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Innovative Multimedia Filtration for Effective Microplastic Removal in Mangrove Ecosystems: A Sustainable Approach to Environmental Health

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ABSTRACT: Microplastic contamination posed a significant threat to mangrove ecosystems, impacting biodiversity and water quality. This study evaluated the effectiveness of a multimedia filtration system using silica sand, zeolite, activated carbon, blood clam shells, and gravel in reducing microplastic levels in mangrove waters. Water samples were collected from the Wonorejo Mangrove Ecotourism in Surabaya, Indonesia, and were treated using two filtration reactors: Reactor 1 with sand media and Reactor 2 with clamshell media. The downward-flow filtration system demonstrated promising results, with Reactor 1 achieving a 54-60% microplastic removal efficiency and Reactor 2 showing superior performance with a 61-65% efficiency. Fiber-type microplastics were most effectively removed, with Reactor 2 achieving a 67% reduction. The findings highlighted the potential of clamshell media in enhancing filtration efficiency and promoting environmental sustainability. While the system offered a viable solution for mitigating microplastic pollution in aquatic environments, challenges such as scalability, cost-effectiveness, and long-term maintenance required further research. Future studies should focus on optimizing filtration media and assessing real-world applicability for broader environmental conservation efforts.

KEYWORDS: Microplastic removal; mangrove ecotourism; multimedia filtration; environmental health; clamshell media

1. Introduction

The issue of microplastic contamination in mangrove ecosystems garnered significant attention due to the critical ecological functions that mangroves served, including coastal protection, biodiversity conservation, and carbon sequestration. Microplastics, defined as plastic particles smaller than 5 mm, originated from the degradation of larger plastic waste and posed substantial threats to the health of these ecosystems. Plastic waste, influenced by water currents and sunlight, broke down into smaller fragments, including plastic particles and microplastics. A significant portion of this waste degraded into fiber and fibrous microplastics, amounting to metric tons annually, which negatively impacted ecosystems and reduced environmental health quality [1, 2]. Furthermore, filaments, granules, and pellets were also part of microplastic waste that posed potential risks to human health, including metabolic disorders, neurotoxicity, reproductive issues, and an increased likelihood of cancer [3, 4].

Mangroves were trees that thrived in brackish water habitats and served essential ecological functions, such as absorbing waste, preventing coastal abrasion, and maintaining air and water quality [5,6]. In Indonesia, mangrove forest areas were designated as protected conservation zones under Presidential Regulation No. 73 of 2012 concerning the National Strategy for Mangrove Ecosystem Management [7]. A significant portion of marine waste originated from rivers, where improper waste disposal by individuals remained a common issue. River currents transported this waste to the sea, with some debris trapped in the roots of mangrove trees [8–10]. The mangrove environment was a highly diverse ecosystem, supporting a wide variety of living organisms [3]. However, microplastics in sediment increased ammonium concentrations in the water column, adversely affecting aquatic organisms [4]. In aquatic environments, microplastics posed significant threats to fish and other biota. Many organisms ingested plastic particles, mistaking them for food, leading to the accumulation of microplastics within their bodies.

Recent research highlighted the detrimental effects of microplastic pollution on mangrove flora and fauna. Studies documented varying concentrations of microplastics in different mangrove regions, with sediment samples from South China exhibiting significantly higher concentrations than those found in other coastal areas [11]. Moreover, research in Southeast Asia demonstrated that mangrove forests, due to their dense vegetation, effectively trapped and accumulated microplastics by reducing water flow and wave energy, functioning as natural filtration systems [12, 13]. Microplastics not only altered sediment composition but also bioaccumulated in marine organisms, disrupting food webs and marine biodiversity. For instance, studies documented the ingestion of microplastics by various species, particularly juvenile fish and crabs, leading to potential toxicological effects [14–16]. This issue was further exacerbated by the ability of microplastics to adsorb persistent organic pollutants (POPs) from the surrounding water, which could be transferred through the food chain, posing additional ecological risks [17, 18].

