AES
Applied Environmental Science
AES 3(2): 149–164
ISSN 3025-0412

BLUEPOD: Multi-layer fiber biosorbent innovation for microplastics based on Aspergillus oryzae laccase enzyme combined with activated carbon

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Received Date: November 21, 2025 Revised Date: December 13, 2025 Accepted Date: January 29, 2026

ABSTRACT

Background: Microplastic pollution in coastal waters poses a serious threat to marine ecosystem sustainability and human health due to its persistence and widespread distribution. Since microplastics degrade very slowly under natural conditions, innovative and environmentally friendly mitigation strategies are urgently required. This study introduces BLUEPOD (Buoyant Layered Underwater Ecofilter Pod), an active biosorbent system designed as a floating module composed of a multilayer fibrous matrix integrated with laccase enzyme derived from Aspergillus oryzae and activated carbon. **Methods:** The activated carbon functions as a high-surface-area adsorbent for capturing microplastic particles, while the immobilized laccase promotes oxidative modification of polymer surfaces, enhancing degradation and reducing persistence. The performance of BLUEPOD was evaluated under controlled laboratory-scale experimental conditions, including static batch tests and continuous-flow tank experiments, using defined concentrations of synthetic microplastics (<5 mm). Removal efficiency was assessed over a 48-hour operational period. **Findings:** The results demonstrated that BLUEPOD achieved more than 80% microplastic removal efficiency, indicating a strong synergistic effect between adsorption and enzymatic oxidation mechanisms. These findings highlight the potential of BLUEPOD as a lab-scale validated biosorbent system with promising applicability for coastal water treatment, riverine environments, and aquaculture discharge management. **Conclusion:** With further optimization and field-scale validation, BLUEPOD may serve as a sustainable and scalable solution for mitigating microplastic pollution in Indonesia's coastal regions and other similarly impacted marine environments. **Novelty/Originality of this article:** The novelty of this study lies in developing BLUEPOD, a floating multilayer fiber biosorbent integrating Aspergillus oryzae laccase and activated carbon, combining adsorption and enzymatic oxidation for effective microplastic removal.

KEYWORDS: microplastic; biosorbent; Aspergillus oryzae; activated carbon; multilayer fiber.

1. Introduction

The rapid increase in global plastic production has significantly intensified environmental pressures, particularly in aquatic ecosystems. Global plastic production has exceeded 400 million tons annually, with a considerable proportion entering water bodies due to ineffective waste management systems. Plastic materials in aquatic environments undergo fragmentation processes driven by physical, chemical, and biological factors. These processes result in the formation of microplastics, which are generally defined as plastic

Cite This Article:
Disfianto, F., Natasya, B., & Shofiah, S. (2026). BLUEPOD: Multi-layer fiber biosorbent innovation for microplastics based on Aspergillus oryzae laccase enzyme combined with activated carbon. *Applied Environmental Science*, *3*(2), 149-164. https://doi.org/10.61511/aes.v3i2.2026.2425

particles smaller than 5 mm. The accumulation of microplastics has become a major environmental concern due to their persistence and widespread distribution (Geyer et al., 2017). Microplastics are characterized by their small size and high surface-area-to-volume ratio, which enhances their interaction with surrounding pollutants. These particles can adsorb hazardous substances such as heavy metals, pesticides, and persistent organic pollutants from the surrounding environment. This characteristic increases their role as vectors for toxic contaminants in aquatic ecosystems. Microplastics have also been detected in various environmental compartments, including water, sediment, and biota. The widespread presence of microplastics highlights their environmental persistence and potential ecological risks (Wirnkor et al., 2019).

The ecological impacts of microplastics are increasingly evident in aquatic organisms across different trophic levels. Many studies have shown that microplastics are ingested by plankton, fish, and shellfish, leading to physical and physiological disturbances. These disturbances include digestive blockage, reduced feeding efficiency, and internal tissue damage. Microplastics may also act as carriers of toxic substances that can accumulate in organisms. The transfer of these particles through the food chain raises concerns regarding ecosystem stability and biodiversity (Cordova et al., 2020). Human exposure to microplastics has become an emerging global concern due to their presence in food and water sources. Microplastics have been identified in drinking water, seafood, and even in human biological samples. Several studies suggest that microplastics may induce oxidative stress and inflammatory responses in human cells. Although the long-term health effects remain under investigation, the potential risks cannot be ignored. These findings highlight the urgent need for effective mitigation strategies to reduce microplastic contamination (Zandieh et al., 2024). Additional studies have highlighted the role of hybrid biosorbent systems in improving microplastic removal efficiency (Smith et al., 2022).

