Poll Res. 45 (4) : 434-448 (2026)
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ISSN 0257–8050
DOI No.: http://doi.org/10.53550/PR.2026.v45i4.015
Journal Home Page: www.envirobiotechjournals.com

A COMPARATIVE STUDY OF SUSTAINABLE REMOVAL OF MICROPLASTICS FROM YAMUNA RIVER WATER USING BIOSORBENTS

MOHINI SINGH[1] AND PUSHPA SAHNI[1*]

[1]Department of Chemistry, Dayalbagh Educational Institute, Agra, U.P., India

(Received 2 July, 2026; Accepted 19 August, 2026)

ABSTRACT

Microplastic (MP) pollution has emerged as one of the most pressing environmental concerns due to its widespread occurrence in aquatic ecosystems and its potential adverse effects on aquatic organisms, food chains, and human health. Conventional wastewater treatment technologies are not specifically designed to remove these persistent particles, allowing significant quantities of microplastics to enter rivers, lakes, and other freshwater bodies. Existing treatment methods such as membrane filtration, coagulation, and advanced oxidation processes often involve high capital and operating costs, substantial energy consumption, and the generation of secondary pollutants. Consequently, there is an urgent need to develop sustainable, economical, and environmentally friendly technologies for the effective removal of microplastics from contaminated water. Biosorption has emerged as a promising green technology that utilizes natural, low-cost bio sorbents derived from waste agricultural residues, plant biomass, algae, fungi, and bacteria for the adsorption of contaminants. In the present study we have systematically explored the potential of bio sorbents including sugarcane bagasse and drumstick powder, for the removal of microplastics from aquatic environments. To understand the preferential adsorption behaviour of biosorbent in the natural systems, biosorption studies were carried out using synthetic microplastic solution and real Yamuna river water highly polluted with microplastics and other toxic pollutants. The removal efficiencies vary widely, with sugarcane bagasse and drumstick powder achieving 86% and 96.6% microplastic removal under laboratory conditions with synthetic microplastic solution. However, in natural real Yamuna River water sample, the removal efficiencies decreased with sugarcane bagasse (SBP) and drumstick powder (DSP) achieving 83.6% and 94.6% microplastic removal respectively. The bio sorbents (SBP and DSP) in the mixed ratio (1:2) showed excellent synergistic potential of the bio sorbents in removing microplastics from real River water system. Dynamic Light Scattering (DLS) analysis was performed to evaluate the particle size distribution of microplastics before and after adsorption. Field Emission Scanning Electron Microscopy (FESEM) revealed noticeable morphological changes on the biosorbent surface after treatment, confirming the adsorption of microplastic particles. Our findings also suggest that an optimized binary biosorbent system may be a promising and sustainable approach for microplastic remediation in real aquatic environments. Our future research directions would focus on enhancing adsorption efficiency greater than 99%, scaling up treatment processes for real water bodies (rivers, lakes, etc.), and ensuring environmental safety.

KEYWORDS: Microplastics, Biosorption, Bioadsorbent, Remediation, Toxic pollutants, Coagulation

Highlights

- The removal efficiency of bio sorbents for MPs using sugarcane bagasse and drumstick powderis presented and discussed separately.
- Synergistic effect of mixed or hybrid bio sorbents on biosorption removal of microplastics have also been covered in the study.

- Preferential adsorption behaviour of bio sorbents for microplastics in the presence of other toxic pollutants in natural systems has been compared and discussed.

INTRODUCTION

The water resources of the world are being polluted through various anthropogenic activities. India possesses one of the world's largest river networks, and contamination of these freshwater resources threatens aquatic biodiversity, ecosystem health, and socioeconomic activities (Kumar *et al*., 2026; Lloyd Chrispin *et al*., 2022). Since freshwater systems (rivers) are the primary source of microplastics entering larger bodies of water, increased river pollution from microplastics poses a serious threat to both humans and aquatic organisms. The River Yamuna, originating from the Yamunotri Glacier in Uttarakhand, is the longest tributary of the Ganges, passing through several Indian states before merging with the Ganges at Prayagraj. Despite its hydrological and cultural importance, the River Yamuna is now regarded as one of the most polluted rivers in India. The Yamuna River has undergone extensive ecological degradation due to sustained and largely uncontrolled discharges of untreated or partially treated sewage, industrial effluents, and illegally dumped solid waste. MPs are generated from the breakdown of larger plastic debris or directly released through consumer products such as synthetic textiles, cosmetics, packaging materials, and industrial processes. They occur in various forms, including fibres, fragments, films, and pellets, typically ranging from 100 to 5000 µm in size. These particles are persistent, bioavailable, and capable of transporting adsorbed toxic compounds, making them ecologically hazardous. Research on MPs has predominantly focused on surface freshwater systems, where they are known to affect aquatic organisms and may enter the food chain. Research studies from various countries have demonstrated that MPs can infiltrate groundwater systems via leaching from landfills, infiltration from polluted rivers, and migration through porous soils. Agra, known as the City of Taj, is undergoing rapid urbanization and industrialization, leading to the increased generation and consumption of plastics. India produces an estimated 8–12 million tons of plastic waste annually. A large fraction of plastic waste is mismanaged, ending up in open drains, dumping sites, or directly in rivers, where it undergoes fragmentation, further increasing the MP burden in the environment. The River Yamuna in Agra at PoiyaGhat site is especially vulnerable to MP contamination due to the accumulation of plastic debris, unregulated solid waste disposal, and ineffective waste management systems. During Monsoon season Yamuna also interacts with local aquifers and there is a potential risk of MP infiltration into groundwater, posing an unquantified risk to both ecosystem health and human well-being. River Yamuna, being considered one of the holy rivers in India, is also often littered with worship materials on the bank shores and plastic products floating in water, as a part of a regular practiced religious activity. This is regarded as one of the key sources for MP abundance in River Yamuna. A recent investigation of the Yamuna River reported an average microplastic abundance of approximately 14,700 particles l^{-1}, predominantly PET, PP, and PS fragments and fibers, with a Pollution Load Index (PLI > 100), indicating severe contamination and the urgent need for effective remediation strategies (Pawak *et al*., 2024; 2025). The Yamuna River is essential to the heritage, beauty, and long-term preservation of the Taj Mahal. Protecting the river from pollution is not only an environmental responsibility but also a cultural necessity to safeguard one of the world's greatest architectural masterpieces for future generations and healthy well-being of the habitants.

Microplastics (MPs), which are repositories of various pollutants, have significant effects on the people and the environment (Hasan *et al*., 2021; Dumichen *et al*., 2015). Studies detected microplastics particles (5-10µm) in human brain (Nihart *et al*., 2023) and placenta on both maternal and fetal sides (Ragusa *et al*., 2021), showing that microplastics can cross biological barriers and reach the developing fetus which alarms us to apply immediate effective procedures for the complete removal microplastics from water bodies. To deal with this growing problem, different ways have been looked into for getting rid of microplastics, such as physical, chemical, and biological methods. Conventional water treatment technologies, including physical methods such as sedimentation, filtration, oil film separation, magnetic separation (X. Li *et al*., 2024) etc., chemical methods such as Fenton oxidation and advanced oxidation technology, coagulation method (Foam Flotation method) (Pawak *et al*., 2023) and biological methods such as membrane-based systems, biochar (Wang *et*

al., 2020), biofilm adsorption (Lopez-Miranda *et al*., 2026), anaerobic–anoxic–aerobic activated sludge, enzymatic degradation (bacterial and fungal) (Sun *et al*., 2023) are often inefficient in removing smaller microplastic particles, particularly in the micrometer and nanometer range as these fine particles can pass through filters and remain suspended in water bodies (Li *et al*., 2024). However, these techniques often suffer from limitations such as incomplete removal, long treatment times, and variable performance depending on the characteristics of the microplastics and operating conditions. Advanced membrane-based technologies, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and membrane bioreactors (MBRs), generally achieve high microplastic removal efficiencies. Nevertheless, their large-scale application is restricted by membrane fouling, high capital and operational costs, energy consumption, and the potential release of polymeric membrane materials during filtration (Acarer, 2023). In contrast, biomass-derived bioadsorbents offer a sustainable, low-cost, and environmentally benign alternative. These materials are characterized by high porosity, large surface area, and the presence of functional groups capable of interacting with microplastic surfaces. Studies have reported removal efficiencies ranging from 31% to nearly 100%, depending on the system conditions and material properties. However, most investigations remain confined to laboratory conditions using synthetic microplastic systems, with limited validation in real environmental matrices such as river water. Therefore, there is an increasing need to develop cost-effective, environmentally friendly, and sustainable alternatives for efficient microplastic removal from natural system (Nasir *et al*., 2024, Puteri *et al*., 2025).