Addressing this multifaceted challenge required a combination of community engagement and systemic improvements in waste management. Public awareness campaigns targeting local fisheries and agricultural communities were essential to highlight the harmful impacts of plastic pollution on human health and mangrove ecosystems [19]. Additionally, enhancing plastic waste management systems, particularly in regions adjacent to mangrove forests, could significantly reduce microplastic influx into these environments. Research underscored the need for strategies that not only focused on reducing plastic consumption but also emphasized the recovery and recycling of plastics before they entered marine ecosystems [20, 21]. Various technologies had been developed and tested to reduce microplastic contamination in water, including filtration, adsorption, coagulation, and advanced oxidation processes (AOPs) [10, 22]. However, technologies specifically designed to reduce seawater microplastics remained limited [23, 24]. Among these, filtration emerged as a promising approach for seawater treatment due to its high efficiency, minimal spatial requirements, and reduced reliance on complex machinery [25]. For example, the use of filter cloths with pore sizes ranging from 57.5 to 194 μm, targeting microplastics larger than 210 μm, had been shown to achieve up to an 85.5% reduction in microplastic levels using gravitational force alone [23,24]. Furthermore, the implementation of stricter regulations on plastic production and disposal was critical to mitigating plastic accumulation in natural environments. Policymakers should consider designating protected areas that restrict human activities contributing to plastic pollution in vulnerable mangrove zones [26, 27]. Additionally, bioremediation approaches utilizing microorganisms capable of degrading plastics, along with conservation initiatives for mangrove restoration, could further alleviate the adverse effects of microplastic contamination [28, 29].

Blood clam shells were effective filtration and absorbent media for water purification, capable of binding colloids in water. Their effectiveness in removing microplastics had been demonstrated in studies [22, 30, 31], showing that clam shells could reduce microplastic concentrations by up to 88.22%. Gravel was another commonly used medium in biofilters for water treatment, and its addition in one of the filtration columns was expected to enhance microplastic removal and support the media above it. Similarly, sand was an effective filtration medium due to its pores and gaps, which helped absorb and retain particles in water [25, 32, 33]. Silica sand and zeolite were widely used filtration media known for their ability to bind pollutants. Zeolite, in particular, was a highly effective absorbent medium often employed in filtration systems [34–36]. Additionally, acrylic glass was considered a more efficient material for constructing filtration columns compared to PVC pipes, as it was made from durable polymer plastic that was less prone to degradation, as noted in the previous studies by G. Reimonn et al. (2019) [37] and J. Li et al. (2019) [38].

2. Materials and Methods

2.1. Sampling point.

Samples for this study were collected at the Wonorejo Mangrove Ecotourism in the Rungkut District of Surabaya City, as shown in Figure 1. Two sampling points were selected: one near residential areas at latitude 7°18'35" S and longitude 112°48'56" E, and the other near estuaries at latitude 7°18'40" S and longitude 112°48'50" E, with a distance of approximately 50 meters between them. The filtration process was conducted at the Environmental Engineering Laboratory of Universitas PGRI Adi Buana Surabaya, while the microplastic sample analysis was performed at the Ecoton Laboratory in Surabaya.

Figure 1. Sampling points.

2.2. Tools and materials.

The filtration column used in this study was constructed from 4-mm thick acrylic, with dimensions of 90 cm in height, 10 cm in width, and 10 cm in length. Additional equipment included a plankton net, a 100 mL small glass bottle, a compass, a mortar and pestle, a water reservoir, a 16 L gallon container, a stopwatch, distilled (DI) water, and a clear hose. The materials required for the study consisted of clam shells, 4–8 mesh silica sand, 14–20 mesh zeolite, 6–12 mesh activated carbon, and 3 cm gravel. All materials were readily available at the Universitas PGRI Adi Buana Surabaya Environmental Engineering Laboratory.

2. 3. Sample technique and preparation.