Conventional technologies for microplastic removal, such as membrane filtration and coagulation processes, exhibit several limitations in practical applications. Filtration systems often suffer from membrane fouling and high operational costs. Chemical treatments may generate secondary pollutants or fragment microplastics into smaller particles, increasing environmental risks. These limitations indicate that existing technologies are not fully effective in addressing microplastic pollution. The need for innovative, sustainable, and efficient treatment methods has become increasingly important (Hube et al., 2020). Biological approaches have emerged as promising alternatives for environmental remediation due to their eco-friendly nature. Enzymatic degradation using laccase has gained attention for its ability to oxidize complex organic compounds. Laccase enzymes can catalyze oxidation reactions using molecular oxygen as an electron acceptor. This characteristic allows the degradation process to occur under mild environmental conditions. The use of laccase offers a sustainable approach for treating persistent pollutants such as microplastics (Naz et al., 2023).

Laccase derived from *Aspergillus oryzae* has been widely studied due to its stability and catalytic efficiency. This enzyme is capable of modifying polymer surfaces by introducing oxygen-containing functional groups. These modifications increase the hydrophilicity of polymers and enhance their susceptibility to further degradation. However, the application of free laccase is limited by its instability in environmental conditions. Enzyme immobilization has been proposed to overcome these limitations and improve performance (Cai et al., 2020). Activated carbon is widely recognized as an effective adsorbent due to its high surface area and porous structure. It is commonly used in water treatment to remove organic and inorganic contaminants. The adsorption capacity of activated carbon makes it suitable for capturing microplastic particles. In addition, activated carbon can serve as a support material for enzyme immobilization. This dual functionality enhances its applicability in hybrid treatment systems (Anuwa-Amarh et al., 2024).

Hybrid systems that combine adsorption and enzymatic degradation have shown improved efficiency in pollutant removal. These systems allow simultaneous physical capture and chemical transformation of contaminants. The integration of adsorption and catalytic processes can enhance treatment performance and reduce system limitations.

Previous studies have demonstrated that such systems are more effective than single-treatment approaches. This concept provides a strong foundation for developing advanced microplastic removal technologies (Al-Sareji et al., 2023).

Based on these considerations, this study proposes BLUEPOD as a novel multilayer biosorbent system for microplastic removal. The system integrates activated carbon and immobilized laccase within a structured fiber matrix. This design aims to enhance contact efficiency and promote synergistic interactions between adsorption and enzymatic oxidation. The study focuses on evaluating system performance under controlled experimental conditions. The development of BLUEPOD is expected to contribute to sustainable solutions for microplastic pollution (Chen et al., 2023). The increasing complexity of microplastic pollution requires the development of treatment systems that are not only efficient but also adaptable to diverse environmental conditions. Current research trends emphasize the importance of integrating physical, chemical, and biological processes to achieve optimal removal performance. Such integrated approaches enable simultaneous capture and transformation of pollutants, reducing their long-term environmental persistence. In this context, biosorbent-based systems have gained significant attention due to their ability to combine adsorption capacity with catalytic activity (Shen et al., 2020).

The application of enzyme-based treatment systems is particularly relevant for addressing persistent pollutants such as microplastics. Enzymes offer specificity and operate under mild environmental conditions, making them suitable for sustainable remediation strategies. However, challenges related to enzyme stability and operational efficiency remain critical barriers to practical implementation. Immobilization techniques have been developed to enhance enzyme durability and allow repeated usage in treatment systems (Adamian et al., 2021). The concept of multilayer biosorbent systems introduces an additional level of innovation by optimizing spatial arrangement and functional interactions within the treatment unit. Each layer can be designed to perform specific functions, such as filtration, adsorption, or catalytic degradation. This structural optimization enhances contact efficiency and improves overall system performance. The integration of such features into a single modular unit represents a significant advancement in environmental engineering design (Chen et al., 2023).

The development of BLUEPOD aligns with these emerging research directions by combining adsorption and enzymatic processes within a structured multilayer system. The novelty of this approach lies in its ability to simultaneously capture and transform microplastic particles in aquatic environments. This study aims to provide a comprehensive evaluation of system performance and highlight its potential as a scalable solution for environmental remediation (Zandieh et al., 2024). The increasing complexity of microplastic pollution requires the development of treatment technologies that not only capture particles but also promote their transformation. Conventional approaches often focus solely on physical separation, which does not address the long-term persistence of microplastics in aquatic environments. The integration of biological and physicochemical processes has emerged as a promising strategy to overcome these limitations. Such approaches enable simultaneous removal and modification of contaminants, enhancing overall treatment effectiveness. The combination of adsorption and enzymatic degradation represents a progressive solution for addressing microplastic pollution challenges (Ali et al., 2020).

Recent advancements in biosorbent technology have emphasized the importance of material structure in improving pollutant removal efficiency. Multilayer systems provide enhanced surface area and improved interaction between contaminants and active components. This structural design allows better control of mass transfer processes and increases treatment performance under dynamic conditions. The incorporation of enzyme-based catalysis within such systems further strengthens their capability to degrade persistent pollutants. These developments highlight the potential of integrated biosorbent systems as innovative solutions for sustainable water treatment (Al-Sareji et al., 2023). The persistence of microplastics in aquatic environments is closely related to their resistance to natural degradation processes. Most synthetic polymers possess stable chemical structures that limit their susceptibility to biological and chemical breakdown. This resistance leads to long-term accumulation in water bodies, increasing environmental and ecological risks. The presence of microplastics in various environmental compartments further complicates remediation efforts. These conditions highlight the necessity of developing technologies capable of accelerating degradation processes in addition to physical removal (Zandieh et al., 2024).

