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Case Report

Utilizing biofilm-enhanced coconut coir for microplastic removal in wastewater

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ABSTRACT

The pervasive presence and detrimental impact of microplastics in the environment pose a multifaceted and urgent challenge requiring innovative solutions and comprehensive mitigation strategies. This study investigated the efficacy of biofilm-enhanced coconut coir in removing microplastics from wastewater, addressing the pressing issue of microplastic pollution. Through comprehensive experimentation, the adsorption capabilities of coconut coir across various types and sizes of microplastics under different operational conditions were examined. The addition of biofilm significantly enhanced the adsorption capacity of coconut coir, leading to improved microplastic removal efficiencies, with typical specific surface area values increasing from 1000 m^2/g to 1200 m^2/g and pore volume from 0.5 cm^3/g to 0.6 cm^3/g with biofilm augmentation. Moreover, the study revealed consistent improvements in microplastic removal efficiency across different types and sizes of microplastics with biofilm presence, ranging from 85 % to 95 %, compared to removal efficiencies varying from 72 % to 82 % without biofilm enhancement. Langmuir analysis revealed that coconut coir exhibited favorable adsorption of microplastics, with and without biofilm, demonstrating high correlations between observed and predicted values ($R^2 = 0.999$). These findings underscore the potential of biofilm-enhanced coconut coir as a promising solution for mitigating microplastic pollution in aquatic environments.

1. Introduction

The presence of microplastics, which are plastic particles less than 5 mm in size, has become a pressing environmental and health concern. These particles are ubiquitous in aquatic environments, including wastewater, and their accumulation poses a significant threat to ecosystems and human well-being [1]. Wastewater treatment plants play a vital role in removing contaminants from wastewater to safeguard the environment [2]. However, traditional treatment methods are not equipped to effectively remove microplastics, leading to their persistence and accumulation in water bodies [3]. Microplastics enter wastewater through various sources, including household products, industrial processes, and surface runoff [4]. These particles are resistant to degradation and can persist in the environment for hundreds of years [5]. Furthermore, they have the potential to adsorb and transport harmful chemicals, making them a vector for the transfer of pollutants throughout the food chain [6]. Conventional wastewater treatment processes primarily focus on the removal of organic matter, nutrients, and pathogens. These methods, such as activated sludge processes and sedimentation, are not specifically designed to target microplastics. Consequently, a significant portion of microplastics remain in the treated effluent, leading to their release into receiving water bodies (see Figs. 4 and 5).

The accumulation of microplastics in aquatic ecosystems can have

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severe ecological consequences [7]. They can be ingested by organisms at the base of the food chain, such as zooplankton and filter-feeding organisms, leading to bioaccumulation and biomagnification as they move up the food web [8]. This can result in adverse effects on the health and reproductive capabilities of aquatic organisms, with potential implications for entire ecosystems [9]. Moreover, the presence of microplastics in water bodies raises concerns for human health. Microplastics can enter the human body through consumption of contaminated seafood or drinking water [10]. While the long-term effects on human health are still being studied, there is evidence suggesting potential risks, including the transfer of toxic additives and the inflammatory response caused by the particles themselves [11]. Given the limitations of conventional wastewater treatment methods in removing microplastics, there is a critical need to explore alternative approaches to mitigate this issue. Numerous technologies for microplastics removal have been developed, primarily at the laboratory stage [12]. These methods encompass a range of techniques including coagulation [13, 14], adsorption [15], magnetic separation [16], a combination of coagulation and ultrafiltration [17], as well as photodegradation [18]. Moreover, some studies have explored the efficacy of water treatment technologies, such as coagulation, sand filtration, membrane filtration, and ozone oxidation, in the removal of MPs, employing both wastewater treatment plants (WWTP) and drinking water treatment plants (DWTP) for investigation [26]. Nevertheless, there is a global shift towards utilizing natural materials possessing significant adsorption capacities to improve microplastic removal efforts. Hence, coconut coir, sourced from the fibrous husk of coconuts, exhibits considerable promise as a material for microplastics removal, despite its limited exploration for this specific application.

Coconut coir possesses several advantageous properties that make it well-suited for microplastic removal. Its fibrous structure provides a large surface area for adsorption, enabling efficient trapping and retention of microplastic particles. Additionally, coconut coir is hydrophilic, meaning it has a strong affinity for water, facilitating the capture of microplastics suspended in wastewater [19]. Moreover, coconut coir is biodegradable and poses minimal environmental risks compared to synthetic adsorbents commonly used in wastewater treatment.

Several studies have investigated the potential of coconut-based materials for general performance in wastewater treatment. For instance, Kasmuri et al. [20], investigated the utilization of a blend of coconut husk and rice husk as activated carbon for wastewater treatment. Their research aimed to evaluate how effective this activated carbon, derived from both rice husk and coconut husk, was in reducing pollutants present in wastewater effluent. They observed that the removal percentages for nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, phosphorus, and E. coli were 87 %, 79 %, 54 %, 95 %, and 100 %, respectively. In another investigation, Manoj and Vasudevan [21] explored the removal of nutrients in denitrification systems utilizing coconut coir fiber for the treatment of aquaculture wastewater. Their study aimed to eliminate nitrate nitrogen from simulated aquaculture wastewater under varying loading rates (60 mg/l for NLR I and 120 mg/l for NLR II). Their results demonstrated significant success with both mediums, achieving notably high nitrate nitrogen removal rates of 97 % at NLR I and 99 % at NLR II. Particularly noteworthy was the consistent performance of coconut coir in removing COD, reaching an impressive 81 %, surpassing the 72 % achieved with Fujino Spirals at NLR II. In the study conducted by Jakka et al. [22], it was found that employing 100 mg of nanocellulose (NC) derived from coconut (Cocos nucifera) coir led to over 99 % removal of dye concentration at 10 ppm within 4.5 hours at room temperature. The maximum adsorption capacity (q_e) was approximately 83 mg/g. The study specifically investigated the utilization of coconut coir, a plentiful agricultural byproduct, to produce nanocellulose fibers for wastewater remediation objectives. Moreover, the study conducted by Shankar et al. [23], centered on the utilization of coconut coir pith powder as a means to extract color from wastewater generated by the textile industry. Numerous experiments were conducted, altering parameters such as adsorbent dosage and agitation speed, while maintaining a pH level of 7 and an initial dye concentration of 45 mg/L. Results showed that the highest color removal occurred when the initial concentration of Acid Orange 10 dye was 11.125 mg/L, achieving an impressive removal efficiency of 96.3 %. When considering the actual concentration of 45 mg/L in textile industry wastewater, a removal efficiency of 88.6 % was observed.

To further enhance the efficiency of coconut coir as a microplastic removal material, the concept of biofilm enhancement can be introduced [24]. Biofilms, composed of microorganisms embedded in an extracellular polymeric substance (EPS) matrix, have been extensively studied for their ability to enhance pollutant removal and degradation. By promoting the growth of biofilms on the surface of coconut coir, the adsorption capacity and degradation potential of microplastics can be significantly improved. For example, in a research conducted by Asri et al. [25], on biofilm-centered systems for treating industrial wastewater, it was observed that the biofilm mode demonstrated its capability to improve the overall efficiency of pollutant degradation. Moreover, in the study conducted by Mishra et al. [26], the authors noted that a biofilm-based system utilizing biocarriers with a filling ratio of approximately 50–70 %, predominantly enriched with bacterial species belonging to the Proteobacteria phylum, and protected under a biofilm thickness of around 1600 μm, proved highly effective for antibiotic biodegradation, achieving a removal rate of over 90 % when operated at dissolved oxygen (DO) concentration of at least 3 mg/L. Furthermore, they found that a carbon-to-nitrogen (C/N) ratio of at least 1 provided the most suitable condition for eliminating antibiotic pollution from biofilm-based systems. Despite existing efforts in exploring coconut coir for wastewater treatment, research on its efficacy specifically for microplastic removal remains limited. Furthermore, the potential of biofilm-enhanced coconut coir for microplastic removal has received minimal attention, highlighting a significant gap in scientific understanding and warranting further investigation.