Biosorbents are biological materials, either in their natural form or after physical and chemical modification, that possess the ability to adsorb and remove pollutants from aqueous environments through various surface interactions (Mulindwa *et al*., 2024; Agarwal *et al*., 2025). Their renewable nature, low cost, biodegradability, and abundance have attracted increasing attention as sustainable alternatives to conventional adsorbents for pollutants remediation. Several studies have explored different biosorbent materials for the removal of microplastics from water. Rodrigue *et al*. (2024) demonstrated that common cattail (*Typha latifolia*) fibres effectively adsorbed polyethylene (PE) and polypropylene (PP) microplastics owing to their fibrous morphology and the presence of hydroxyl- and cellulose-rich surface functional groups. The study reported promising removal efficiencies under controlled laboratory conditions. However, the experiments were conducted using synthetic water containing only selected microplastic types, and the influence of competing contaminants, natural organic matter, and long-term reusability of the biosorbent was not investigated, limiting its applicability to real wastewater systems. Similarly, Moghri *et al*. (2025) investigated pine pollen grains as a natural biosorbent for polystyrene (PS) microplastics. The porous exine structure and chemically active functional groups on the pollen surface resulted in high adsorption efficiency and rapid adsorption kinetics. Despite these encouraging findings, the study was limited to a single polymer type under controlled experimental conditions and did not evaluate the regeneration, durability, or large-scale applicability of the biosorbent in complex environmental matrices. Marine macroalgae have also emerged as promising biosorbents for microplastic remediation. Li *et al.* (2023) reported that the seaweeds *Caulerpa lentillifera* and *Gracilaria tenuistipitata* effectively adsorbed polyamide (PA) and polystyrene (PS) microplastics. Among the two species, *G. tenuistipitata* exhibited superior adsorption performance due to its higher extracellular polymeric substance (EPS) content, which provided additional binding sites for microplastics. Nevertheless, the investigation was confined to batch adsorption studies, and the effects of environmental factors such as fluctuating pH, salinity, natural organic matter, and repeated adsorption–desorption cycles were not comprehensively evaluated. Supporting the potential of marine biomass, Amjad *et al*. (2023) demonstrated that the brown seaweed *Fucus vesiculosus* efficiently removed microplastics from aqueous media through surface adsorption. The study highlighted the sustainability and eco-friendly nature of seaweed biomass; however, adsorption performance was evaluated primarily under laboratory conditions, and further research was recommended to assess regeneration efficiency, long-term stability, and performance in real wastewater containing mixed pollutants. Apart from raw biomass, biochar-derived biosorbents have also shown considerable potential. Studies on jute stick activated charcoal (JSAC) reported efficient adsorption of polyvinyl chloride (PVC) micro

plastics due to its high surface area and porous carbonaceous structure. However, the work mainly focused on laboratory-prepared solutions, and further investigations were suggested to optimize operating conditions, evaluate regeneration, and validate the technology using actual environmental water samples. Natural coagulants have also been explored as sustainable alternatives for microplastic removal. Studies investigating *Moringa oleifera* and *Benincasahispida* extracts for the removal of microplastics released from disposable plastic cups reported maximum removal efficiencies of approximately 94% and 88%, respectively. *M. oleifera* exhibited optimum performance at a dosage of 30 mg^{-1} and pH 7, whereas *B. hispida* showed relatively stable removal over a broader pH range. Despite their promising coagulation efficiencies, the authors acknowledged that the experiments were performed using synthetic water systems and recommended validation using real wastewater matrices to determine the effects of co-existing ions, dissolved organic matter, and suspended solids. In addition to microplastic remediation, *Moringa oleifera* seed biomass has been extensively investigated for the biosorption of heavy metals and the improvement of conventional water quality parameters (Kumari *et al.,* 2006). Although these studies have demonstrated high adsorption capacities for various contaminants, limited research has examined its effectiveness for the removal of environmentally weathered microplastics under realistic aquatic conditions. Therefore, further investigation is required to evaluate its adsorption mechanism, regeneration potential, and practical applicability for large-scale microplastic remediation. So far, no attempt has been made to use drumstick pod powder and sugarcane bagasse powder for the removal of microplastics from real water bodies.

The present study investigates the potential of drumstick (pod) powder and sugarcane bagasse powder as sustainable biosorbents for the removal of microplastics from both synthetic microplastic suspensions and natural water samples (river water). Attempt was also made to study the adsorption performance of each biosorbent individually, followed by an assessment of their combined performance at different mixing ratios to examine possible synergistic effects and identify the optimum composition for enhanced microplastic removal.

METHODOLOGY

Preparation of stock solution

Stock solution of 100 µm monodisperse polystyrene microspheres of concentration 10^4 particles/l was prepared. For the Langmuir/Freundlich adsorption study, working concentrations (50–500 particles/l) were prepared from stock solutions. Mix the stock solution thoroughly (vortex) before preparing working standards because microspheres settle over time. To determine the adsorption mechanism and capacity of the biosorbent, a synthetic microplastic solution is used because adsorption isotherms are intended to characterize the intrinsic adsorption behavior of the adsorbent, not the complexity of a natural water sample.

River Water Sampling

Yamuna river water samples were collected along riverbanks and from the midstream using the composite sampling method. From each site, 20 litres of water (0–30 cm depth) were collected using a stainless-steel bucket. Plastic instruments were avoided, with glass or metal alternatives used instead. Before use, the glassware was rinsed with sample water. This river water sampling methodology was adapted from Vaid *et al*. (2022).

Laboratory Methods for the Analysis of MPs

Following the standard procedure outlined by the NOAA Marine Debris Program (National Oceanic and Atmospheric Administration) soil, open drain, and river water samples were subjected to chemical analysis and MP extraction. The collected water samples were filtered through a 0.45–5 µm membrane filter to retain suspended microplastic particles. The retained residue is treated with 30% hydrogen peroxide to remove organic matter without damaging the plastics. Density separation using saturated sodium chloride was performed to isolate microplastics from inorganic particles. The recovered particles are examined under a stereo zoom microscope and Image J software. The initial concentration of microplastics (Co) in the river water sample was calculated.

Biosorbent preparation

Agriculture wastes such as *Moringa oleifera* mature drumsticks (fruit pods) and sugarcance bagasse from DEI biodiversity park, DEI, Agra, were collected in February 2026. The biomass was washed

thoroughly with double-distilled water to remove adhering dirt, dried at 65 °C for 24 h, crushed and finally sieved through (75, 105, 210 and 420 µm) mesh copper sieve. The collected plant biomass was ground to a fine powder using a blender. No other chemical or physical treatments of the bio sorbents were done before the adsorption experiments. The adsorption performance of each biosorbent was evaluated individually, followed by an assessment of their combined performance at different mixing ratios to examine possible synergistic effects and identify the optimum composition for enhanced microplastic removal.