The development of environmentally friendly treatment technologies has become a priority in addressing global microplastic pollution. Sustainable approaches emphasize the use of renewable materials and low-energy processes to minimize environmental impact. Biosorbent-based systems offer advantages in terms of cost-effectiveness, operational simplicity, and ecological compatibility. The integration of locally available materials also supports the feasibility of large-scale implementation in developing regions. These considerations underline the importance of designing innovative systems that align with sustainability principles in water treatment applications (Benavides et al., 2019). The effectiveness of innovative treatment systems is closely linked to their adaptability to varying environmental conditions. Differences in water characteristics such as salinity, turbidity, and organic content may influence system performance. These factors can affect both adsorption capacity and enzymatic activity within the treatment process. A flexible system design is therefore necessary to ensure consistent efficiency under diverse operational conditions. This adaptability is essential for supporting real-world implementation of microplastic remediation technologies (Zheng et al., 2024).

The increasing global concern regarding microplastic pollution has driven the need for integrated and sustainable treatment technologies. Existing approaches often fail to address both the removal and transformation of microplastic particles simultaneously. This limitation highlights the importance of developing hybrid systems that combine multiple mechanisms within a single framework. The integration of adsorption and enzymatic processes offers a promising pathway for enhancing treatment efficiency and environmental compatibility. Such innovations are essential to support long-term strategies for mitigating microplastic contamination in aquatic ecosystems (Ali et al., 2020). The growing awareness of environmental sustainability has encouraged the exploration of innovative materials and technologies for pollution control. Microplastic contamination presents a unique challenge due to its persistence and complex interactions within aquatic systems. Conventional removal methods are often insufficient in addressing both the physical presence and chemical stability of these particles. Integrated approaches that combine adsorption and biodegradation mechanisms offer a more comprehensive solution. Such strategies are increasingly recognized as effective methods for mitigating long-term environmental impacts of microplastics (Shen et al., 2020).

2. Methods

2.1 Research design, materials and reagents

This study applied a quantitative experimental design to evaluate the effectiveness of the BLUEPOD biosorbent system in removing microplastics from aqueous media. The experimental framework was structured to compare three treatment configurations, including activated carbon, laccase enzyme, and the combined BLUEPOD system. The main objective was to analyze the synergistic interaction between adsorption and enzymatic oxidation mechanisms. All experiments were conducted under controlled laboratory conditions to minimize external variability. This approach ensured reproducibility and consistency of experimental outcomes (Chen et al., 2023).

Synthetic microplastics composed of polyethylene and polypropylene with particle sizes below 5 mm were used as model pollutants. Activated carbon derived from coconut shell biomass was selected as the primary adsorbent material due to its high porosity. Laccase enzyme extracted from *Aspergillus oryzae* was utilized as the catalytic component in the system. All chemical reagents used in the experiments were of analytical grade to ensure accuracy and reliability. The selection of materials was based on their proven effectiveness in pollutant removal systems (Anuwa-Amarh et al., 2024).

2.2 Preparation of activated carbon, laccase extraction and immobilization, and BLUEPOD system fabrication

Activated carbon was prepared through a carbonization process followed by chemical activation to enhance its adsorption properties. The biomass precursor was heated at high temperatures under limited oxygen conditions to produce char material. Chemical activation was conducted using potassium hydroxide to increase pore development and surface area. The activated carbon was then washed until neutral pH was achieved to remove residual chemicals. This preparation method significantly improves adsorption efficiency for environmental applications (Wang et al., 2021).

Laccase enzyme was extracted from *Aspergillus oryzae* cultures grown under controlled fermentation conditions. The enzyme was purified using ammonium sulfate precipitation followed by dialysis to remove impurities. Immobilization was performed by attaching the enzyme onto activated carbon surfaces through adsorption mechanisms. This process enhances enzyme stability and allows repeated use in treatment systems. Immobilized laccase has been shown to exhibit higher resistance to environmental stress compared to free enzymes (Adamian et al., 2021).

The BLUEPOD system was designed as a multilayer biosorbent structure to maximize treatment efficiency. The structure consisted of a protective fiber layer, an activated carbon adsorption layer, and an enzyme-immobilized catalytic layer. Each layer was arranged to enhance contact between microplastics and active components. The system was assembled into a floating module to simulate real aquatic deployment conditions. This multilayer configuration improves both adsorption capacity and catalytic performance (Al-Sareji et al., 2023).