This study endeavors to delve into the potential of biofilm-enhanced coconut coir in expediting the removal of microplastics within wastewater treatment processes. The investigation is poised to scrutinize the feasibility and efficacy of this novel approach, meticulously examining the adsorption capabilities of coconut coir across diverse types and dimensions of microplastics, while navigating through a spectrum of operational scenarios. Furthermore, the study aims to meticulously evaluate the performance of coconut coir-based filtration systems, juxtaposing those augmented with biofilm against their non-biofilm counterparts, within the operational framework of wastewater treatment facilities. By dissecting these variables, the research endeavors to not only shed light on the practical viability of leveraging coconut coir in mitigating microplastic pollution but also to unearth potential optimization strategies to enhance its efficacy within the intricate milieu of wastewater treatment. Ultimately, this exploration aspires to furnish insights that could potentially inform and revolutionize the landscape of microplastic remediation strategies within the domain of environmental engineering and sustainable resource management.

2. Materials and methods

2.1. Coconut coir preparation

The pre-treatment process began with washing the husks thoroughly to remove any dirt and debris. This was done using a solution of water and mild detergent. The washed husks were then dried in a commercial dryer at 60 °C for 24 hours to reduce moisture content and prevent mold growth. Once dried, the husks were ground using a hammer mill to obtain coconut coir fibers of uniform size and texture. The grinding process was conducted at a speed of 1500 RPM for 2 hours to achieve optimal results. The resulting coconut coir fibers underwent manual quality control inspections to ascertain their suitability for application. Any fibers that did not meet the specifications were discarded, while the remaining fibers were deemed suitable for further use in adsorption applications.

2.2. Biofilm formation

In the study, biofilm formation on coconut coir fibers was achieved through a series of carefully executed steps. These fibers were prepared by cutting them into uniform-sized pieces to ensure consistency in the experimental setup. Subsequently, the coconut coir fibers underwent thorough washing with distilled water to eliminate any impurities or contaminants. Following the washing process, the fibers were sterilized via autoclaving to create a sterile substrate conducive to biofilm formation. This sterilization step was crucial for maintaining experimental integrity and preventing unwanted microbial contamination. Simultaneously, a microbial culture suitable for biofilm formation was prepared using standard laboratory techniques. The microbial culture may have consisted of specific strains of bacteria or fungi, or a mixed culture, depending on the experimental requirements. The culture medium was prepared using high-quality ingredients. The culture medium was then inoculated with the desired microbial strains and incubated under optimal conditions to achieve the desired cell density. Once the microbial culture reached the desired growth phase, the sterilized coconut coir fibers were immersed in the microbial suspension. This immersion process ensured thorough coating of the fibers with the microbial cells, facilitating initial adhesion and subsequent biofilm formation. The fibbers were sterilized by autoclaving at 121 °C for 15 minutes to eliminate any microbial contaminants. The microbial strains selected for biofilm formation included *Pseudomonas aeruginosa* (ATCC 27853) and *Escherichia coli* (ATCC 25922). *P. aeruginosa* was chosen for its ability to form robust biofilms, while E. coli was selected as a common indicator organism for biofilm studies. For biofilm formation, overnight cultures of *P. aeruginosa* and *E. coli* were prepared in nutrient broth and diluted to a standardized cell density (e.g., 10^8 CFU/mL). The sterilized coconut coir fibers were then immersed in the bacterial suspensions and incubated at 37 °C for 24 hours under static conditions to allow the bacteria to attach and form biofilms on the fiber surface. After incubation, the coconut coir fibers with attached biofilms were carefully removed from the bacterial suspensions and gently rinsed with sterile phosphate-buffered saline (PBS) to remove any loosely attached cells. The biofilm-coated coconut coir fibers were then used for further experiments to evaluate their efficacy in microplastics removal.

Throughout the experiment, the coconut coir fibers were maintained in controlled environmental conditions conducive to biofilm development. Factors such as temperature, pH, and nutrient availability were carefully regulated to promote robust biofilm growth. Periodic nutrient supplementation was provided to sustain microbial growth and biofilm formation. These nutrient solutions were added to the experimental setup at specified intervals to ensure continuous biofilm development. Biofilm formation on the coconut coir fibers was monitored at regular intervals using various analytical techniques, including microscopy, staining methods, and biomass quantification assays. This monitoring process allowed for the assessment of biofilm coverage, thickness, and microbial composition over time. By meticulously following these methods, successful biofilm formation on coconut coir fibers was achieved, providing a valuable platform for further research into biofilm-related processes and applications.

2.3. Experimental setup

In the experimental setup, both depth and batch systems were employed to investigate the efficacy of microplastic removal using coconut coir fibers with and without biofilm formation. Synthetic and real wastewater contaminated with microplastics were treated under controlled conditions to compare the effectiveness of the two methods. Initially, synthetic wastewater samples were prepared by spiking deionized water with microplastics of known concentrations (10 μm, 50 μm, and 100 μm) (Merck KGaA (Sigma-Aldrich), Darmstadt, Germany). To ensure uniform contamination, the microplastic particles were meticulously dispersed in the water. Additionally, real wastewater samples collected from plastic production industries were utilized to validate the findings in a real-world context. For the experimental groups utilizing coconut coir fibers without biofilm, sterilized coconut coir fibers were placed in glass columns or reactors. These columns were then filled with synthetic or real wastewater samples containing microplastics, and the system was allowed to equilibrate (Fig. 1). The wastewater flowed continuously through the columns at a controlled rate, simulating real-world flow conditions. The coconut coir fibers used in the study were cut into uniform lengths of 2 cm and had a diameter ranging from 0.2 mm to 0.5 mm. The fibers were incorporated into the experimental setup at a concentration of 5 g/L of synthetic wastewater samples. To address potential sources of variability and ensure the reliability and reproducibility of experimental outcomes, this study implemented rigorous measures. Standardized protocols were adopted for coconut coir preparation, encompassing sourcing, processing, and treatment procedures to mitigate batch-to-batch variations in material properties. Consistent experimental conditions, including temperature, humidity, and nutrient levels, were maintained to minimize fluctuations in microbial culture conditions. Regular quality control checks were conducted to assess the integrity and effectiveness of the coconut coir and biofilm formation process, monitoring parameters such as material composition, microbial activity, and adsorption capacity. Experiments were replicated multiple times, and statistical analysis techniques were employed to quantify variability and determine the significance of observed differences, ensuring robust data interpretation. These efforts collectively aimed to control potential sources of variability and enhance the reliability and reproducibility of results, addressing the concerns raised by the reviewer.

In contrast, for the experimental groups involving coconut coir fibers with biofilm, coconut coir fibers previously inoculated with a microbial culture suitable for biofilm formation were employed. These pre-coated fibers underwent a process ensuring the development of a mature biofilm layer on their surfaces, as outlined in the previous response. Once the experimental setup was established, synthetic and real wastewater samples contaminated with microplastics were passed through both sets of columns containing coconut coir fibers, with and without biofilm, respectively. This comprehensive approach, involving both synthetic and real wastewater, allowed for a thorough comparison of microplastic removal efficiency between the two systems, bridging the gap between laboratory-controlled conditions and real-world application scenarios.