BIOSORPTION STUDIES

Sorption studies using standard practices were carried out in batch experiments (triplicates) as functions of biomass dosage (0.5–6.0 g), contact time (20–100 min), standard synthetic microplastics concentration (20–500 particles l^{-1}), pH (5–9), and bio sorbent particle size (105–420 µm) and solution/ sample volume (1-5L) to optimize the conditions for maximum biosorption of MPs. The synthetic MP solutions were taken in separate Erlenmeyer flasks. After pH adjustments, a known quantity of dried biosorbent was added and the MPs bearing suspensions were kept under magnetic stirring until the equilibrium conditions were reached. After shaking, the suspension was allowed to settle down. The residual biomass sorbed with MPs was filtered using a filter paper. The filtrate was collected and subjected for MPs estimation and analysis using stereo zoom microscope and Image J software. The MPs concentrations before and after adsorption were recorded. The percent MPs removal by the sorbent was computed using the equation:

Per cent Sorption=Co—Ce/Co*100,

where Co and Ce are the initial and final concentration of microplastics in the solution.

Same batch adsorption procedure was adopted with the natural real water system after optimization of the adsorption condition. A comparative adsorption studies of biosorption was performed using sugarcane bagasse and drumstick powder independently and in different combination ratio under optimized condition.

The characterization of bio sorbents before and after adsorption was carried out using Field Emission Scanning Microscope (FESEM) followed by Energy-Dispersive X-ray Spectroscopy (EDX) analysis for determination of elemental compositions of the bio sorbents. The water sample was also subjected to Dynamic Light Scattering (Zeta Sizer) analysis for understanding the distribution of microplastic particle size before and after biosorption.

RESULTS AND DISCUSSION

The concentration of MPs after biosorption on sugarcane bagasse and drumstick powder under different experimental conditions have been recorded and presented (Tables 1, 2). A perusal of the Tables, in general, shows the following trends of sorption.

Effect of MPs concentration

The sorption behavior of MPs was carried out in the concentration range (50–500 particles l^{-1}) at pH 8.0. In general, the adsorption of MPs on drumstick powder and sugarcane bagasse powder increased with the increasing concentration of the MPs reaching the optimum level 86% and 96.6%; respectively at the MPs concentration (300 particles l^{-1}) after which the percentage sorption did not increase significantly (Table 1 and 2).

Effect of sorption time

The effect of contact time on the biosorption of MPs on the drumstick powder and sugarcane bagasse powder was studied for duration of 30–100 min at pH 8.0. The percent sorption of MP as a function of time indicated a biphasic pattern with a rapid initial uptake up to 60 min, which gradually reached an equilibrium after a period of 60 min. Similar trends were observed in both the bio sorbents (Fig. 1a and 1b).

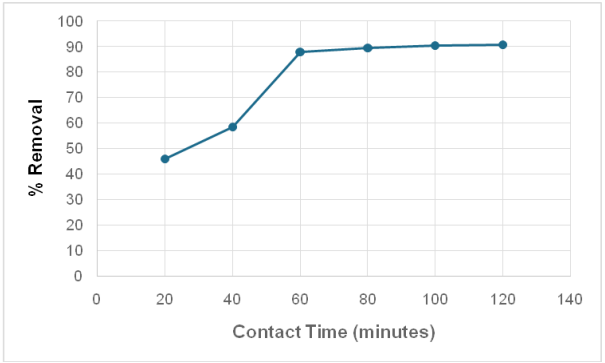


Fig. 1a. Effect of sorption time on microplastics biosorption

Table 1. Percentage removal of MP after maximum biosorption at optimum time (60 min.) at pH 8.0 and biosorbent particle size (75µm) using sugarcane bagasse powder as a function of MP concentration, biomass dosage and volume of the test solution.

MP Initial concentration (particles l^{-1})	% Removal of Monodisperse Polystyrene microplastics			
	1.0 g	2.0 g	4.0 g	6.0 g
Volume of the test solution (100 ml)				
50 particles L^{-1}	66.0	71.8	72.2	74.9
150 particles L^{-1}	67.9	74.2	76.0	77.4
300 particles L^{-1}	73.6	80.2	83.2	85.6
500 particles L^{-1}	78.9	83.9	84.6	85.9
Volume of the test solution (200 ml)				
50 particles L^{-01}	67.3	76.8	78.2	79.6
150 particles L^{-1}	70.6	78.0	80.1	81.7
300 particles L^{-1}	74.1	80.9	81.2	83.9
500 particles L^{-1}	80.1	85.3	86.2	87.9
Volume of the test solution (300 ml)				
50 particles L^{-1}	68.4	78.6	80.9	81.1
150 particles L^{-1}	71.1	80.2	81.5	82.4
300 particles L^{-1}	79.4	88.0	89.1	91.4
500 particles L^{-1}	82.3	89.6	91.3	93.8
Volume of the test solution (400 ml)				
50 particles L^{-1}	70.6	79.8	81.2	84.6
150 particles L^{-1}	71.9	81.9	83.5	83.9
300 particles L^{-1}	81.9	89.8	90.6	94.2
500 particles L^{-1}	83.0	90.7	92.2	93.9

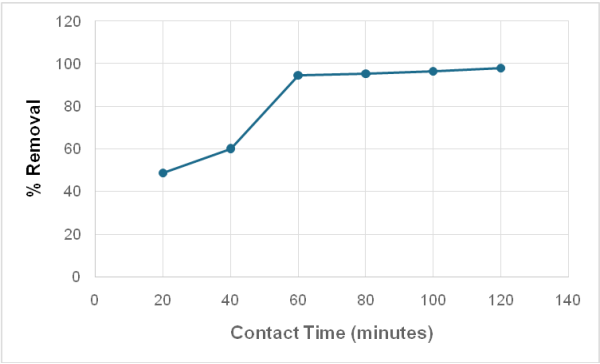


Fig. 1b. Effect of sorption time on microplastics biosorption

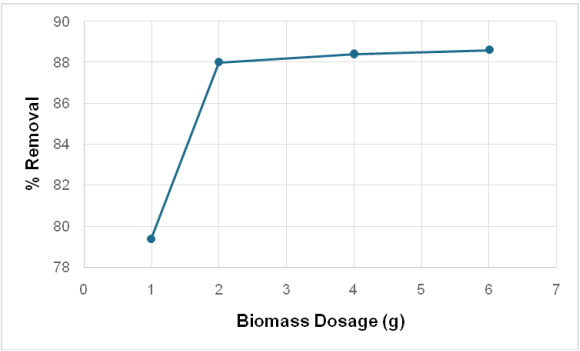


Fig. 2a. Effect of biomass dosage on microplastics biosorption

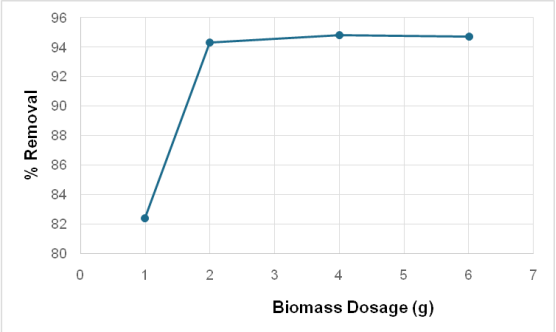


Fig. 2b. Effect of biomass dosage on microplastics biosorption

Effect of biomass dosage

While observing the influence of the dry weight of drumstick powder and sugarcane bagasse powder on the sorption potential at pH 8.0, it was noted that the sorption potential of MP increased with increased biomass dosages (0.5–2.0 g). No significant increment in the sorption tendency was observed on further raising the biomass dosages from 2.0 g onwards (Fig. 2a and 2b)..

Table 2. Percentage removal of MP after maximum biosorption at optimum time (60 min.) at pH 8.0 and biosorbent particle size (75µm) on drumstick powder as a function of MP concentration, biomass dosage and volume of the test solution.