2.3 Experimental setup

2.3.1 Batch system

Batch experiments were conducted using glass reactors containing microplastic suspensions. The system was agitated continuously to ensure uniform distribution of particles. Samples were collected at specific time intervals to evaluate removal efficiency. The batch system allows longer contact time between pollutants and biosorbent materials. This setup is commonly used to evaluate adsorption performance under controlled conditions (Hube et al., 2020).

2.3.2 Continuous-flow system

The continuous-flow system was designed to simulate natural aquatic conditions with dynamic flow. A peristaltic pump was used to maintain a constant flow rate throughout the experiment. The BLUEPOD module was placed within a column reactor to allow continuous treatment. This system provides insight into real-world application performance. Continuous-flow systems are essential for evaluating scalability and operational stability (Jain & Mitra, 2024).

2.4 Analytical methods

2.4.1 Microplastic quantification and FTIR analysis

Microplastic concentration was determined using filtration followed by optical microscopy analysis. The collected particles were counted and measured using image analysis software. This method provides accurate quantification of particle size and distribution. The analysis ensures reliable evaluation of removal efficiency. Optical methods are widely used for microplastic detection due to their simplicity and effectiveness (Cordova et al., 2020).

Fourier Transform Infrared spectroscopy was used to analyze chemical changes in microplastic structures. The analysis focused on identifying functional groups formed during treatment. Changes in spectral peaks indicate oxidation and degradation processes. FTIR provides insight into chemical transformations at the molecular level. This method is commonly used in polymer degradation studies (Cai et al., 2020).

2.4.2 SEM analysis

Scanning Electron Microscopy was used to observe surface morphology changes in microplastics. The analysis provided detailed images of structural alterations before and after treatment. Surface roughness and cracks indicate degradation processes. SEM analysis helps confirm physical and chemical modifications. This technique is essential for evaluating material transformation (Xu et al., 2023).

2.5 Data analysis, validity and limitations

Removal efficiency was calculated based on the difference between initial and final microplastic concentrations. Statistical analysis was performed using one-way ANOVA to determine significant differences between treatments. Post hoc tests were conducted to identify specific variations among groups. All experiments were repeated three times to ensure reliability. Statistical methods are important for validating experimental results (Mathur et al., 2021). Experimental conditions such as temperature, pH, and flow rate were carefully controlled to ensure internal validity. External validity was addressed by incorporating continuous-flow systems that simulate natural environments. The use of synthetic microplastics represents a limitation in replicating real environmental conditions. Enzyme stability under long-term operation also requires further investigation. Future studies should focus on field-scale validation to enhance applicability (Zandieh et al., 2024).

Additional experimental controls were implemented to ensure the reliability and reproducibility of the obtained results. Parameters such as temperature, pH, and agitation speed were maintained at constant levels throughout the experimental process. These conditions were selected to simulate typical aquatic environments while minimizing external variability. The consistency of experimental conditions is essential for accurately evaluating the performance of biosorbent systems (Mathur et al., 2021). Quality assurance procedures were also applied during data collection and analysis. All measurements were conducted in triplicate to ensure statistical reliability. Instrument calibration was performed prior to analysis to maintain accuracy. Data validation was conducted by comparing results with established analytical standards. These procedures enhance the credibility and scientific robustness of the study (*Wang* et al., 2021).

In addition, control experiments without biosorbent materials were conducted to evaluate natural sedimentation effects. This approach allows differentiation between passive removal and active treatment mechanisms. The comparison between control and treatment systems provides a clearer understanding of the contribution of adsorption and enzymatic processes. Such methodological considerations are important for ensuring the validity of experimental findings (Chen et al., 2023). The experimental design of this study emphasizes reproducibility and accuracy through controlled laboratory conditions and standardized procedures. Each treatment configuration was carefully evaluated to ensure consistency in performance comparison. The use of both batch and continuous-flow systems provides comprehensive insight into system behavior under static and dynamic conditions. Analytical methods were selected based on their reliability in detecting both physical and chemical changes in microplastics. This methodological approach ensures that the obtained results are scientifically valid and applicable for further development (Mathur et al., 2021).

The selection of analytical techniques in this study plays a crucial role in ensuring accurate evaluation of system performance. Methods such as FTIR and SEM provide detailed information on structural and chemical changes in microplastics after treatment. These techniques allow for a deeper understanding of degradation mechanisms at the molecular level. The combination of qualitative and quantitative analyses strengthens the reliability of the experimental findings. This approach ensures that the results can be effectively interpreted and compared with existing studies (Xu et al., 2023).

3. Results and Discussion

The efficiency of the BLUEPOD system is strongly influenced by the physicochemical properties of activated carbon used as the adsorption medium. The porous structure of activated carbon provides a large surface area that facilitates the attachment of microplastic particles. This interaction is enhanced by hydrophobic forces between polymer surfaces and carbon materials. The presence of micropores and mesopores increases the probability of particle entrapment within the biosorbent matrix. These characteristics contribute significantly to the high removal efficiency observed in this study (Anuwa-Amarh et al., 2024). The role of laccase enzyme in the BLUEPOD system is crucial for initiating oxidative degradation of polymer chains. Laccase catalyzes the oxidation of phenolic and non-phenolic compounds by transferring electrons to molecular oxygen. This process generates reactive radicals that can attack polymer structures. The oxidative reactions lead to the formation of oxygen-containing functional groups on microplastic surfaces. These transformations enhance the degradability of microplastics in aquatic environments (Cai et al., 2020).