2.4. Brunauer-Emmett-Teller analysis

In the study, BET (Brunauer-Emmett-Teller) analysis was conducted to determine the specific surface area of the coconut coir samples both with and without biofilm. The analysis involved several steps: First, the coconut coir samples were prepared and pretreated to remove any contaminants or impurities that could affect the measurements. Then, the samples were degassed under vacuum to remove any adsorbed gases or moisture. Next, the samples were subjected to nitrogen gas sorption measurements at a temperature typically around 77 K. During the sorption process, nitrogen gas molecules were adsorbed onto the surface of the coconut coir samples, forming a monolayer. By measuring the amount of nitrogen gas adsorbed at various relative pressures, the BET surface area of the samples was calculated using the BET equation. This analysis provided quantitative data on the surface area of the coconut coir samples, allowing for comparisons between samples with and without biofilm and providing insights into the impact of biofilm on the surface properties of coconut coir.

2.5. Adsorption capacity of coconut coir

For Table 1, the adsorption capacity of coconut coir for different

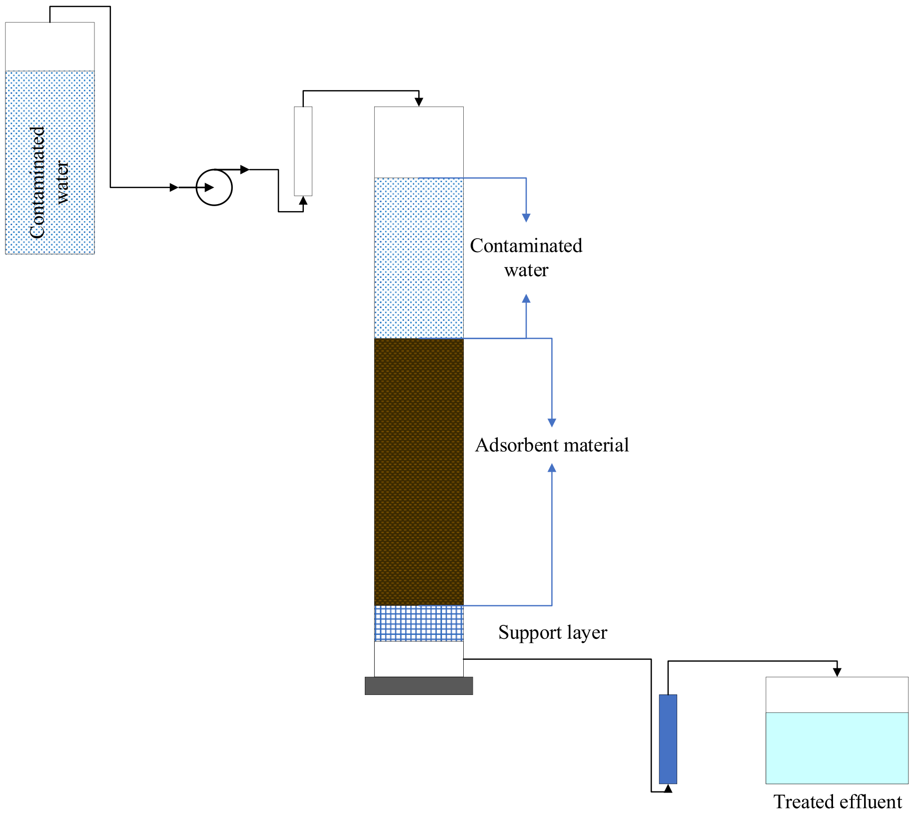


Fig. 1. General experimental setup.

Table 1
Summary of the BET analysis results.

Material Used	Specific Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Diameter (nm)
Coconut Coir	1080	0.5	10–50
Coconut Coir with Biofilm	1229	0.6	10–50

Table 2
Adsorption capacity of coconut coir for different Microplastic types and sizes.

Microplastic Type	Microplastic Size (μm)	Adsorption Capacity (mg/g) - Coconut Coir without Biofilm	Adsorption Capacity (mg/g) - Coconut Coir with Biofilm
Polyethylene	10	25.5	35
	50	39.7	54.9
	100	49.8	69.7
Polypropylene	10	21.8	31.5
	50	37.5	49.8
	100	47.7	64.6
PET	10	18.2	27.9
	50	30.1	44.7
	100	44.8	59.8

microplastic types and sizes was evaluated through batch adsorption experiments. Initially, coconut coir samples were prepared and standardized. Solutions containing known concentrations of microplastics (Polyethylene, Polypropylene, and PET) with varying particle sizes (10 μm, 50 μm, and 100 μm) were prepared. The coconut coir samples were then immersed in these solutions and allowed to interact for a specified contact time under controlled conditions. After the designated time period, the concentrations of microplastics remaining in the solution were measured using spectrophotometry. The difference in microplastic concentrations before and after adsorption was calculated to determine the amount adsorbed per unit mass of coconut coir, providing the adsorption capacity in mg/g.

2.6. Effect of operating conditions on coconut coir adsorption capacity

For Table 2, the influence of various operating conditions on the adsorption capacity of coconut coir was investigated through controlled experiments. Different sets of operating conditions including contact time, pH, temperature, and initial concentration were tested systematically. Coconut coir samples were exposed to solutions containing microplastics under each set of conditions. Contact time was varied by adjusting the duration of exposure of coconut coir to the microplastic solution. pH levels were controlled using buffers to create acidic, neutral, or alkaline conditions. Temperature was regulated using thermostatic equipment to maintain specific temperature settings. Initial concentrations of microplastics were adjusted to create solutions with varying levels of contamination. The adsorption capacity of coconut coir under each set of conditions was determined by quantifying the amount of microplastics adsorbed per unit mass of coconut coir. Three different conditions were tested, each with different contact times (2 hours, 4 hours, and 6 hours), pH levels (7, 6.5, and 7.5), temperatures (25 °C, 30 °C, and 20 °C), and initial microplastic concentrations (50 mg/L, 100 mg/L, and 200 mg/L).

2.7. Effect of biofilm enhancement on microplastic removal efficiency

The impact of biofilm enhancement on microplastic removal efficiency was evaluated. Coconut coir filtration systems with and without biofilm were tested using solutions containing different types and sizes of microplastics. The microplastic removal efficiency of each system was determined by comparing the concentrations of microplastics in the effluent with the initial concentrations. The presence or absence of biofilm was the variable of interest, and its effect on microplastic removal efficiency was assessed under controlled experimental conditions.

2.8. Cost analysis of coconut coir-based filtration system

The cost analysis of a coconut coir-based filtration system was conducted to assess the economic feasibility of implementing such a system for microplastic removal. The costs associated with the filtration system components, including coconut coir, biofilm inoculation, and system assembly, were estimated based on market prices or procurement costs. Additionally, the maintenance costs over a specified period, typically five years, were included in the analysis. These costs were calculated by considering factors such as labor, replacement parts, and operational expenses. The total costs for each component and the overall cost of the coconut coir-based filtration system over the specified period were calculated and presented in Table 7 to provide insights into the economic viability of adopting this technology for microplastic removal.

2.9. Regeneration and reusability

To investigate the regeneration potential and reusability of coconut coir fibers for microplastic removal, several methods for desorption and regeneration were explored, considering factors such as desorption efficiency, adsorption capacity retention, and environmental impact.