MP Initial concentration (particles L^{-1})	% Removal of Monodisperse Polystyrene microplastics			
	1.0 g	2.0 g	4.0 g	6.0 g
Volume of the test solution (100 ml)				
50 particles L^{-1}	76.2	80.8	81.2	81.9
150 particles L^{-1}	77.9	81.2	82.0	83.4
300 particles L^{-1}	78.6	82.6	83.2	85.6
500 particles L^{-1}	78.4	83.9	84.6	85.9
800 particles L^{-1}	80.6	86.8	87.3	88.6
Volume of the test solution (200 ml)				
50 particles L^{-1}	77.9	82.8	83.2	84.6
150 particles L^{-1}	78.6	83.9	84.6	85.7
300 particles L^{-1}	80.1	84.9	85.2	86.9
500 particles L^{-1}	80.1	87.3	86.2	87.9
800 particles L^{-1}	80.8	88.8	89.2	90.4
Volume of the test solution (300 ml)				
50 particles L^{-1}	80.8	86.6	87.9	89.2
150 particles L^{-1}	81.1	89.1	91.6	92.4
300 particles L^{-1}	82.4	94.3	93.1	95.1
500 particles L^{-1}	84.3	95.9	95.3	96.8
800 particles L^{-1}	84.2	95.2	95.5	96.3
Volume of the test solution (400 ml)				
50 particles L^{-1}	80.6	91.8	93.2	94.6
150 particles L^{-1}	81.3	92.6	93.5	93.9
300 particles L^{-1}.	83.2	94.9	93.6	94.2
500 particles L^{-1}	84	95.8	95.2	96.9
800 particles L^{-1}	84.3	94.6	95.8	96.3

Effect of sample volume on sorption

The percentage sorption of the MP on the target biomass (SBP and DSP) was recorded under optimum experimental conditions in a different set of volumes (100–400 ml) of the test solution. Maximum sorption was found in the volume of 300 ml of the test solution with both the biosorbents, biomass dosage (2 g), particle size of the biosorbent (75 µm), pH 8.5, MP concentration (300 particles/L) and contact time (60 minutes). There was no significant increment in the percentage sorption of MP with further increase in the volume of the test solution (Fig. 3).

Effect of particle size of the biosorbent

Different sizes of the biosorbent particle (75, 105, 210 and 420 µm) of the drumstick powder and sugarcane bagasse powder were used to observe the pattern of the biosorption behaviour of MPs. A decrease in particle size in the range (420–75 µm)

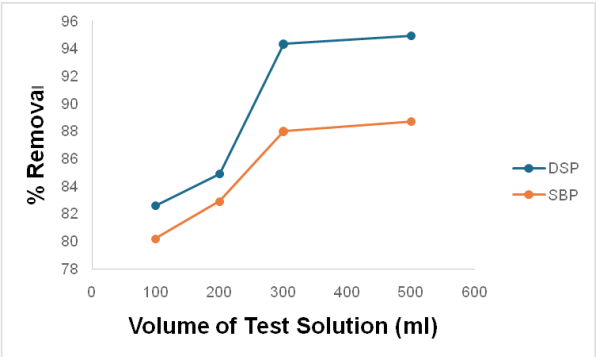


Fig. 3. Effect of sample volume on microplastics biosorption

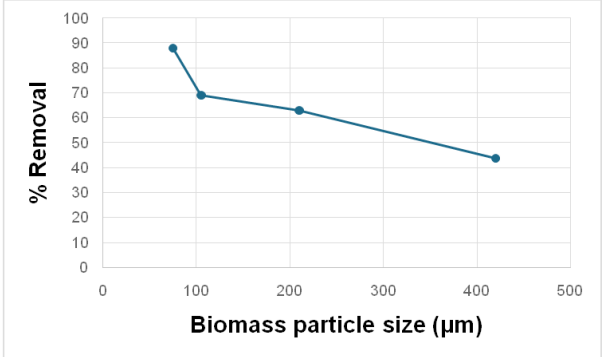


Fig. 4a. Effect of sugarcane bagasse biomass particle size on microplastics biosorption

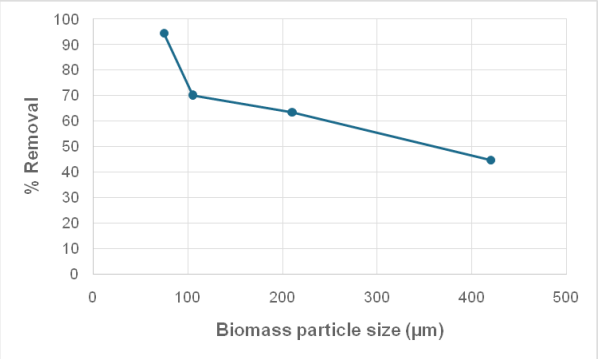


Fig. 4b. Effect of drumstick powder biomass particle size on microplasticsbiosorption

had a favourable effect on the biosorption of the MPs (Fig. 4a and 4b).

Effect of the pH

Figure1 represents the percentage removal as a function of the pH at optimum MP concentration (300 particles L^{-1}). The optimum sorption (88%) of the MP by the biosorbent sugarcane bagasse was obtained in the pH range of 6.5–8.5. The optimum percentage removal of MP with drumstick powder was obtained in the pH range of 7.5–8.5 (Fig. 5). The percentage sorption of the MP on the target biomass, enhanced as the pH of the test solution was increased from 5.5 to 10.0, and attained the optimum value of 88% and 94.3% with sugarcane bagasse and drumstick powder respectively. However, there was no significant increase in the biosorption with further increase in the pH from 8.5 to 10.0 (Fig. 5).

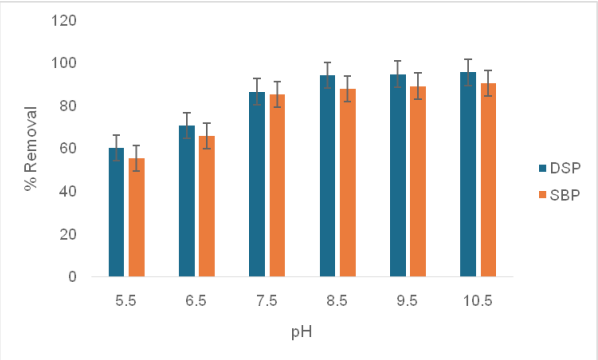


Fig. 5. Effect of pH on microplastics biosorption

Adsorption isotherm

The Freundlich isotherm model is applied to the experimental data set. From the Freundlich isotherm (Fig.6), it is inferred that the biosorbent (DSP) achieved high removal efficiencies, demonstrating good removal performance over the tested concentration range. The biosorbent drumstick powder offers favourable conditions for adsorption and has high adsorption capacity. The calculated values of K_f and n are 1.33 and 1.2 respectively.

The Freundlich isotherm is represented by the equation:

$$\log qe = \log K_f + (1/n)\ \log Ce$$

where, qe is the uptake of the MP per unit weight of the biosorbent, Ce the equilibrium (residual) concentration of the MP in solution (particles/L), K_f and n are the characteristic constants. Our experimental data could not fit well in the Langmuir model.

The Freundlich constants indicate that the biosorbent is an effective and favourable adsorbent for the removal of microplastics from water. The adsorption process occurs on a heterogeneous surface and is likely to involve multilayer adsorption rather than the formation of a single adsorbate layer. The value of (K_f = 1.33) demonstrates a satisfactory adsorption capacity, while (n = 1.20) confirms that adsorption is favourable across the investigated concentration range. These findings, together with the high removal efficiencies observed experimentally, suggest that the biosorbent has good potential for application in the treatment of microplastic-contaminated water.