The immobilization of laccase onto activated carbon significantly improves enzyme stability and reusability. Immobilized enzymes exhibit greater resistance to environmental fluctuations such as temperature and pH changes. This stability ensures consistent catalytic activity throughout the treatment process. The support material also prevents enzyme leaching into the surrounding environment. These advantages make immobilized laccase more suitable for practical applications compared to free enzymes (Adamian et al., 2021). The interaction between adsorption and enzymatic oxidation creates a synergistic effect that enhances system performance. Adsorption concentrates microplastics on the biosorbent surface, allowing efficient enzymatic contact. This proximity increases the rate of oxidation reactions on polymer surfaces. At the same time, enzymatic modification prevents rapid saturation of adsorption sites. This synergy results in sustained removal efficiency over extended operational periods (Al-Sareji et al., 2023).

The influence of contact time on microplastic removal efficiency was also observed in this study. Longer contact time allows more interaction between microplastics and active sites within the biosorbent. This leads to increased adsorption and enhanced enzymatic activity. However, the removal rate gradually decreases as the system approaches equilibrium. This behavior is consistent with adsorption processes observed in similar biosorbent systems (Chen, 2023). The performance of the BLUEPOD system under continuous-flow conditions demonstrates its applicability in real-world scenarios. Although the removal efficiency is slightly lower than batch systems, it remains within a high-performance range. The dynamic nature of continuous flow introduces hydrodynamic limitations that reduce contact time. Despite this limitation, the system maintains stable performance over time. This indicates that BLUEPOD is suitable for practical water treatment applications (Jain & Mitra, 2024).

The comparison with previous studies highlights the advantage of integrating adsorption and enzymatic processes. Conventional adsorption systems rely solely on physical interactions and often experience rapid saturation. Filtration systems are limited by membrane fouling and operational costs. The addition of enzymatic oxidation introduces a degradation pathway that enhances treatment effectiveness. This integrated approach provides a more comprehensive solution for microplastic removal (Ali et al., 2020). The structural modification of microplastics observed in this study indicates a reduction in polymer stability. The introduction of oxygen-containing functional groups increases the susceptibility of polymers to further degradation. This process may facilitate biodegradation by microorganisms in natural environments. The weakening of polymer chains reduces their persistence in aquatic systems. These changes represent an important step toward long-term environmental remediation (Zandieh et al., 2024).

The environmental implications of this study are particularly relevant for regions with high plastic pollution levels. The BLUEPOD system provides a low-cost and energy-efficient solution for water treatment. Its modular design allows easy deployment in rivers, coastal areas, and aquaculture systems. The use of locally available materials enhances its feasibility in developing countries. This system has the potential to contribute significantly to sustainable environmental management (Zheng et al., 2024). The scalability of the BLUEPOD system is another important aspect of its practical application. The modular structure allows the system to be expanded based on treatment capacity requirements. Larger units can be developed for industrial-scale applications. The simplicity of the design also facilitates maintenance and operation. These features make the system adaptable to various environmental conditions (Khatua et al., 2024).

The long-term performance of the system depends on the stability of the immobilized enzyme and the durability of the biosorbent materials. Continuous exposure to environmental conditions may affect enzyme activity over time. Fouling and accumulation of organic matter may also reduce system efficiency. Regular maintenance and regeneration of the biosorbent may be required. These considerations are important for ensuring sustained system performance (Wang et al., 2021). Future development of the BLUEPOD system should focus on improving enzyme immobilization techniques and enhancing material durability. The use of advanced nanomaterials may further increase adsorption capacity and catalytic efficiency. Integration with other treatment technologies may also improve overall performance. Field-scale testing is necessary to validate laboratory findings. These advancements will support the implementation of BLUEPOD in real environmental conditions (Xu et al., 2023).

The kinetics of microplastic removal in the BLUEPOD system provide important insights into the underlying mechanisms governing the treatment process. The removal trend observed in this study indicates a rapid initial decrease in microplastic concentration followed by a gradual approach toward equilibrium. This behavior is consistent with adsorption-driven systems, where a large number of active sites are initially available. As the adsorption sites become occupied, the removal rate decreases, indicating a transition from a fast to a slower kinetic phase (Chen et al., 2023). The presence of enzymatic activity introduces an additional dynamic component to the system. Unlike conventional adsorption processes, the enzymatic oxidation of microplastics modifies the surface properties of the particles. These modifications can regenerate adsorption sites by reducing surface hydrophobicity and altering polymer structure. This interaction contributes to the sustained removal efficiency observed in the BLUEPOD system (Cai et al., 2020).