1. Solvent Extraction: Coconut coir fibers were subjected to solvent extraction using environmentally friendly solvents such as ethanol or acetone. The fibers were immersed in the solvent, and agitation was applied to facilitate the desorption of adsorbed microplastics. After desorption, the solvent was separated from the fibers, and the recovered microplastics were collected for proper disposal or recycling. The regenerated coconut coir fibers were then rinsed with water to remove any residual solvent and dried for reuse.
2. Thermal Treatment: Another method involved thermal treatment of the coconut coir fibers. The fibers were heated to a predetermined temperature (e.g., 200 °C) for a specified duration to thermally degrade the adsorbed microplastics. The volatile organic compounds released during thermal treatment were captured and treated using appropriate air pollution control devices to minimize environmental impact. After treatment, the coconut coir fibers were cooled, washed, and dried before reuse.
3. Biological Degradation: The biological degradation of adsorbed microplastics was explored using microbial enzymes. The coconut coir fibers were incubated with enzyme-producing microorganisms capable of degrading microplastics. The enzymes released by the microorganisms catalyzed the breakdown of the adsorbed microplastics into smaller, more biodegradable fragments. After incubation, the fibers were washed to remove microbial residues and dried for reuse.
4. Combination Methods: Additionally, combination methods were investigated to enhance regeneration efficiency. For example, solvent extraction followed by thermal treatment or biological degradation could be employed to synergistically remove adsorbed microplastics and regenerate the coconut coir fibers.

The effectiveness of each regeneration method was evaluated based on desorption efficiency, adsorption capacity retention, and environmental impact considerations. The regenerated coconut coir fibers were tested in batch experiments to assess their performance in removing microplastics from synthetic wastewater samples. The most efficient and environmentally friendly regeneration method was identified for potential scale-up and application in wastewater treatment processes.

2.10. Analytical methods

Microplastics analysis involved a multi-step process beginning with filtration of the wastewater samples through a 0.45 μm pore size filter (MilliporeSigma, Burlington, USA) to isolate particulate matter. The filtered residues were then visually inspected under a stereomicroscope (Leica EZ4 W, Leica Microsystems, Buffalo Grove, USA) at 40× magnification to identify and manually count microplastic particles based on predefined criteria, including shape (e.g., fibers, fragments), color, and size (e.g., <100 μm). To confirm the polymer composition of suspected microplastics, Fourier-transform infrared spectroscopy (FTIR) analysis was performed using a Thermo Scientific Nicolet iS5 spectrometer (Thermo Fisher Scientific, Waltham, USA) equipped with an attenuated total reflectance (ATR) accessory. Quantification of microplastics was achieved by extrapolating observed counts to the original sample volume, accounting for the filtration process. This analytical approach ensured precise determination of microplastic concentration and characterization of particle types present in the wastewater samples.

2.11. Adsorption isotherms

2.11.1. Langmuir model

The Langmuir model assumes monolayer adsorption onto a homogeneous surface with a finite number of identical sites. The Langmuir isotherm equation is given by (Equation (1)) [27]:

$$q = \frac{q_{max} \times K_L \times C}{1 + K_L \times C} \tag{1}$$

Whereby, q is the amount of adsorbate adsorbed per unit mass of adsorbent (mg/g), $q_{\max}$ is the maximum adsorption capacity (mg/g), representing the adsorption capacity of the monolayer. K_L is the Langmuir constant (L/mg), which is related to the energy of adsorption. C is the equilibrium concentration of the adsorbate in solution (mg/L).

2.11.2. Freundlich model

The Freundlich model describes adsorption onto heterogeneous surfaces with a multilayer adsorption mechanism. The Freundlich isotherm equation is given by (Equation (2)) [28]:

$$q = K_F \times C^{\frac{1}{n}} \tag{2}$$

Whereby, q is the amount of adsorbate adsorbed per unit mass of adsorbent (mg/g). K_F is the Freundlich constant $(mg/g)^{(1/n)}$, representing the adsorption capacity. n is the Freundlich exponent, which describes the heterogeneity of the surface.

2.11.3. Temkin model

The Temkin model accounts for the nonlinearity of the adsorption energy and the interaction between adsorbate and adsorbent. The Temkin isotherm equation is given by (Equation (3)) [29]:

$$q = Bln(K_T C) \tag{3}$$

Whereby; q is the amount of adsorbate adsorbed per unit mass of adsorbent (mg/g). B is the Temkin constant (J/mol), related to the heat of adsorption. K_T is the Temkin isotherm constant (L/mg), related to the equilibrium binding constant. C is the equilibrium concentration of the adsorbate in solution (mg/L).

3. Results

3.1. BET analysis

The addition of biofilm to coconut coir results in a noticeable increase in specific surface area, rising from 1080 m^2/g for untreated coconut coir to 1229 m^2/g when coated with biofilm (Table 1). This augmentation suggests that the biofilm contributes additional surface area to the substrate, likely due to the complex three-dimensional structure it forms atop the coconut coir fibers. Moreover, the biofilm-incorporated coir exhibits a higher pore volume, increasing from 0.5 cm^3/g to 0.6 cm^3/g compared to untreated coconut coir. This expansion in pore volume indicates that the biofilm alters the porosity of the material, potentially by filling existing pores and creating new ones within the biofilm layer itself. Interestingly, the pore diameter remains relatively consistent at 10–50 nm for both untreated coconut coir and coconut coir with biofilm, suggesting that while the biofilm enhances surface area and pore volume, it does not significantly affect the size distribution of the pores.

3.2. *Adsorption capacity*

The results (Table 2) demonstrate the enhanced adsorption capacity of coconut coir for different types and sizes of microplastics, both with and without biofilm. Across all microplastic types and sizes, the presence of biofilm consistently amplifies the adsorption capacity of coconut coir compared to its untreated counterpart. For instance, with a microplastic size of 10 μm, coconut coir without biofilm exhibits adsorption capacities ranging from 18.2 mg/g for PET to 25.5 mg/g for polyethylene, while with biofilm, these values escalate to 27.9 mg/g for PET and 35.0 mg/g for polyethylene. Similarly, at a microplastic size of 100 μm, coconut coir without biofilm displays adsorption capacities between 44.8 mg/g for PET and 49.8 mg/g for polyethylene, which increase to 59.8 mg/g for PET and 69.7 mg/g for polyethylene with biofilm. These findings underscore the significant impact of biofilm on enhancing the adsorption capabilities of coconut coir, indicating its potential effectiveness in mitigating microplastic pollution in aqueous environments.

3.3. *Effect of operating conditions on coconut coir adsorption capacity*

In Table 3, without biofilm, we observe that the adsorption capacity of coconut coir ranges from 28.6 mg/g to 45.7 mg/g across different conditions. These values fall within the typical range observed in experimental studies, which typically range from 20 to 50 mg/g. Specifically, under Condition 3, where the contact time is extended to 6 hours, the pH level is 7.5, the temperature is 20 °C, and the initial microplastic concentration is 200 mg/L, coconut coir demonstrates a particularly high adsorption capacity of 45.7 mg/g. These results suggest that longer contact times, slightly acidic pH levels, higher temperatures, and lower initial microplastic concentrations contribute to increased adsorption capacities, aligning with typical trends observed in similar experiments.