Sampling was conducted at two predetermined locations. The collection process took place in the morning when the current conditions were stable. A plankton net was used for sampling by submerging it into the river current, facing upstream, for 10 minutes at a depth of approximately 20–30 cm below the water surface. The collected water samples were transferred into 100 mL sample bottles for initial testing. Samples intended for filtration column processing were stored in black-painted plastic gallon containers to prevent sunlight exposure, which could alter the interaction between aquatic biota components and affect the quality of the water samples before processing.

The downward-flow filtration method was equipped with a water tap at its base. The filtration process was carried out using two columns with different media configurations, each tested in duplicate, with 4 liters of water filtered per column. The media arrangement in Reactor 1 (from bottom to top) consisted of sand (20 cm), silica sand (10 cm), zeolite (10 cm), activated carbon (20 cm), and gravel (10 cm). Meanwhile, Reactor 2 used clamshell media (20 cm), silica sand (10 cm), zeolite (10 cm), activated carbon (20 cm), and gravel (10 cm). Each layer of media was separated with coconut fibers to prevent mixing. After filtration, the water was passed through a plankton net, transferred into a 100 mL glass container, and analyzed at the Ecoton Laboratory. An illustration of the reactor used in this study is shown in Figure 2.

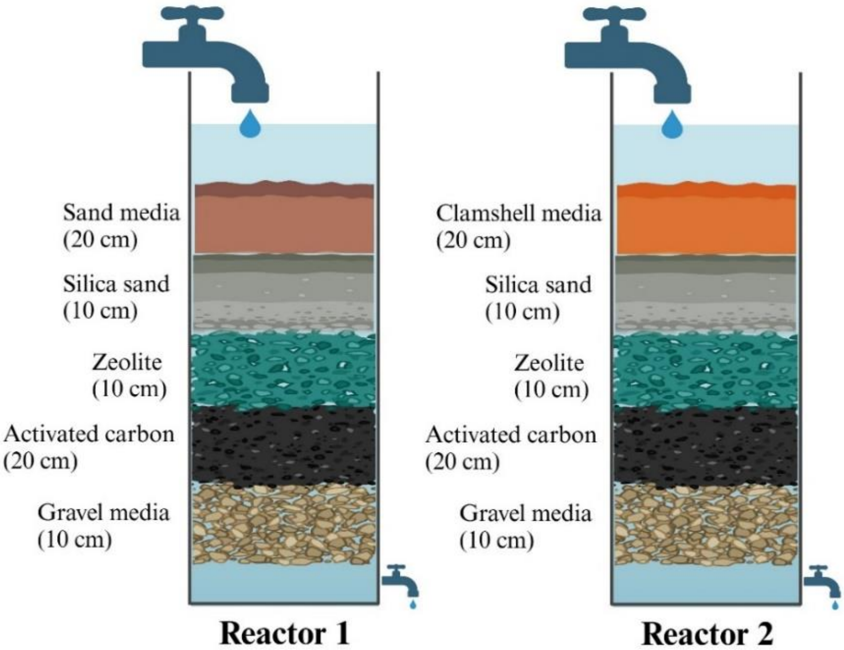

Figure 2. Schematic reactor configuration for the microplastic filtration.

These materials were selected based on their availability, cost-effectiveness, and proven efficacy in water filtration applications. Sand was chosen for its excellent mechanical filtration properties, while clamshells were incorporated for their potential to enhance filtration through calcium carbonate dissolution, which can aid in pH stabilization and contaminant removal. Additionally, clamshells serve as an environmentally friendly alternative, as they promote the reuse of natural waste materials.