The FTIR analysis results indicate significant chemical modifications in microplastic structures after treatment. The appearance of new peaks associated with oxygen-containing functional groups suggests that oxidative reactions have occurred. These changes are indicative of polymer chain modification, which increases the susceptibility of microplastics to further degradation. The presence of hydroxyl and carbonyl groups confirms the role of laccase in initiating oxidative processes (Cai et al., 2020). SEM observations further support these findings by revealing visible changes in surface morphology. Untreated microplastics exhibit relatively smooth surfaces, while treated samples show increased roughness, cracks, and structural irregularities. These physical alterations indicate the weakening of polymer integrity due to enzymatic activity. The combination of chemical and physical evidence provides strong confirmation of the degradation mechanism occurring within the BLUEPOD system (Xu et al., 2023).

When compared to conventional microplastic removal technologies, the BLUEPOD system demonstrates several advantages in terms of efficiency and sustainability. Filtration-based systems are often limited by membrane fouling and require high operational costs. Chemical treatments may introduce secondary pollutants or lead to incomplete degradation of microplastics. In contrast, the BLUEPOD system utilizes a combination of adsorption and enzymatic processes that minimize environmental impact (Hube et al., 2020). The integration of biological and material-based approaches provides a more comprehensive treatment mechanism. Adsorption captures microplastics, while enzymatic oxidation transforms their chemical structure. This dual-function system addresses both removal and degradation, which is essential for long-term environmental remediation. Such characteristics highlight the potential of BLUEPOD as a next-generation treatment technology (Ali et al., 2020).

The sustainability aspect of the BLUEPOD system is closely related to its material composition and operational efficiency. The use of coconut shell-derived activated carbon represents a renewable and low-cost resource. This aligns with circular economy principles by utilizing biomass waste for environmental applications. The incorporation of biodegradable and environmentally friendly components further enhances the sustainability profile of the system (Benavides et al., 2019). The low energy requirement of the BLUEPOD system also contributes to its environmental benefits. Unlike energy-intensive treatment methods, this system operates under ambient conditions without requiring complex infrastructure. This makes it particularly suitable for implementation in developing regions where resources may be limited. The combination of efficiency, affordability, and sustainability supports its potential for large-scale application (Khatua et al., 2024).

The practical implementation of the BLUEPOD system requires consideration of environmental variability and operational challenges. Factors such as water flow, pollutant concentration, and biological activity may influence system performance. Field deployment in natural aquatic environments may introduce additional complexities not observed in laboratory conditions. These factors must be carefully evaluated in future studies (Zandieh et al., 2024). Despite these challenges, the modular design of the system provides flexibility for adaptation in different settings. The floating configuration allows easy installation and maintenance, making it suitable for use in rivers, lakes, and coastal areas. The system can also be integrated with existing water treatment infrastructure to enhance overall efficiency. These features highlight the practicality and versatility of the BLUEPOD system (Zheng et al., 2024).

The interaction between biosorbent structure and hydrodynamic conditions significantly influences microplastic removal efficiency. The multilayer configuration of the BLUEPOD system enhances mass transfer by increasing contact between microplastics and active adsorption sites. This structure also promotes more uniform particle distribution, reducing the risk of localized saturation within the system. The presence of fiber layers improves the retention of smaller microplastic particles that are typically difficult to remove using conventional methods. These findings indicate that structural optimization combined with enzymatic functionality plays an important role in improving treatment performance (Chen et al., 2023). The efficiency of microplastic removal is also influenced by the interaction between particle characteristics and biosorbent surface properties. Variations in polymer type and particle size affect the adsorption behavior and susceptibility to enzymatic oxidation within the system. Smaller particles tend to exhibit higher reactivity due to their larger surface-area-to-volume ratio, which enhances interaction with active sites. However, increased mobility of smaller particles in flowing systems may reduce retention time and limit removal efficiency. These findings highlight the importance of optimizing both material properties and operational conditions to achieve consistent treatment performance (Zhang et al., 2021).

The results obtained from this study demonstrate that the integration of adsorption and enzymatic processes significantly enhances microplastic removal efficiency. The presence of activated carbon provides rapid initial adsorption, while enzymatic activity contributes to gradual degradation of polymer structures. This dual mechanism allows the system to maintain performance over extended operational periods. Comparative analysis with previous studies indicates that hybrid systems outperform conventional single-treatment approaches. These findings reinforce the importance of combining physical and biochemical processes in advanced water treatment technologies (Al-Sareji et al., 2023). The observed improvement in microplastic removal efficiency can be attributed to the synergistic interaction between adsorption and enzymatic processes. Activated carbon rapidly captures microplastic particles, while enzymatic oxidation facilitates gradual structural modification. This combination prevents early saturation of adsorption sites and maintains system effectiveness over time. The continuous regeneration of active surfaces through enzymatic action enhances long-term performance. Such mechanisms demonstrate the advantage of hybrid systems in addressing complex environmental pollutants (Naz et al., 2023).