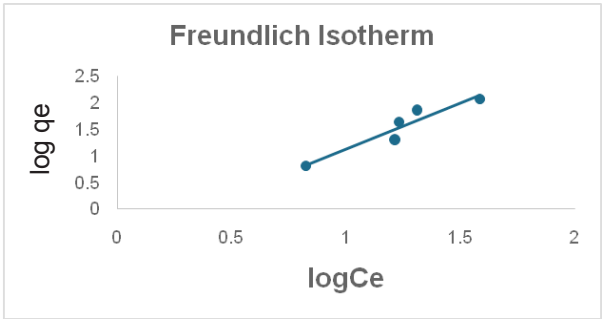


Fig. 6. Freundlich adsorption isotherm of microplastic adsorption on drumstick powder at optimum condition

The above set of experiments standardize the optimum conditions for the biosorption of MP using target plant biomass sugarcane bagasse and drumstick powder: biomass dosage (2.0 g), MP (300 particles/L), contact time (60 min) and volume of the test solution (300 ml) at pH 8.0 (Fig. 4).

Biosorption of MP on mixed bio sorbents

The chemical nature of both the bio sorbents-sugarcane bagasse and drumstick powder varies

significantly. To evaluate the synergistic effect of biosorbent on biosorption of MP, batch experiments were performed with bio sorbents mixed in three different ratios (sugarcane bagasse and drumstick powder; 1:1, 1:2, and 2:1) under optimized condition. Interestingly, the sorption percent with 1:2 was found maximum (96.4%) (Table 3). This findings add novelty to our study and open up new insight into adsorption studies.

Table 3 reflects a very interesting finding on biosorption of microplastics with the mixed combination ratio of selected bio sorbents. Three ratios of mixed biomass (SBP: DSP; 1:1, 1:2 and 2:1) were considered in the present biosorption experiment. Maximum % removal of MP (96.4%) was achieved with 1:2 mixed biomass ratio. The biosorption results (Table 1, 2 and 3) indicate that the biosorbent drumstick powder (DSP) exhibited a higher adsorption capacity for microplastics than sugarcane bagasse powder, demonstrating its greater effectiveness for microplastic removal from water. It is also inferred from the data that both the biosorbents in mixed ratio showed a synergistic effect on biosorption of MPs. The main chemical constituents of sugarcane bagasse are cellulose, hemicellulose and lignin and the drumstick (pod) powder is rich in protein, fat, fibre, carbohydrate, ascorbic acid etc. Biosorption could be greatly affected by the chemical constituents, functional groups and surface charges of both the biosorbents which led to more number of active sites for interaction with MP.

Biosorption of MPs from Yamuna river water

The batch adsorption experiment was carried out on Yamuna River water for MP removalunder optimized conditions (Biomass dosage: 2g, biomass particle size: 75 µm, sample volume: 300ml, pH: 8.0, contact time: 60 min.). The pH of river water sample was found slightly alkaline in nature ranging from 7.4 to 8.5. The sample was filtered after adsorption equilibrium was achieved and the filtrate was collected for further analysis of MP. The filtrate was processed by wet peroxide oxidation (WPO) and density separation methods to determine the final concentration of microplastics (after adsorption). Microplastics counting analysis was carried out using stereo zoom microscope. Dynamic Light Scattering analysis (zeta sizer) was also carried out for untreated Yamuna river water and treated filtrate (after adsorption) of river water to find out MP particle size distribution before and after treatment.

The biosorption study demonstrated that both bio sorbents were effective in removing microplastics from the Yamuna River water sample, which had an initial microplastic concentration of 580 particles l^{-1}. Biosorbent (SBP) achieved a removal efficiency of 80.2%, whereas Biosorbent (DSP) exhibited a significantly higher removal efficiency of 91.9%,

Table 3. Percentage removal of MP after maximum biosorption at optimum time (60 min.) at pH 8.0, biosorbent particle size (75µm), MP concentration (500 particles L^{-1}) and volume of the test solution (400 ml) on the mixed ratio of biomass dosage sugarcane bagasse powder (SBP) and drumstick powder (DSP).

Mixed biomass ratio (SBP:DSP)(Total biomass dosage: 3g)	% Removal of Monodisperse Polystyrene microplastics	% Removal of microplastics from Yamuna River water sample (Initial concentration of MP in river water: 580 particles L^{-1})
1:1	89.6	80.2
1:2	96.4	91.9
2:1	93.8	89.4

Table 4. Percentage removal of MP after maximum biosorption at optimum condition: contact time (60 min.) at pH 8.0, biosorbent particle size (75µm), biomass dosage (2g), Initial MP concentration in Yamuna river water (580 particles L^{-1}) and volume of the test solution (500 ml) on biosorbents.

Biosorbents	% Removal of microplastics from Yamuna River water sample (Initial concentration of MP in river water: 580 particles L^{-1})
Sugarcane bagasse powder (SBP)	80.2
Drumstick powder (DSP)	91.9
SBP:DSP; 1:2	93.4

indicating its superior adsorption performance under the experimental conditions (Table 4). The enhanced performance of Biosorbent (DSP) may be attributed to its chemical constituents, greater availability of active adsorption sites, favourable surface chemistry, higher porosity, or stronger affinity towards microplastic particles. Furthermore, the combined application of Biosorbent (SBP) and Biosorbent (DSP) in a 1:2 ratio resulted in the highest microplastic removal efficiency of 93.4% (Table 4). Although the improvement over Biosorbent (DSP) alone was modest (1.5 percentage points), it suggests that combining the two bio sorbents may provide a complementary or synergistic effect by increasing the diversity of adsorption sites and improving interactions with microplastic particles. The results indicate that the binary biosorbent system can enhance adsorption performance compared with the individual bio sorbents.

Characterization of Biomass

Surface Morphological analysis of Biosorbent using FESEM

Field Emission Scanning Electron Microscopy (FESEM) analysis was carried out to examine the surface morphology of the bio sorbents before and after adsorption of microplastics. The EDX analysis was also done that confirmed the presence of carbon and oxygen in the biosorbent indicates the possible of availability of active functional surface sites responsible for adsorption.

The FESEM image (Fig. 7a) of native sugarcane bagasse powder shows fibrous lignocellulosic network which is a characteristic of sugarcane bagasse. The FESEM micrograph of the native sugarcane bagasse biosorbent exhibited a rough, irregular, and heterogeneous surface morphology characterized by numerous pores, cavities, grooves, and fibrous structures. Such surface irregularities increase the specific surface area and provide abundant active sites for the adsorption of microplastic particles (Fig. 7a). The porous lignocellulosic architecture is expected to facilitate both surface adsorption and physical entrapment of microplastics.

After adsorption, a marked alteration in surface morphology was observed (Fig. 7b). The biosorbent surface became comparatively smoother, denser, and more compact due to the deposition of microplastic particles. Several pores and cavities

Fig. 7a. FESEM image of native Sugarcane bagasse (before biosorption)

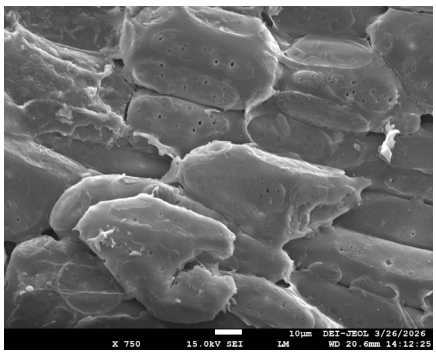


Fig. 7b. FESEM image of MP adsorbed Sugarcane bagasse (after biosorption)

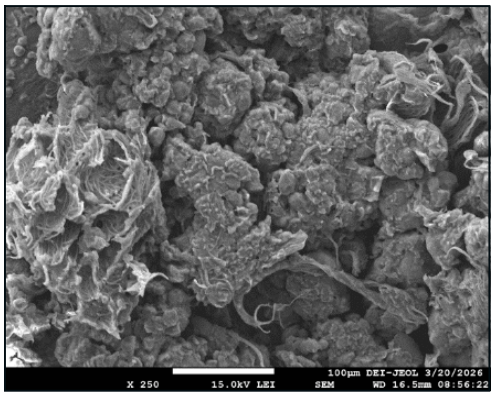


Fig. 8a. FESEM image of native drumstick powder (before biosorption)