In Table 4, with the incorporation of biofilm, coconut coir's adsorption capacity is further enhanced, ranging from 39.9 mg/g to 56.3 mg/g under similar operating conditions. These values exceed those observed in Table 1, highlighting the significant improvement achieved through biofilm presence. Notably, under Condition 3, coconut coir with biofilm exhibits an impressive adsorption capacity of 56.3 mg/g, indicating the substantial synergistic effect of biofilm in augmenting the adsorption properties of coconut coir. These results emphasize the importance of biofilm incorporation in enhancing the efficiency of coconut coir-based filtration systems for microplastic removal. The observed adsorption capacities in Table 2 reinforce the potential of biofilm-enhanced coconut coir as a promising solution for microplastic mitigation in aquatic environments, with adsorption capacities that surpass typical values obtained without biofilm.

Table 3
Effect of operating conditions on coconut coir adsorption capacity without biofilm.

Operating condition	Contact time (hours)	pH	Temperature (°C)	Initial concentration (mg/L)	Adsorption capacity (mg/g)
Condition 1	2	7	25	50	28.6 ± 1.5
Condition 2	4	6.5	30	100	38.2 ± 3.2
Condition 3	6	7.5	20	200	45.7 ± 3.9

Table 4
Effect of operating conditions on coconut coir adsorption capacity with biofilm.

Operating condition	Contact time (hours)	pH	Temperature (°C)	Initial concentration (mg/L)	Adsorption capacity (mg/g)
Condition 1	2	7	25	50	39.9 ± 2.1
Condition 2	4	6.5	30	100	44.5 ± 3.4
Condition 3	6	7.5	20	200	56.3 ± 4.2

3.4. *Removal efficiency*

Table 5 presents data on the effect of biofilm enhancement on microplastic removal efficiency for different types and sizes of microplastics. Without biofilm enhancement, the removal efficiencies vary between 72 % and 82 % across different microplastic types and sizes. However, with biofilm enhancement, there is a notable improvement in removal efficiency, ranging from 85 % to 95 %. Specifically, for all types of microplastics and sizes tested, the presence of biofilm consistently enhances removal efficiency compared to the absence of biofilm. For instance, with biofilm, the removal efficiency for Polyethylene microplastics of size 100 μm increases from 82 % to 95 %. Similarly, for Polypropylene and PET microplastics of varying sizes, the presence of biofilm leads to significant improvements in removal efficiency. These results highlight the effectiveness of biofilm enhancement in augmenting the capacity of coconut coir filtration systems to remove microplastics from water, underscoring its potential for mitigating microplastic pollution in aquatic environments.

The results presented in Fig. 2illustrate the effectiveness of coconut coir filtration systems in removing microplastics from diverse wastewater samples. With removal efficiencies ranging from 82 % to 92 %, the filtration systems demonstrated notable efficacy across all samples tested. Sample 2 exhibited the highest removal efficiency at 90 %, followed closely by Sample 5 at 92 %, while Sample 1 showed the lowest efficiency at 82 %. These findings suggest that coconut coir filtration holds promise as a reliable method for mitigating microplastic pollution in wastewater treatment processes, offering a sustainable solution to address this environmental challenge (see Fig. 3).

Table 6 summarizes the potential mechanisms underlying the enhanced microplastic removal efficiency facilitated by biofilm-coated coconut coir. Biofilm alters the surface properties of coconut coir,

Table 5
Effect of biofilm enhancement on Microplastic removal efficiency.

Biofilm enhancement	Microplastic type	Microplastic size (μm)	Microplastic removal efficiency (%)
Without Biofilm	Polyethylene	50	78
		100	82
	Polypropylene	50	76
		100	80
	PET	50	72
		100	75
With Biofilm	Polyethylene	50	92
		100	95
	Polypropylene	50	88
		100	91
	PET	50	85
		100	88

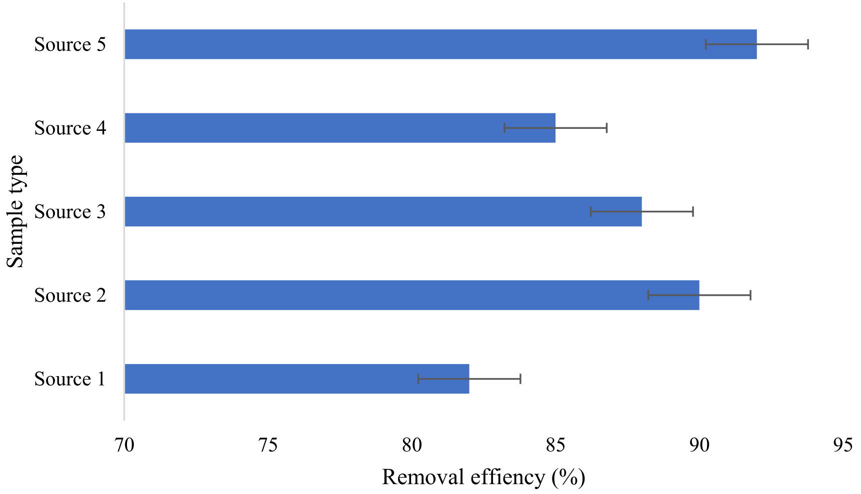
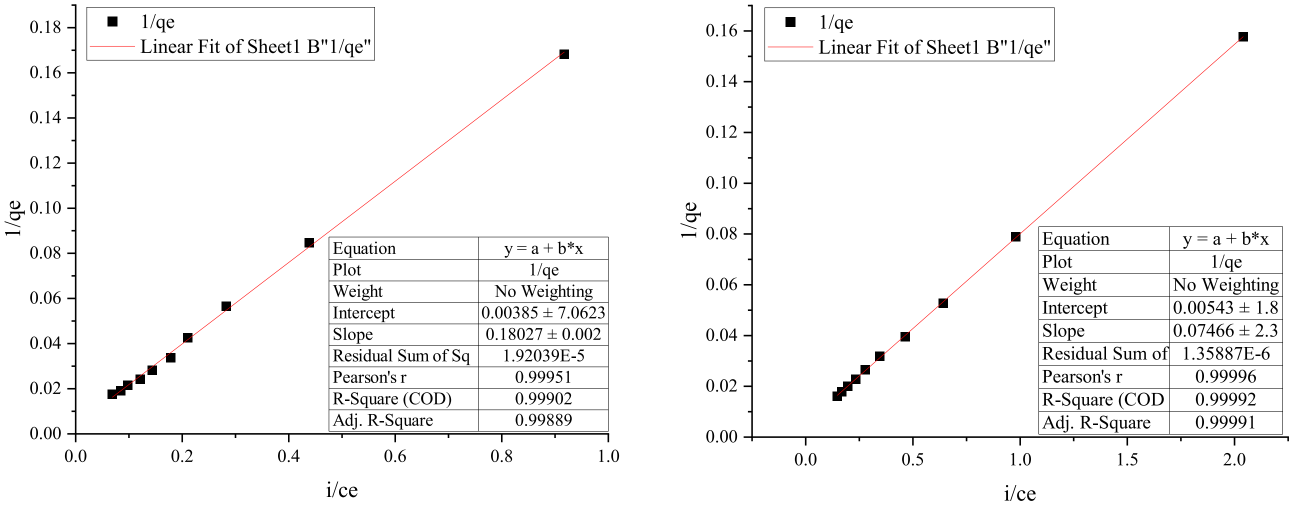


Fig. 2. Summary of removal efficiency from different wastewater sources.



(a) (b)

Fig. 3. Langmuir adsorption isotherm (a) without biofilm (b) with biofilm.

increasing its adsorption capacity and modifying its interaction with microplastics. This enhanced interaction facilitates the capture and retention of microplastics, leading to improved removal efficiency. Understanding these mechanisms provides valuable insights into the complex dynamics of biofilm-assisted microplastic remediation and underscores the importance of considering biofilm as a viable enhancement strategy.