2.4. Analysis method.

Water samples collected from the study sites were periodically analyzed in the laboratory to assess microplastic reduction in each reactor. Processed samples were collected twice, and the differences between Sample 1 and Sample 2 for each reactor were observed. The distinction between the two samples lay in their respective sampling locations. Observations were conducted over a single day to monitor changes in microplastic reduction following treatment with the filtration method. The efficiency of microplastic reduction was calculated using Eq. 1 [39,40]. The resulting data were processed using Microsoft Excel, and data visualization was performed with Origin Pro 2024 software (OriginLab Corporation, Northampton, MA, USA).

$$\text{Removal ratio } (\%)\varepsilon = \frac{C_{0\text{ - }C}}{C_0} \text{ x } 100 \qquad (1)$$

Where ε is the efficiency, C_0 is the initial concentration, and C is the final concentration.

3. Results and Discussion

3.1. Identification of microplastics in samples.

The purpose of microplastic identification was to determine the type and quantity of microplastics present in the samples. The samples used for this analysis were initial, unprocessed samples that had not undergone filtration. The overall results from these initial samples, collected from different locations, are presented in Table 1. Table 1 shows the presence of five types of microplastics in the samples: fibers, filaments, fragments, granules, and pellets. The data indicate that the highest concentration of microplastics was found near Point 1 (Sample 1). In Sample 1, fiber-type microplastics were the most prevalent, with a concentration of 34 particles per liter, while granule-type microplastics were the least common, with only 1 particle per liter. Similarly, in Sample 2, filament-type microplastics were the most dominant, with 25 particles per liter, whereas granules and pellets were the least abundant, each recorded at 1 particle per liter.

Table 1. Initial test results before filtration.

No	Sample Name	Microplastic Types (particles/liter)					Number
		Fiber	Filament	Fragment	Granules	Pellets	(particles/liter)
1	Initial sample 1	34	23	10	1	4	72
2	Initial sample 2	11	25	2	1	1	40

3.2. Microplastic removal in reactor 1.

Filtration units are known to be highly efficient at removing microplastics from water [41]. Sand media filters are among the most commonly used filtration methods. The detention time in sand media filtration has minimal impact on microplastic removal efficiency [42]. Instead, the grain size of the filter media plays a critical role in determining filtration performance. The effectiveness of microplastic removal largely depends on the physical properties of the microplastics, such as size and shape. If the microplastic particles are smaller than the gaps between the filter media grains, they can pass through the filter and remain unfiltered [10]. Figure 3 illustrates the reduction in microplastic levels across each sample in Reactor 1, incorporating variations in sand media. Table 2 summarizes the efficiency of microplastic reduction in Samples 1 and 2 using Reactor 1 with sand media.

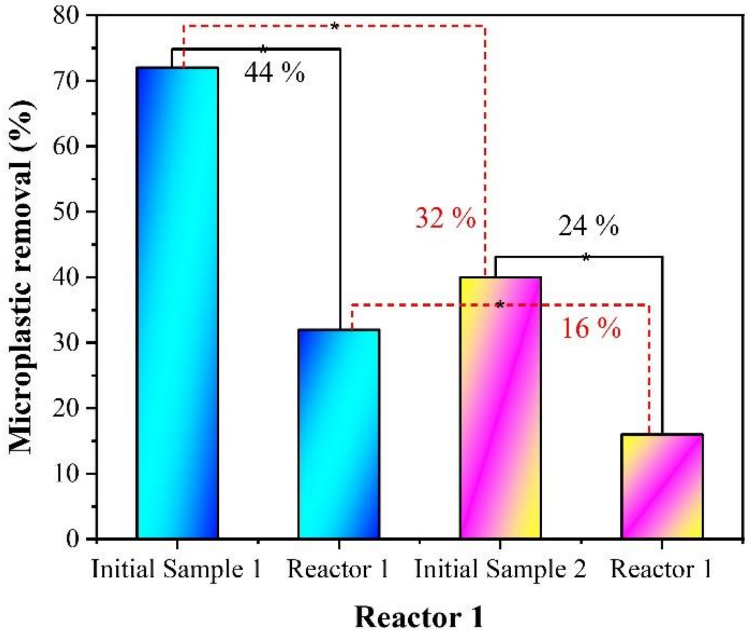

Figure 3. Graph of microplastic reduction in reactor 1 for samples 1 and 2.