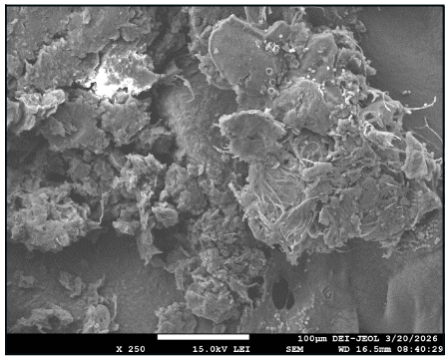
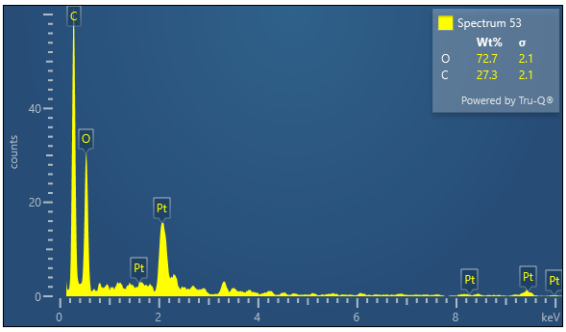


Fig. 8b. FESEM image of MP adsorbed drumstick biosorbent (after biosorption)

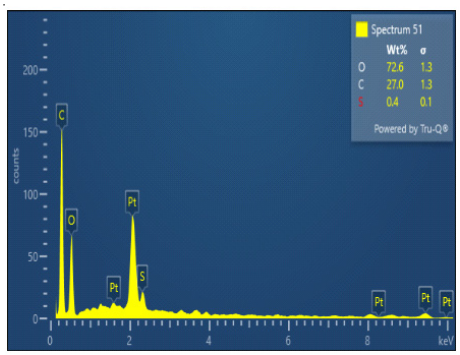
appeared partially or completely blocked, while the fibrous network was covered by adhered particles, indicating successful adsorption onto the biosorbent surface. The reduction in surface roughness and pore visibility suggests that the available adsorption sites were occupied during the adsorption process. Furthermore, the adhered particles were distributed over the biosorbent matrix rather than remaining as isolated aggregates, indicating effective interaction between the microplastics and the surface functional groups of the biosorbent. The observed morphological changes are consistent with adsorption through a combination of physical entrapment within the porous structure, hydrogen bonding, hydrophobic interactions, van der Waals forces, and, depending on the solution pH, electrostatic interactions.

The EDX spectrum of the native biosorbent (DSP) shows carbon (72.7 wt%) and oxygen (27.3 wt%) as the predominant elements, confirming the lignocellulosic nature of the material composed mainly of cellulose, hemicellulose, and lignin (Fig. 9 a). Minor phosphorus peaks are also visible in the spectrum, probably originating from naturally occurring mineral constituents of the biomass.

After adsorption, the biosorbent retained carbon (72.8 wt%) and oxygen (27.2 wt%) as the major elements, indicating that the overall elemental composition remained largely unchanged. However, the appearance of a weak sulfur peak (0.4 wt%) and slight variations in peak intensities suggest surface modification following adsorption (Fig. 9 b). The preservation of the carbon- and oxygen-rich composition indicates that the adsorption process predominantly involved surface interactions rather than chemical degradation of the biosorbent.



a. Before adsorption



b. After adsorption

Fig. 9 (a and b). Comparative EDX analysis of biosorbent before and after adsorption

The combination of the EDX spectra with the FESEM observations, which showed coverage of the porous surface by deposited particles, supports the successful attachment of microplastics onto the biosorbent. Since most common microplastics (e.g., polyethylene and polypropylene) are composed primarily of carbon and hydrogen - and hydrogen cannot be detected by EDX- only minimal changes in elemental composition are expected after adsorption. Therefore, the slight differences in elemental peaks, together with the observed morphological changes, provide qualitative

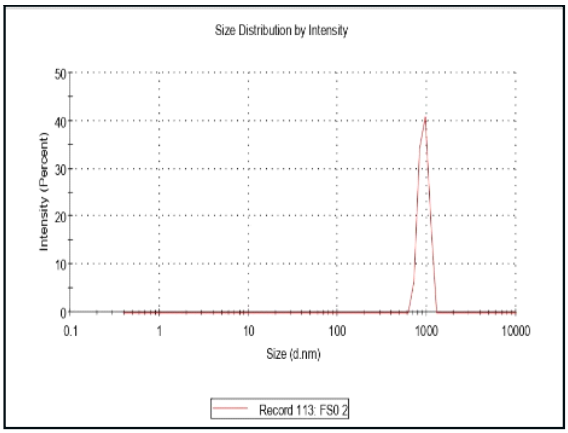


Fig.10 a. DLS spectrum before adsorption

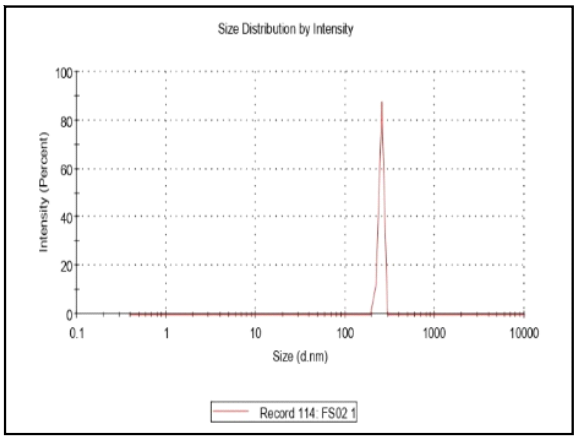


Fig.10 b. DLS spectrum after adsorption (1.0g)

evidence of microplastic adsorption.

Zetasizer or Dynamic Light Scattering (DLS)

Dynamic Light Scattering (DLS) analysis was performed to determine the particle size distribution, aggregation behaviour, and stability of microplastics under the different treatments using *Moringa oleifera* drumstick (pod) powder as biosorbent**.**

The DLS particle size distribution before and after adsorption exhibits a single, narrow, and well-defined peak, indicating that the suspended MP particles are relatively monodisperse with minimal aggregation.The particle size distribution in the filtrate before adsorption (Fig.10 a) shows a sharp peak centered at approximately 900–1000 nm, indicating that the majority of the microplastic particles were present within this size range. The narrow peak suggests a uniform particle size distribution and good dispersion of the microplastics in the suspension. Following adsorption, the peak shifted markedly toward a smaller hydrodynamic diameter of approximately 150–200 nm, accompanied by an increase in the intensity of the peak (Fig.10 b). This reduction in particle size distribution indicates that a substantial fraction of the larger microplastic particles was removed from the suspension through adsorption onto the biosorbent. Consequently, only smaller residual particles remained dispersed in the solution. Overall, the pronounced shift in particle size distribution from approximately 900–1000 nm to 150–200 nm demonstrates the effectiveness of the biosorbent in reducing the average hydrodynamic size of suspended microplastic particles. These observations are consistent with the FESEM results, which showed deposition of microplastics on the biosorbent surface, and support the conclusion that the biosorbent effectively removed microplastics from the aqueous medium.

DISCUSSION

The present work has demonstrated the tremendous potential of drumstick powder as a biosorbent for the removal of toxic MP from aqueous systems. It becomes imperative to understand the mechanistic aspects of interactions of constituents of drumstick powder with MP, thus, highlighting the nature of chemical functional groups playing the pivotal role in efficient biosorption, as obtained in present experiments. A study of the isotherm provides the extent of the adsorption capacity of the sorbent for the removal of the target MP from the solution at standardized conditions. The sorption capacity of the both target plant biomass for MP has been mathematically examined. The high degree of linearity obtained in Freundlich isotherm shows that the data are best fitted to the model (Fig. 6), thus indicating the easy separation and removal of MP from water bodies.

