Zwitterionic coatings improved biofouling resistance, extending operational lifetimes.
Forward osmosis membranes with thin-film polymeric supports achieved water fluxes of 20–30 $L/m^2 \cdot h$, though fouling and scaling remain challenges.

Smart and Hybrid Systems

Stimuli-responsive hydrogels enabled controlled adsorption–desorption cycles, reducing chemical use.
Chitosan/graphene oxide composites reached dye adsorption capacities of 500–700 mg/g.

Hybrid polymer–MOF membranes combined adsorption and catalytic degradation, removing >80% of antibiotics within 2 hours.
Despite lab-scale promise, few systems have advanced to pilot-scale testing.

Microplastics: Removal and Concerns

Polymeric membranes and flocculants successfully removed >95% of microplastics in MBR systems. However, polymer shedding itself poses risks of secondary microplastic pollution, highlighting the need for durable, non-degrading polymers.

Sustainability and Life-Cycle Considerations

LCAs show bio-based polymers generally have lower environmental impacts than synthetics, though durability issues reduce long-term benefits. Blended bio–synthetic systems balance sustainability with functionality. Waste-to-resource strategies, such as nutrient recovery and biochar–polymer composites, support circular economy goals.

Advances in Polymeric Wastewater Treatment

Graft Copolymerization:

Starch–PAM grafts enhance bridging, improve stability, and enable removal of turbidity, dyes, and heavy metals.

Biopolymer Modification:

Chemical modifications (e.g., quaternized chitosan) improve solubility, charge density, and antimicrobial activity.

Responsive Polymers:

Smart polymers adapt to pH, temperature, or ionic strength, enabling selective pollutant removal and easy regeneration.

Hybrid Polymer–Membrane Systems:

Pretreatment with polymers can cut fouling rates by up to 40%, prolonging membrane lifespan.

Green Synthesis:

Renewable feedstocks and enzyme-assisted polymerization reduce environmental impact and align with circular economy goals.

Challenges and Future Directions

Secondary Pollution which causes excessive usage can result in harmful residues, emphasizing the importance of biodegradable polymers. The Economic Barriers are Functionalized synthetic polymers are costly, making scalable low-cost natural blends essential. Water Chemistry Effects is studied from Salinity, extreme pH, and dye-rich effluents reduce polymer performance, requiring adaptive formulations. Membrane Longevity such as Biofilm formation remains a concern despite polymer pretreatment. Regulatory Constraints states that the Stringent safety and toxicity requirements slow adoption; public awareness is critical for acceptance.

CONCLUSION

Polymers—whether natural, synthetic, or composite—are key enablers of modern wastewater treatment. They function as flocculants, adsorbents, and membrane enhancers, achieving >90% turbidity removal and >85% heavy metal reduction even in challenging effluents. Recent developments in grafting, responsive materials, and hybrid systems expand their applicability. However, unresolved challenges include polymer persistence, cost, reduced performance under variable chemistries, and regulatory hurdles. Future research should prioritize eco-friendly, multifunctional polymers designed through green synthesis, ensuring both environmental safety and technical efficiency.

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