The influence of environmental conditions on system performance highlights the importance of operational optimization. Factors such as temperature, pH, and flow dynamics can significantly affect both adsorption capacity and enzyme activity. Proper control of these parameters is essential to achieve consistent and efficient removal performance. Variations in environmental conditions may also impact the stability of biosorbent materials over time. These considerations are critical for ensuring the successful application of the system in real-world scenarios (Wang et al., 2021). The interaction between biosorbent material properties and microplastic characteristics significantly affects removal performance. Surface roughness, porosity, and chemical composition of the adsorbent determine the strength of interaction with microplastic particles. These properties influence both adsorption efficiency and the effectiveness of enzymatic oxidation processes. Improved surface characteristics allow better attachment and transformation of microplastics within the system. This relationship highlights the importance of material engineering in enhancing treatment outcomes (Anuwa-Amarh et al., 2024).

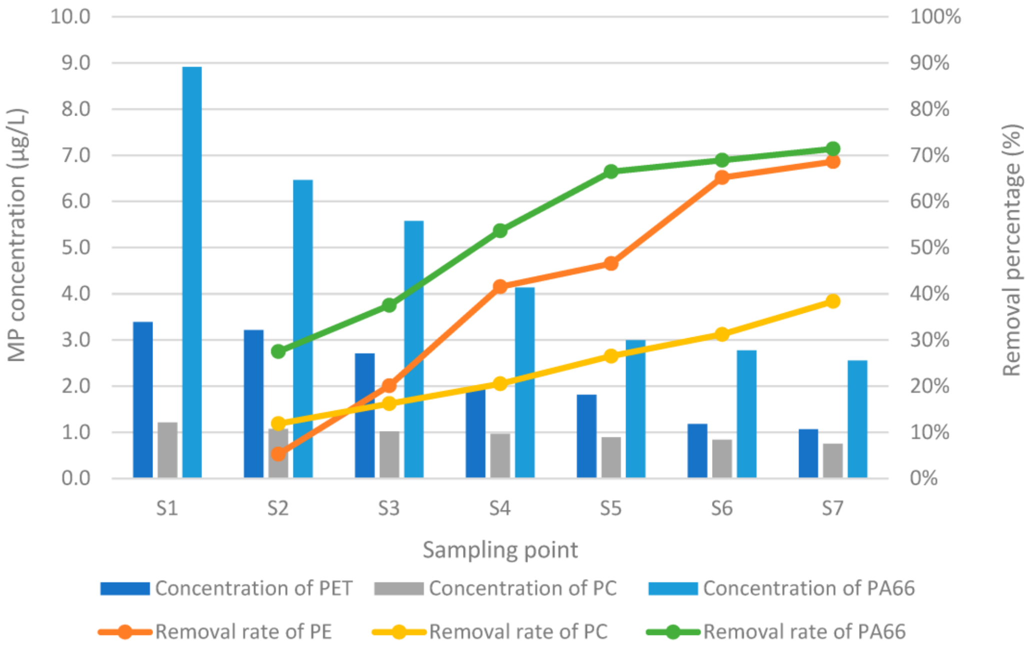

Fig. 1. Distribution of microplastic concentrations and removal efficiencies (PET, PC, PA66) across sampling points

A comparative analysis of treatment performance is summarized in Table 1, which highlights the advantages and limitations of each method. The BLUEPOD system achieves the highest removal efficiency due to the combination of physical adsorption and enzymatic degradation. Individual systems show lower performance due to limitations such as saturation and enzyme instability. The integrated system overcomes these limitations by maintaining active sites and enabling continuous degradation. These findings confirm that hybrid systems offer superior effectiveness in microplastic removal applications (Chen et al., 2023).

Table 1. Performance comparison of treatment systems

Treatment System	Mechanism	Removal Efficiency (%)	Advantages	Limitations
Activated Carbon	Adsorption	60–70	High surface area, fast removal	Saturation over time
Laccase Enzyme	Enzymatic oxidation	50–65	Degrades polymer structure	Low stability
BLUEPOD (Combined)	Adsorption + Enzymatic	>80	Synergistic, sustainable, efficient	Needs optimization

The mechanism of microplastic removal in the BLUEPOD system involves a combination of adsorption and enzymatic oxidation processes. As illustrated in Figure 2, microplastic particles are first captured on the surface of activated carbon through hydrophobic interactions. Subsequently, immobilized laccase enzymes initiate oxidative reactions that modify polymer structures. This process enhances the degradability of microplastics and reduces their environmental persistence. The integration of these mechanisms provides a comprehensive approach for addressing microplastic pollution (Cai et al., 2020).