Two initial samples, Initial Sample 1 and Initial Sample 2, were processed through Reactor 1 to assess changes in microplastic removal efficiency. For Initial Sample 1, microplastic removal decreased from approximately 72% to 32%, resulting in a 44% reduction in removal efficiency. In Initial Sample 2, removal efficiency declined from 40% to 16%, reflecting a 24% reduction. Reactor 1 demonstrated a higher removal efficiency for Initial Sample 1 than for Initial Sample 2, with a difference of approximately 20%. This variance highlights potential differences in the initial sample characteristics or variability in Reactor 1’s performance. The red dashed lines in the analysis indicate specific percentage reductions: a 32% reduction for Initial Sample 1 transitioning to Sample 2 in Reactor 1 and a 16% difference between the Reactor 1 outputs of the two samples. These findings suggest that Reactor 1 processed Initial Sample 1 more effectively, yielding higher microplastic removal efficiency than Initial Sample 2. The observed differences may result from factors such as the size, type, or concentration of microplastics in the initial samples. Optimization of Reactor 1 may be necessary to improve consistency in removal efficiency across different samples and enhance overall performance. Particulate removal is primarily driven by physical processes, where larger particulates become trapped between sand grains as they pass through the filter media—a process known as mechanical straining. Smaller particles adhere to the surface of sand grains due to van der Waals forces, a phenomenon referred to as physical adsorption [43].

Table 2. Reduction of microplastic abundance in samples 1 and 2 with reactor 1 containing sand media.

Reactor 1	Type of microplastic (particle/liter)					Total (particle/liter)
	Fiber	Filament	Fragment	Granules	Pellets	
Sample 1	24	6	3	0	0	33
Sample 2	9	7	0	0	0	16

Reactor 1 effectively removed microplastics from both sample types, particularly granules and pellets. In Sample 1, filament-type microplastics exhibited the most significant reduction, decreasing from 23 to 6 particles per liter, while other microplastic types showed relatively smaller reductions. Similarly, in Sample 2, filament-type microplastics experienced a greater reduction compared to other microplastic types. These findings suggest that filament microplastics are more effectively filtered by sand media. Although this study did not account for microplastic size, the results imply that filament microplastic particles are likely larger than the pore size of the sand media, allowing them to be efficiently trapped within the filter. During sand media filtration, microplastics are either adsorbed onto or trapped within the sand grains [44]. The shape and size of microplastics are critical factors influencing filtration efficiency. Studies indicate that sand media can effectively remove microplastics larger than 200 μm [45]. Fiber-shaped microplastics, due to their elongated form, tend to be the most effectively trapped type in sand media filtration [46].

3.3. Microplastic removal in reactor 2.

Figure 4 illustrates the reduction in microplastic levels in water samples processed through Reactor 2 with clamshell media variations. It includes initial sample data collected from settlement and estuary sites, along with post-filtration results from Reactor 2. The figure also highlights the decrease in microplastic levels for each sample. Table 3 provides a detailed summary of microplastic reduction in Reactor 2 using clamshell media. It compares initial and post-filtration data from both collection points, offering a clear assessment of microplastic removal efficiency.