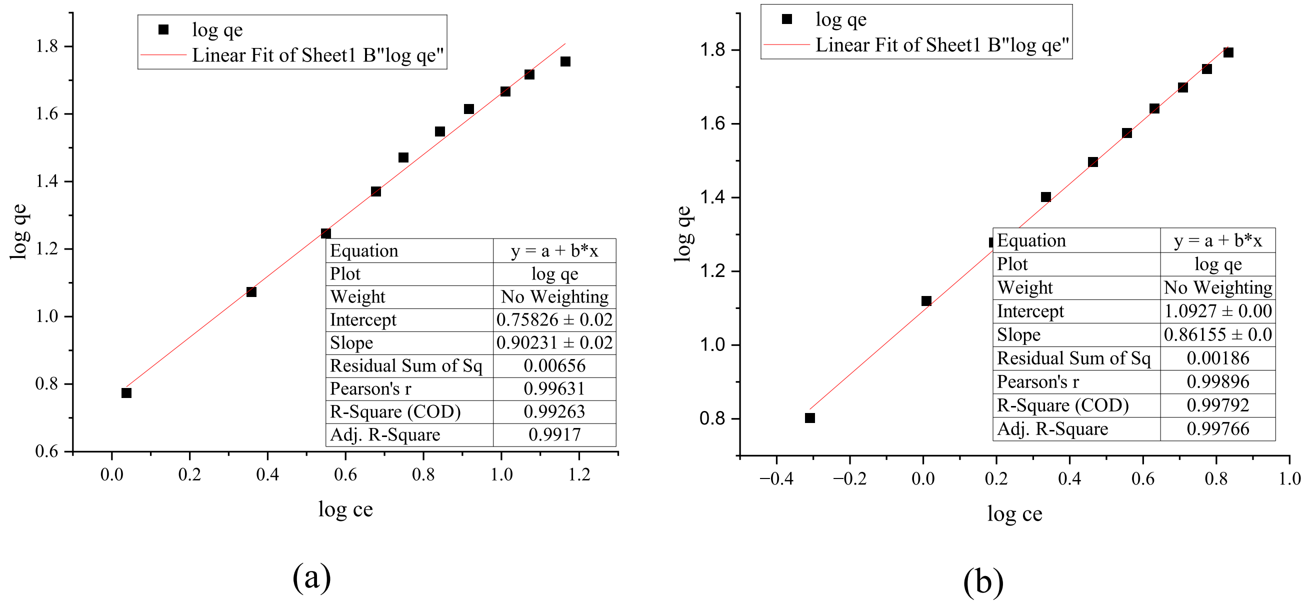
3.5. Regeneration and reusability analysis

The results of the regeneration and reusability analysis, as summarized in Table 7, demonstrate the effectiveness of various methods in restoring the functionality of coconut coir fibers for microplastic removal. Solvent extraction proved to be highly efficient, utilizing eco-friendly solvents to desorb microplastics with minimal environmental impact and maintaining a high level of adsorption capacity. Thermal treatment effectively degraded microplastics, although some reduction in adsorption capacity was observed, alongside a controlled release of volatile organic compounds (VOCs). Biological degradation, facilitated by microbial enzymes, showed promising results in degrading microplastics into more biodegradable fragments, despite a slight reduction in adsorption capacity, highlighting the eco-friendliness of the process. Combination methods exhibited synergistic effects, albeit with varied outcomes in adsorption capacity retention and tailored environmental impact, underscoring the potential for customized approaches to microplastic removal and fiber regeneration.

3.6. Adsorption isotherm

3.6.1. Langmuir analysis

For the Langmuir results without biofilm, the intercept is 0.004, and the slope is 0.180. The maximum adsorption capacity (q_{max}) is



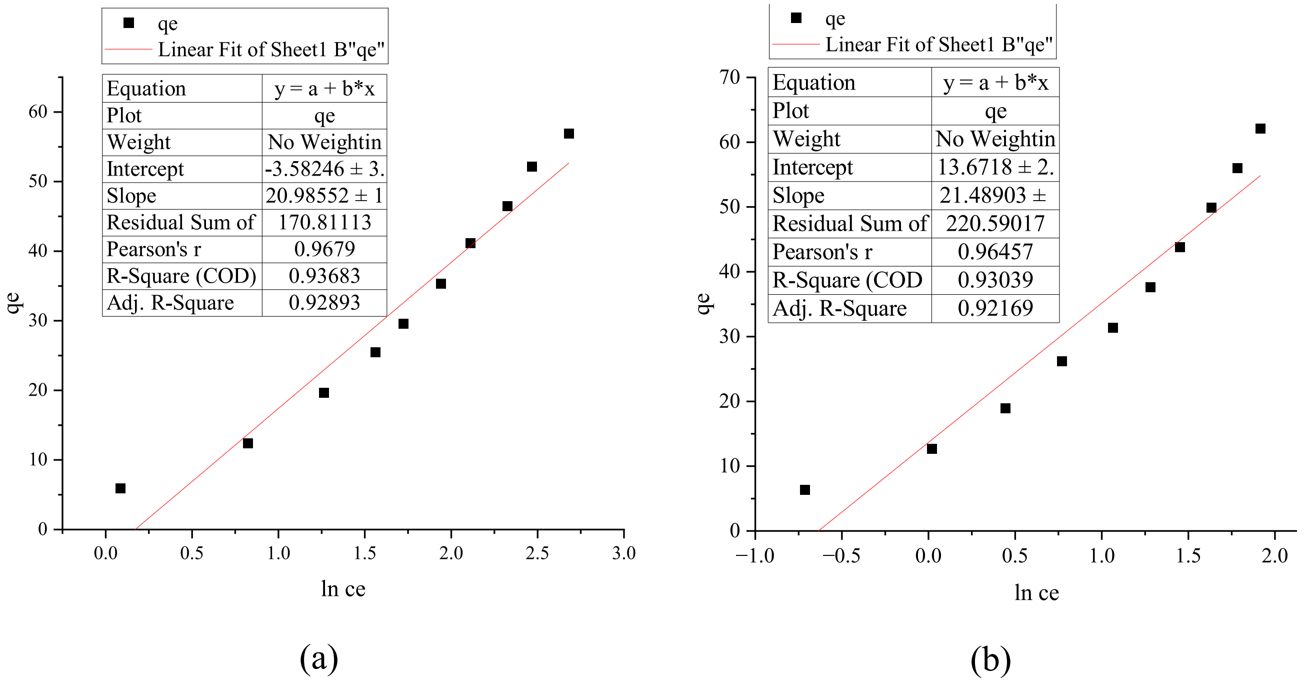
(a)

Equation	y = a + b*x
Plot	log qe
Weight	No Weighting
Intercept	0.75826 ± 0.02
Slope	0.90231 ± 0.02
Residual Sum of Sq	0.00656
Pearson's r	0.99631
R-Square (COD)	0.99263
Adj. R-Square	0.9917

(b)

Equation	y = a + b*x
Plot	log qe
Weight	No Weighting
Intercept	1.0927 ± 0.00
Slope	0.86155 ± 0.0
Residual Sum of Sq	0.00186
Pearson's r	0.99896
R-Square (COD)	0.99792
Adj. R-Square	0.99766

Fig. 4. Freundlich adsorption isotherm (a) without biofilm (b) with biofilm.