The pH profile and the concentration of the MP employed in our experiments provide an insight into the biosorption process involving the interaction of chemical constituents of drumstick powder with MP. It is reported that an aqueous solution of the drumstick is a heterogeneous complex mixture, having cationic polypeptides with various functional groups, especially low molecular weight amino acids. Amino acids have been reported as efficient phytochelators that work even at low concentrations and having the tendency to interact with MP and significantly enhance their mobility. Glycine, Arginine, Leucine, Valine, Phenylalanine, Threonine, Methionine, Histidine, Cystidine, Trypsin and Lysine are the prominently found low molecular weight amino acid in the drumstick powder (Muyibi, 2001). The polypeptides, depending upon the pH, possess both the negatively and positively charged ends and are, thus, capable of generating the appropriate surface charge for adsorbing the MPs. The majority of amino acids present in the target biomass have isoelectric points in the range 5.5–8.0. In this range of pH, over 90% of the amino acid molecules are in the ionized state. The MPs having some surface charge may be held by the positively and negatively charged group of amino acids/charged polypeptides. The interaction between biosorbents and microplastics can take place by hydrogen bonding, dipole-dipole interaction, van der Waals interaction and hydrophobic interactions. With the increase in pH range, the carboxylic group of the amino acids would progressively be deprotonated as carboxylate ligands, simultaneously protonating the amino group. Such positively charged amino groups (NH_3^+) facilitate the drumstick powder-MP binding. Drumstick powder contains proteins and has a net positive charge at pH below 8.5 (pKa>8.6) (Comet and Dyosi, 2023). These positively charged proteins are also considered to be active moieties for binding microplastics. The observation that Protein/ Amino acid–MP interactions appear to be an ion exchange process, contributing a significant role in

the biosorption of MP using drumtick powder, finds further support by the decreasing trend in sorption at high MP concentration (500–1000 particles/L).

The percentage sorption of MP on the target sugarcane bagasse bio sorbents increased as the pH of the test solution varied from 5.5 to 10.5, had optimum sorption (88%) with sugarcane bagasse bio sorbents in the pH range 7.5 – 10.5 and no increase occurred in the percent sorption at higher pH (8.5–10.0). Optimum biosorption (88%) in the pH range 7.5–10.5 can be easily assigned to the availability of the large number of charged surface sites on the biosorbent, which interacts with the surface charge of microplastics. Sugarcane bagasse is a lignocellulosic biomass composed of cellulose, hemicellulose, lignin, proteins, extractives, and mineral ash (Ameram *et al.*, 2019). Several of these constituents provide functional groups that can interact with microplastics through electrostatic attraction, hydrogen bonding, hydrophobic interactions, van der Waals forces, and π–π interactions (for aromatic plastics). At pH 7.5–10.5, sugarcane bagasse exhibits a predominantly negative surface charge due to the deprotonation of carboxyl (–COOH) groups in hemicellulose and phenolic hydroxyl groups in lignin, forming $–COO^-$ and $Ar–O^-$ species. In the pH range of 7.5–10.5, it is also expected that electrostatic attraction alone is not the dominant mechanism for most common weathered microplastics. Instead, hydrophobic interactions (from lignin), hydrogen bonding (from hydroxyl and carboxyl groups), and physical trapping within the fibrous matrix are likely to make the largest contributions to adsorption.

Experiments on the characterization of the bioactive principle of sugarcane bagasse and drumstick powder, and desorption studies of MP adsorbed drumstick powder, using various eluting agents for its subsequent reuse, are in progress. The present piece of work represents a simple physico-chemical scheme for the removal of appreciable amounts of MPs, using sugarcane bagasse and drumstick powder from water bodies. This method largely depends on the MP concentration, biomass dosage, size of the biosorbent particle, contact time and the pH. Isotherm studies support the suitability of the proposed method and explain the easy separation of MP from wastewater and a high biosorption capacity. Drumstick powder in combination with sugarcane bagasse showed remarkable MP removal efficiency of 93.4 % from Yamuna river water (Table 4). Mixed bio sorbents provide an exciting opportunity under the domain of Green Processes for domestic, environment friendly, low-cost methods for the removal of MP from aqueous systems. This study suggests that the mixed or hybrid bio sorbents provide sufficient surface charge for the removal of different nature and types of microplastics. Overall, the findings demonstrate that biosorbent (DSP) is more effective than biosorbent (SBP) for the removal of microplastics from natural river water, while the 1:2 combination of biosorbent (SBP) and biosorbent (DSP) exhibited the highest removal efficiency, suggesting that an optimized binary biosorbent system may be a promising and sustainable approach for microplastic remediation in real aquatic environments. Our results in the present study was found to be consistent with already published work (Mulindwa *et al*., 2024 and Shirani *et al*., 2018).

CONCLUSION

The present study successfully demonstrates the potential of *Moringa oleifera* based biosorbent for the removal of microplastics from river water. The Freundlich adsorption constants (K_f = 1.33) and (n = 1.20)) indicate that the biosorbent possesses a favourable adsorption capacity and affinity towards microplastics. The value of (n > 1) confirms that adsorption is favourable and occurs on a heterogeneous surface through multilayer adsorption. These results, coupled with the high removal efficiencies obtained experimentally, demonstrate that the biosorbent is a promising, efficient, and environmentally sustainable material for the removal of microplastics from aqueous systems. The hybrid bio sorbents in the mixed ratio (1:2) showed excellent synergistic potential of the bio sorbents in removing microplastics from real River water system. Our future endeavour would be to achieve >99% removal efficiency for all types and sizes of MPs pollutants present in the water bodies.

Conflict of Interest - None

ACKNOWLEDGEMENTS

The authors are deeply grateful to Revered Prof. P.S. Satsangi, Chairman, Advisory Committee on Education, Dayalbagh Educational Institutions for his constant guidance and encouragement. The authors gratefully acknowledge Ministry of Jal Shakti, Government of India for financial support

under the Jal Shakti Hackathon 2025 Award. Department of Chemistry is supported by DST-FIST Grant and has provided the necessary facilities and infrastructure.

REFERENCES

Acarer Arat, Seren, 2023. A review of microplastic removal from water and wastewater by membrane technologies. *Water Science & Technology*. 88: 199-219. 10.2166/wst.2023.186.

Agarwal, P., Prakash, S. and Saini, G. 2025. Evaluating the Effectiveness of Moringaoleifera in Microplastic Removal through Response Surface Methodology. *Water Conservation Science and Engineering*. 10(2). https://doi.org/10.1007/s41101-025-00419-3

Amjad, M., Intisar, A., Afzal, A. and Hussain, N. 2023. Biological methods for the removal of microplastics from water. *Advances in Chemical Pollution, Environmental Management and Protection*. 9: 65-78. https://doi.org/10.1016/BS.APMP.2022.10.003

Ameram, Nadiah, Muhammad, Shariman,Yusof, Nik, Ishak, Syarmila, Arlina, Ali, Shoparwe, Noor and Ter, Teo. 2019. Chemical composition in sugarcane bagasse: Delignification with sodium hydroxide. *Malaysian Journal of Fundamental and Applied Sciences*. 15: 232-236. 10.11113/mjfas.v15n2.1118.