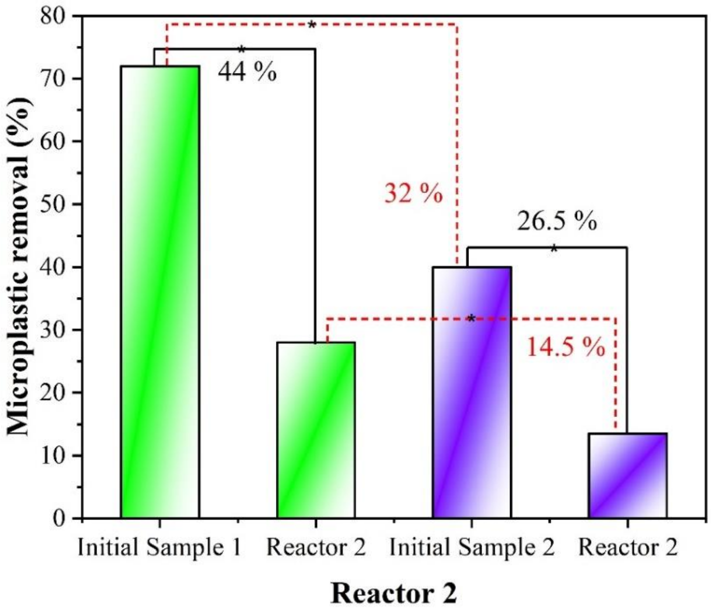

Figure 4. Graph of microplastic reduction in reactor 2 in samples 1 and 2.

The microplastic removal efficiency for initial sample 1 began at a high value of approximately 72%. After processing in reactor 2, this percentage decreased to ~28%, indicating a 44% reduction, as noted in the black annotation. For initial sample 2, the initial removal efficiency was ~40%, which dropped significantly to ~13.5% after reactor 2, representing a reduction of approximately 26.5 percentage points. Additionally, the figure highlighted a 14.5% absolute difference between the post-processed removal efficiencies of initial sample 1 and initial sample 2. The percentage reduction in removal efficiency between initial sample 1 and its post-processing value in reactor 2 was larger, at 32%, as annotated in red. After processing, the final removal efficiencies for both samples converged at approximately 14.5%. This consistent decrease indicated that reactor 2 significantly reduced microplastic removal effectiveness for both samples, revealing a limitation in its ability to maintain the initial removal rates. The larger absolute drop in removal efficiency for initial sample 1 compared to initial sample 2, along with the observed differences in removal rates before and after processing, highlighted reactor 2's performance variability. These results suggested the need for further investigation into the factors influencing the reactor's efficiency and potential optimizations to address these limitations.

In their journey, microplastics absorbed various substances in water, such as residual persistent organic pollutants and heavy metals. The hydrophobicity of microplastics allowed the absorption of halogenated by-products resulting from the production and use of cleaning agents [47–49]. The removal mechanism of microplastics was influenced by pollutants carried along with microplastics in water. Agglomeration of microplastics could chemically change the plastic's surface and affect its density, which in turn impacted the buoyancy of microplastics in water [50]. The buoyancy of microplastics in water affected the removal process in the treatment unit. Microplastics with low buoyancy were effectively removed in gravity-based processes such as sedimentation and filtration, while microplastics with high buoyancy were removed by flotation [51–54].

Table 3. Reduction in microplastic abundance in samples 1 and 2 with reactor 2 containing clamshell media.

Reactor 2	**Type of microplastic (particle/liter)**					**Total (partikel/liter)**
	Fiber	**Filament**	**Fragment**	**Granules**	**Pellets**	
Sample 1	24	4	0	0	0	28
Sample 2	8	6	0	0	0	14

The table shows that reactor 2, using clamshell media, reduced the total microplastic abundance in sample 1 from 28 particles per liter to 14 particles per liter, achieving a 50% reduction. The reduction was most significant for fibers, which decreased from 24 to 8 particles per liter (a 67% reduction). However, filaments increased from 4 to 6 particles per liter (a 50% increase), potentially due to the breakdown of fibers into smaller filament-like pieces during treatment. No fragments, granules, or pellets were present before or after treatment, indicating either their absence in the sample or that the reactor process did not generate or affect these microplastics.

The difference in filtration efficiency is due to the size of the media. Sand is smaller than clamshells and can better filter pollutants in water. The calculation results show that clamshells are more efficient in reducing microplastic levels than sand. This is due to the chitin content in the shells. Some adsorbents that show potential in microplastic removal are sponges and foams made from various chemical constituents. Sponges formed by chitin effectively adsorb various types of microplastics (pure polystyrene, carboxylate-modified polystyrene, and amine-modified polystyrene) from water. The efficiency ranges between 70% and 90%, and the sorption process is largely pH-dependent. The best performance occurs at pH 6, while the lowest is at pH 10 [55–59].