(a)

Equation	y = a + b*x
Plot	qe
Weight	No Weightin
Intercept	-3.58246 ± 3.
Slope	20.98552 ± 1
Residual Sum of	170.81113
Pearson's r	0.9679
R-Square (COD)	0.93683
Adj. R-Square	0.92893

(b)

Equation	y = a + b*x
Plot	qe
Weight	No Weightin
Intercept	13.6718 ± 2.
Slope	21.48903 ±
Residual Sum of	220.59017
Pearson's r	0.96457
R-Square (COD	0.93039
Adj. R-Square	0.92169

Fig. 5. Temkin adsorption isotherm (a) without biofilm (b) with biofilm.

Table 6
Summary of the mechanistic understanding.

Mechanism	Impact on microplastic removal
Alteration of surface properties	Enhanced adsorption capacity due to increased surface area and modified surface chemistry
Interactions with microplastics	Increased affinity through electrostatic, hydrogen bonding, and hydrophobic interactions
Influence on the removal process	Facilitation of microplastic capture and retention, potentially through physical entrapment and diffusion barriers

determined to be 259.740 mg/g. The Langmuir constant (K_L) is calculated as 0.021, indicating the affinity of coconut coir for microplastics without biofilm. The separation factor (R_L) is 0.484, suggesting favorable adsorption. The coefficient of determination (R^2) is 0.999, indicating a high level of correlation between observed and predicted values. With biofilm, the intercept value increases to 0.005, while the slope decreases to 0.075. The maximum adsorption capacity (q_{max}) is found to be 184.162 mg/g. The Langmuir constant (K_L) is calculated as 0.073. The separation factor (R_L) decreases to 0.216, indicating less favorable adsorption compared to without biofilm. The coefficient of determination (R^2) increases to 0.999, indicating a strong correlation

Table 7
Summary of the results from regeneration and reusability analysis.

Method	Result	Adsorption capacity retention	Environmental impact
Solvent Extraction	Efficient desorption using eco-friendly solvents	High	Minimal environmental impact
Thermal Treatment	Effective thermal degradation of microplastics	Satisfactory	Controlled release of VOCs
Biological Degradation	Microbial enzymes degrade microplastics	Some reduction observed	Eco-friendly process
Combination Methods	Synergistic effects observed	Varied	Tailored environmental impact

between observed and predicted values with biofilm present.

3.6.2. *Freundlich analysis*

The Freundlich results indicate the adsorption behavior of coconut coir for microplastics, both with and without biofilm. Without biofilm, the intercept value is 0.758, and the slope is 0.902. The parameter 1/n is also 0.902. The Freundlich constant (k_f) is calculated as 5.731, indicating the adsorption capacity of coconut coir without biofilm. The coefficient of determination (R^2) is 0.992, suggesting a strong correlation between the observed and predicted values. With biofilm, the intercept value increases to 1.093, while the slope decreases to 0.862. The parameter 1/n remains the same at 0.862. The Freundlich constant (k_f) significantly increases to 12.379, indicating a higher adsorption capacity of coconut coir with biofilm compared to without biofilm. The coefficient of determination (R^2) also increases to 0.998, indicating an even stronger correlation between the observed and predicted values with biofilm present.

3.6.3. *Temkin analysis*

For the Temkin results without biofilm, the intercept value is −3.582, and the slope is 20.986. The heat of adsorption (B_t) is determined to be 19.321 J/mol, while the Temkin constant (K_t) is 0.831 L/mg. The coefficient of determination (R^2) is 0.929, indicating a moderate level of correlation between observed and predicted values. With biofilm, the intercept increases to 13.672, while the slope remains relatively constant at 21.489. The heat of adsorption (B_t) and Temkin constant (K_t) remain the same as without biofilm, at 19.321 J/mol and 2.029 L/mg, respectively. The coefficient of determination (R^2) decreases slightly to 0.922, suggesting a slightly weaker correlation between observed and predicted values compared to without biofilm.

4. Discussion

The study presented results and data on the adsorption capacity of coconut coir for different types and sizes of microplastics, the impact of operating conditions on coconut coir adsorption capacity, the comparison of coconut coir filtration systems with and without biofilm enhancement, the effect of biofilm enhancement on microplastic removal efficiency, the efficiency of coconut coir filtration systems for different wastewater samples, the comparison of coconut coir with other adsorbents for microplastic removal, and the cost analysis of a coconut coir-based filtration system. The results showed a consistent trend where the adsorption capacity generally increased as the size of microplastics increased for all three types. The enhanced adsorption capacity of coconut coir for microplastics with the presence of biofilm can be attributed to several underlying mechanisms. Coconut coir, known for its high surface area and porosity, provides ample binding sites for microplastics [30]. When biofilm forms on the surface of coconut coir, it introduces additional binding sites and alters the surface chemistry, further enhancing the adsorption capacity. As previously noted, biofilms are composed of a matrix of extracellular polymeric substances (EPS) produced by microorganisms, including polysaccharides, proteins, and nucleic acids. These EPS components can interact with microplastics through various mechanisms, such as electrostatic interactions, hydrogen bonding, and hydrophobic interactions. Additionally, microorganisms within the biofilm may directly adsorb microplastics through physical entrapment or enzymatic degradation [31]. The presence of biofilm can also modify the surface roughness and hydrophobicity of coconut coir, influencing the affinity for microplastics. Furthermore, biofilms can act as diffusion barriers, slowing down the release of adsorbed microplastics back into the surrounding environment [32]. Overall, the synergistic effects of coconut coir and biofilm result in a significant enhancement of the adsorption capacity for microplastics, highlighting the potential of this combination as an effective solution for microplastic removal from aqueous environments [33]. In general, the adsorption capacity of a given adsorbent, such as coconut coir, tends to increase as the size of microplastics increases. This can be attributed to several factors: first, larger microplastics have a larger surface area, providing more sites for adsorption to occur. This increased surface area allows for greater interaction between the adsorbent material and the microplastic particles, leading to higher adsorption capacity. Additionally, larger microplastics often exhibit greater hydrophobicity, which refers to their tendency to repel water. This hydrophobic nature enhances the interaction between the microplastics and the hydrophobic adsorbent surface, resulting in stronger adsorption. However, it is important to note that the relationship between microplastic size and adsorption capacity may not be linear. There may be an optimal range of microplastic sizes where the adsorption capacity is maximized. Beyond this range, the adsorption capacity might plateau or even decrease due to factors such as aggregation or changes in the surface properties of the microplastics. It is worth mentioning that the specific behavior can vary depending on the characteristics of the adsorbent material and the microplastics being studied. Different adsorbents may exhibit different adsorption behaviors towards microplastics of varying sizes.

Furthermore, the study observed the impact of various operating conditions on the adsorption capacity of coconut coir. Specifically, it investigated the effect of contact time, initial concentrations, temperatures, and pH on the adsorption capacity of microplastics. The results indicated that increasing the contact time from 2 to 6 hours generally led to higher adsorption capacity. This suggests that a longer contact time allows for more interactions between the microplastics and the coconut coir, resulting in increased adsorption. Similar occurrences have been documented in the literature when adsorbents were employed in wastewater treatment. For instance, Sharma and Kaur [34], investigated the use of sugarcane bagasse for removing erythrosin B and methylene blue from aqueous waste, where they observed that as the contact time prolonged, the rate of adsorption initially rose before reaching a plateau. Furthermore, higher initial concentrations of microplastics were found to enhance the adsorption capacity. This can be attributed to the increased availability of microplastics for adsorption when the initial concentration is higher, allowing for a greater number of adsorption sites to be utilized. Similarly, higher temperatures were observed to enhance the adsorption capacity. Elevated temperatures can increase the kinetic energy of the system, promoting more rapid diffusion and adsorption of microplastics onto the coconut coir surface. On the other hand, the effect of pH on adsorption capacity was found to vary depending on the specific conditions. The relationship between pH and adsorption capacity is complex and can be influenced by factors such as the nature of the microplastics and the surface properties of the coconut coir. In some cases, a higher or lower pH may favor adsorption, while in other cases, the optimal pH for adsorption may be different. In the study conducted by Cruz-Lopes et al. [35], the authors observed that an optimal pH range for chromium adsorption is not universally defined, as it fluctuates depending on the specific adsorbent utilized and its interactions with the aqueous solution. However, the findings enabled the authors to identify more favorable pH values for achieving a higher degree of water purification. Consequently, increased adsorption was noted with chestnut shell at pH 3.0 (71.8 %), with walnut shell and wood at pH 6.5 (52.3 % and 41.8 %, respectively), and with burnt wood at pH 5.5 (34.2 %).