Barceló, D. 2024. Microplastics in the environment: analytical chemistry methods, sorption materials, risks and sustainable solutions. *Analytical and Bioanalytical Chemistry*. 416(15): 3479-3485. https://doi.org/10.1007/S00216-024-05319-4/METRICS

Comet Manesa, K. and Dyosi, Z. 2023. Review on Moringaoleifera, a green adsorbent for contaminants removal: characterization, prediction, modelling and optimization using Response Surface Methodology (RSM) and Artificial Neural Network (ANN). *Journal of Environmental Science and Health. Part A, Toxic/Hazardous Substances & Environmental Engineering*. 58(13): 1014-1027. https://doi.org/10.1080/10934529.2023.2291977

Dümichen, E., Barthel, A. K., Braun, U., Bannick, C.G., Brand, K., Jekel, M. and Senz, R. 2015. Analysis of polyethylene microplastics in environmental samples, using a thermal decomposition method. *Water Research*. 85: 451-457. https://doi.org/10.1016/J.WATRES.2015.09.002

Hasan Anik, A., Hossain, S., Alam, M., Binte Sultan, M., Hasnine, M.T. and Rahman, M.M. 2021. Microplastics pollution: A comprehensive review on the sources, fates, effects, and potential remediation. *Environmental Nanotechnology, Monitoring & Management*. 16: 100530. https://doi.org/10.1016/J.ENMM.2021.100530

Kumar, A., Poddar, V.K., Sardar, S., Mistri, A. and Srivastava, A. 2026. Microplastic pollution in rivers and lakes of India: Sources, ecotoxicological impacts, and removal strategies. *NanoImpact*. 41. https://doi.org/10.1016/j.impact.2025.100604

Kumari, P. 2006. Biosorption studies on shelled *Moringaoleifera* Lamarck seed powder: Removal and recovery of arsenic from aqueous system. *International Journal of Mineral Processing*. 78(3): 131-139.

Li, X., Liu, W., Zhang, J., Wang, Z., Guo, Z., Ali, J., Wang, L., Yu, Z., Zhang, X. and Sun, Y. 2024. Effective removal of microplastics by filamentous algae and its magnetic biochar: Performance and mechanism. *Chemosphere*. 358: 142152. https://doi.org/10.1016/J.CHEMOSPHERE.2024.142152

Li, Y., Chen, P., Tang, Y., Yang, Y., Zhou, C., Bu, J. and Zhong, S. 2024. Microplastics in Water: A Review of characterization and removal methods. In: *Sustainability (Switzerland)* (Vol. 16, Number 10). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su16104033

Li, Z., Fu, D., Lü, S. and Liu, Z. 2023. Interaction between macroalgae and microplastics: *Caulerpalentillifera* and *Gracilariatenuistipitata* as microplastic bio-elimination vectors. *Journal of Oceanology and Limnology*. 41(6): 2249-2261. https://doi.org/10.1007/S00343-023-2298-Z

Lloyd Chrispin, C., Ananthan, P. S., Ramasubramanian, V., Sugunan, V.V., Panikkar, P. and Landge, A.T. 2022. Rapid reservoir fisheries appraisal (r-RAPFISH): Indicator based framework for sustainable fish production in Indian reservoirs. *Journal of Cleaner Production*. 379: 134435. https://doi.org/10.1016/J.JCLEPRO.2022.134435

Lopez-Miranda, J.L., Rios-Vargas, M., Mancera, E.S., Velázquez-Hernández, I. and Estevez, M. 2026. Study of the removal of microplastics in aquatic environments using Sargassum spp. from the Mexican Caribbean. *MRS Advances*. 11(2): 233-237. https://doi.org/10.1557/S43580-026-01627-2

Moghri, P., Sabahi, H., Rezayan, A.H. and Akbari, B. 2025. A green approach: Utilizing untreated pine pollen grains as a natural biosorbent for microplastic removal from water systems. *Journal of Contaminant Hydrology*. 274. https://doi.org/10.1016/j.jconhyd.2025.104675

Mulindwa, P., Kasule, J.S., Nantaba, F., Wasswa, J. and Expósito, A.J. 2024. Bioadsorbents for removal of microplastics from water ecosystems: a review. *International Journal of Sustainable Engineering*. 17(1): 13-30. https://doi.org/10.1080/19397038.2024.2374003

Muyibi, Suleyman, MegatMohd Noor, Megat Johari, Ong, Ding and Kai, Khor. 2001. *Moringa oleifera* seeds as a flocculant in waste sludge treatment. *International Journal of Environmental Studies*. 58. 185-195. 10.1080/00207230108711326.

Nasir, M.S., Tahir, I., Ali, A., Ayub, I., Nasir, A., Abbas, N., Sajjad, U. and Hamid, K. 2024. Innovative technologies for removal of micro plastic: A review of recent advances. *Heliyon*. 10(4): e25883. https://doi.org/10.1016/J.HELIYON.2024.E25883

Nihart, A.J., Garcia, M.A., El Hayek, E., Liu, R., Olewine, M., Kingston, J.D., Castillo, E.F., Gullapalli, R.R., Howard, T., Bleske, B., Scott, J., Gonzalez-Estrella, J., Gross, J.M., Spilde, M., Adolphi, N.L., Gallego, D. F., Jarrell, H.S., Dvorscak, G., Zuluaga-Ruiz, M. E. and Campen, M.J. 2025. Bioaccumulation of microplastics in decedent human brains. *Nature Medicine*. 31(4): 1114-1119. https://doi.org/10.1038/S41591-024-03453-1

Pawak, 2025. Study on Microplastics in River Yamuna and Groundwater in Delhi FINAL REPORT. (2025). www.teriin.org

Pawak, V.S., Bhatt, V.K., Sabapathy, M. and Loganathan, V. A. 2024. Multifaceted analysis of microplastic pollution dynamics in the Yamuna river: Assessing anthropogenic impacts and ecological consequences. *Journal of Hazardous Materials*. 480. https://doi.org/10.1016/j.jhazmat.2024.135976

Pawak, V.S., Loganathan, V.A. and Sabapathy, M. 2023. *Efficient removal of nanoplastics from synthetic wastewater using electrocoagulation*. https://arxiv.org/pdf/2302.08451

Puteri, Mentari Ṇoviyanti, 2015. Technologies to eliminate microplastic from water: Current approaches and future prospects. *Environment International.* 199: 109397.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M.C.A., Baiocco, F., Draghi, S., D'Amore, E., Rinaldo, D., Matta, M. and Giorgini, E. 2021. Plasticenta: First evidence of microplastics in human placenta. *Environment International*. 146: 106274. https://doi.org/10.1016/J.ENVINT.2020.106274

Rodrigue, D.P., Villa, F., Boselli, V.A., Bhagwat, K.P., Rodrigue, D. and Romero-Zerón, L. 2024. Effective removal of microplastic particles from wastewater using hydrophobic bio-substrates. *Pollutants.* 4(2): 231-250. https://doi.org/10.3390/POLLUTANTS4020015

Shirani, Z., Santhosh, C., Iqbal, J. and Bhatnagar, A. 2018. Waste Moringaoleifera seed pods as green sorbent for efficient removal of toxic aquatic pollutants. *Journal of Environmental Management*. 227: 95-106. https://doi.org/10.1016/j.jenvman.2018.08.077

Sun, X.L., Xiang, H., Xiong, H.Q., Fang, Y.C. and Wang, Y. 2023. Bioremediation of microplastics in freshwater environments: A systematic review of biofilm culture, degradation mechanisms, and analytical methods. *Science of The Total Environment*. 863: 160953. https://doi.org/10.1016/J.SCITOTENV.2022.160953

Wang, Z., Sedighi, M. and Lea-Langton, A. 2020. Filtration of microplastic spheres by biochar: removal efficiency and immobilisation mechanisms. *Water Research.* 184: 116165. https://doi.org/10.1016/J.WATRES.2020.116165

Zhao, X., Wang, J., Yee Leung, K.M. and Wu, F. 2022. Color: An important but overlooked factor for plastic photoaging and microplastic formation. *Environmental Science & Technology*. 56(13): 9161-9163. https://doi.org/10.1021/ACS.EST.2C02402