3.4. Limitation of the study.

While this study provides valuable insights into the effectiveness of multimedia filtration for microplastic removal in mangrove ecosystems, certain limitations should be acknowledged. These limitations highlight areas for improvement and future research directions:

– Limited scope of microplastic types: The study primarily focuses on fiber-type microplastics, which showed the highest removal efficiency. However, other microplastic forms, such as fragments, granules, and pellets, were less analyzed, and their removal effectiveness remains uncertain.
– Short-term testing period: The filtration process and its efficiency were evaluated over a single day. A long-term assessment would be beneficial to understand the stability, potential clogging, and durability of the filtration system under continuous use.
– Fixed sampling location and environmental conditions: The study was conducted exclusively at the Wonorejo Mangrove Ecotourism area, which may limit its applicability to different water bodies with varying environmental conditions, microplastic compositions, and hydrodynamic factors.
– Controlled laboratory setting: The study was performed in a controlled laboratory environment, which may not fully replicate real-world operational challenges, such as fluctuating water flow rates, seasonal variations, and biofouling effects that could impact filtration performance.
– Potential clogging and maintenance issues: The study does not discuss the potential clogging of the filtration media over extended use, which could affect filtration efficiency and maintenance requirements. Future studies should assess the long-term operational feasibility of these filtration systems.
– Absence of comparative analysis with other filtration methods: While the multimedia filtration system demonstrated effectiveness, the study does not compare its performance with other microplastic removal technologies, such as coagulation, adsorption, or membrane filtration, which could provide a better understanding of its relative advantages and limitations.
– Limited investigation of chemical interactions: The study primarily focuses on physical filtration and does not explore potential chemical interactions between microplastics and the filtration media. Investigating whether materials such as activated carbon and zeolite contribute to additional adsorption of contaminants would be valuable.
– Scalability and economic considerations: The study does not address the cost-effectiveness or scalability of implementing this filtration system for large-scale environmental applications. Assessing the economic feasibility of widespread adoption is necessary for practical implementation.

Acknowledging these limitations provides a foundation for further research to optimize the filtration system, improve its efficiency, and explore its real-world applicability in various environmental settings.

4. Conclusion

This study demonstrates that multimedia filtration systems incorporating sand, zeolite, activated carbon, clamshells, and gravel effectively reduce microplastic contamination in mangrove waters, with reactor 2 (clamshell media) achieving up to 65% removal efficiency. The effectiveness of clamshells in adsorbing and trapping microplastics highlights their potential as a sustainable filtration medium, particularly for fiber-type microplastics, which showed a 67% reduction. While promising, scaling up this filtration system presents challenges, including high initial construction and operational costs, maintenance concerns such as media clogging and biofouling, and the need for adaptive protocols to ensure consistent performance in varying environmental conditions. Practical deployment requires careful site selection, community engagement, and integration with existing waste management initiatives, along with feasibility assessments for decentralized versus centralized applications. Long-term studies are necessary to evaluate cost-effectiveness, durability, and adaptability to different water bodies, while collaboration with policymakers and researchers can facilitate widespread adoption. Despite these challenges, this filtration approach has significant potential to contribute to environmental conservation by mitigating microplastic pollution in aquatic ecosystems. Future improvements could focus on optimizing media and testing in different environments to further improve performance. These technologies offer a practical solution to protect sensitive ecosystems such as mangroves and enhance water quality.

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Author Contribution

Yoso Wiyarno: conceptualization, methodology, data collection, data analysis, writing, and funding; Sri Widyastuti: conceptualization, methodology, writing, and supervision; Muhammad Al Kholif: conceptualization, writing, and supervision; Wawan Gunawan: conceptualization, methodology, writing, supervision, funding.

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