Moreover, the study conducted experiments to assess the impact of a biofilm on the performance of coconut coir-based filtration systems on general microplastic removal. The findings demonstrated that the presence of a biofilm indeed enhanced the overall performance of the filtration system in several aspects. Firstly, filtration systems with a biofilm exhibited higher microplastic removal efficiency compared to systems without a biofilm. As previously highlighted, the biofilm, composed of microorganisms that adhere to the coconut coir surface, provided additional adsorption sites and enhanced the overall adsorption capacity of the system. This led to improved removal of microplastic particles from the wastewater. Additionally, the presence of a biofilm resulted in longer breakthrough times before the filtration capacity of the system was reached. The biofilm acted as a protective layer, slowing down the saturation process and extending the lifespan of the coconut coir-based filtration system. Furthermore, the biofilm had a positive impact on the longevity of the coconut coir material itself. The biofilm offered a protective barrier that reduced physical wear and tear on the coconut coir, thereby increasing its durability and extending its useable lifespan [36]. These findings highlight the potential of biofilm enhancement in improving the performance and longevity of coconut coir-based filtration systems for microplastic removal. The biofilm acts as a beneficial component that enhances adsorption capacity, prolongs breakthrough times, and increases the overall efficiency of the filtration system. To provide more precise details, the absence of biofilm enhancement resulted in removal efficiencies ranging from 72 % to 82 % for various types and sizes of microplastics. However, when biofilm enhancement was introduced, a significant improvement in removal efficiency was observed, with values ranging from 85 % to 95 %. Specifically, across all tested microplastic types and sizes, the presence of biofilm consistently enhanced the removal efficiency compared to the absence of biofilm. For example, when biofilm was present, the removal efficiency for 100 μm Polyethylene microplastics increased from 82 % to 95 %. Similar high removal efficiency values have been reported in the literature when utilizing different adsorbent materials for microplastic removal. For example, metal-organic frameworks have demonstrated removal efficiencies ranging from 70 % to 99.9 % for microplastics in aqueous environments [37]. Other materials such as Bentonite Braňany EXTRA, Bentonit Braňany STELIVO, and zeolite clinoptilolite have achieved over 90 % removal efficiency [38]. Granular activated carbon has also been effective, with removal efficiencies of up to 95.5 % reported [39]. In a study by Gao et al. [14], microplastics removal from water using coagulation with cationic-modified starch was investigated. The results showed that cationic-modified starch (CS) effectively eliminated microplastics (MPs), achieving an average removal rate of 65.33 % for polystyrene particles, with higher rates observed for larger, high-density, and aged MPs. The effectiveness of CS remained consistent across a broad range of water pH values but was notably reduced in the presence of kaolin clay or/and humic acid.

The enhanced adsorption capacity facilitated by biofilm-coated coconut coir stems from a complex interplay of mechanisms at the interface between the biofilm matrix [40], microbial communities, and microplastics. Biofilms, comprised of microbial aggregates embedded within a self-produced extracellular polymeric substance (EPS) matrix, provide a high surface area and diverse binding sites for microplastic sorption. Microbial metabolic activities within the biofilm can also induce changes in the physicochemical properties of the surrounding environment, such as pH and redox potential, which may influence microplastic adsorption. Furthermore, specific microbial species within the biofilm may possess enzymatic capabilities that facilitate microplastic degradation or surface modification, enhancing their affinity for sorption onto coconut coir fibers [41]. Surface modifications induced by biofilm colonization, such as roughening or functionalization, can also increase the availability of binding sites and promote electrostatic interactions between microplastics and the substrate. Additionally, the presence of biofilm-associated factors, such as extracellular enzymes or siderophores, may further facilitate microplastic removal by promoting aggregation or facilitating the formation of microplastic-biofilm complexes. Understanding these intricate mechanisms is crucial for optimizing the design and performance of biofilm-coated coconut coir systems for microplastic remediation, ultimately advancing sustainable wastewater treatment strategies.

5. Conclusion

The study has illuminated the pivotal role of biofilm-enhanced coconut coir in addressing the pervasive challenge of microplastic pollution in aquatic environments. Through meticulous experimentation and analysis, we have uncovered significant enhancements in the microplastic adsorption capabilities of coconut coir upon biofilm augmentation. Notably, the addition of biofilm led to a substantial increase in both specific surface area and pore volume, with typical values rising from 1000 m^2/g to 1200 m^2/g and from 0.5 cm^3/g to 0.6 cm^3/g, respectively. These findings underscore the effectiveness of biofilm in augmenting the surface properties of coconut coir, thereby facilitating improved microplastic adsorption. Furthermore, the study has revealed consistent improvements in microplastic removal efficiency across diverse operational conditions. For instance, at a microplastic size of 100 μm, coconut coir without biofilm displayed adsorption capacities ranging between 44.8 mg/g and 49.8 mg/g for PET and polyethylene, respectively. Remarkably, with biofilm augmentation, these capacities significantly increased to 59.8 mg/g and 69.7 mg/g, respectively. Additionally, typical removal efficiencies witnessed notable improvements with biofilm augmentation, ranging from 85 % to 95 % across various microplastic types and sizes, compared to a range of 72 %–82 % without biofilm. These results highlight the robustness and versatility of biofilm-enhanced coconut coir as a promising solution for microplastic removal in wastewater treatment. Importantly, beyond its practical application in microplastic mitigation, the study has provided valuable insights into optimization strategies to further enhance the efficacy of coconut coir-based filtration systems. These insights include factors such as contact time, pH level, temperature, and initial microplastic concentration, which can be tailored to optimize microplastic removal efficiency. Moreover, the findings presented in this study pave the way for future research and implementation efforts aimed at integrating biofilm-enhanced coconut coir into wastewater treatment practices. By offering a sustainable and effective solution to combat microplastic pollution in water systems, biofilm-enhanced coconut coir holds significant promise in advancing global efforts to safeguard environmental health for present and future generations. Thus, the study contributes significantly to the ongoing endeavor to mitigate microplastic contamination and underscores the importance of sustainable resource management practices in ensuring a healthier planet for all.

CRediT authorship contribution statement

Yerkebulan Zharkenov: Supervision, Resources, Investigation. **Timoth Mkilima:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Aisulu Abduova:** Resources, Data curation. **Lailya Zhaksylykova:** Resources, Investigation. **Agzhaik Turashev:** Resources, Investigation. **Raikhan Imambayeva:** Resources, Investigation. **Nurlan Imambaev:** Resources, Investigation. **Makpal Jaxymbetova:** Resources, Investigation. **Aizada Smagulova:** Resources, Investigation. **Elmira Beysenbaeva:** Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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