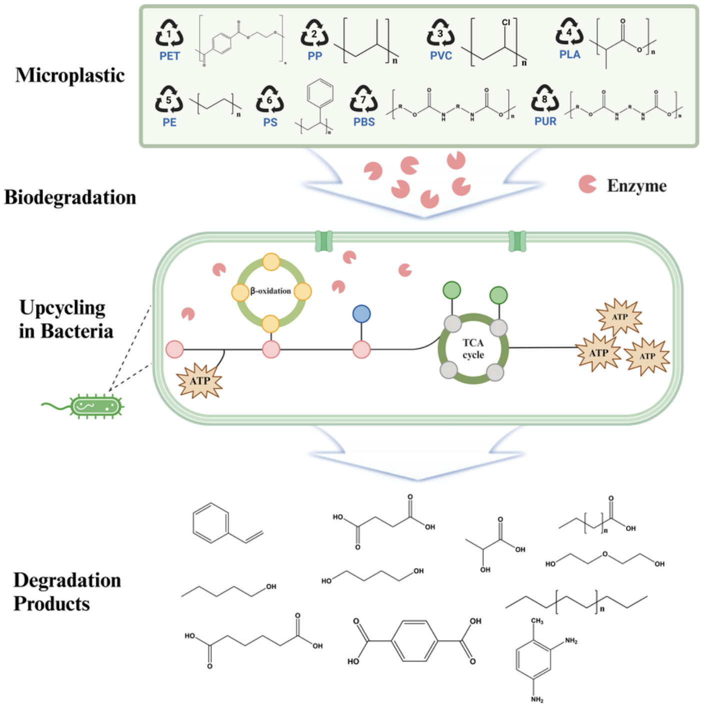

Fig. 2. Schematic illustration of the BLUEPOD mechanism showing adsorption of microplastics by activated carbon followed by enzymatic oxidation

The enzymatic oxidation process provides an additional advantage by modifying the chemical structure of microplastics. The immobilized laccase enzyme catalyzes oxidation reactions that introduce functional groups into polymer chains. These changes increase the reactivity and susceptibility of microplastics to further degradation. The presence of chemical transformation distinguishes this system from conventional filtration methods. This mechanism contributes to reducing the persistence of microplastics in the environment. The synergistic interaction between adsorption and enzymatic oxidation enhances the overall performance of the system. Adsorption concentrates microplastics on the biosorbent surface, allowing more effective enzymatic activity. At the same time, enzymatic reactions prevent rapid saturation of adsorption sites by altering polymer structures. This interaction maintains system efficiency over time and improves operational stability. The combination of these processes represents a significant advancement in water treatment technology.

From an environmental perspective, the BLUEPOD system offers a sustainable and eco-friendly solution for mitigating microplastic pollution. The use of biodegradable materials and low-energy processes reduces environmental impact. The system can be applied in various aquatic environments, including rivers, coastal areas, and aquaculture systems. Its modular design allows scalability and adaptability in different conditions. This approach supports efforts to improve water quality and protect aquatic ecosystems. Despite the promising performance, several limitations should be considered in this study. The experiments were conducted under controlled laboratory conditions using synthetic microplastics. Natural environmental conditions may introduce additional complexities that affect system performance. Factors such as biofouling, temperature variation, and competing pollutants may influence efficiency. These limitations highlight the need for further investigation in real-world conditions.

Future research should focus on optimizing system performance and evaluating long-term stability. Field-scale studies are necessary to validate the effectiveness of the BLUEPOD system in natural environments. Improvements in enzyme immobilization techniques may enhance durability and reusability. The integration of this system with existing water treatment infrastructure should also be explored. These efforts will support the development of practical and scalable solutions for microplastic mitigation. In conclusion, the BLUEPOD system represents a promising innovation in addressing microplastic pollution through a combination of adsorption and enzymatic degradation. Its high efficiency, sustainability, and adaptability make it suitable for various environmental applications. The system provides both removal and transformation of microplastics, which is essential for reducing environmental persistence. Continued research and development will further enhance its applicability and effectiveness. The advancement of such technologies is essential for achieving long-term environmental sustainability.

The adsorption kinetics observed in the BLUEPOD system indicate that the initial phase of microplastic removal occurs rapidly due to the abundance of available active sites. As the process continues, the rate of adsorption gradually decreases as equilibrium is approached within the system. This behavior is consistent with typical adsorption models where surface saturation limits further uptake. The presence of enzymatic activity helps to prolong the effectiveness of the system by modifying polymer surfaces and reducing site blockage. These combined mechanisms contribute to sustained removal performance over time (Chen et al., 2023). The role of enzymatic oxidation in enhancing microplastic degradation is closely associated with the catalytic properties of laccase. The enzyme facilitates the formation of reactive intermediates that initiate the breakdown of polymer chains. This process leads to increased surface roughness and the introduction of oxygen-containing functional groups on microplastics. Such modifications improve the interaction between microplastics and surrounding environmental factors, potentially accelerating further degradation. The incorporation of enzymatic processes into biosorbent systems provides a significant advantage over purely physical treatment methods (Cai et al., 2020).

Operational parameters such as flow rate, temperature, and pH play an important role in determining the efficiency of the BLUEPOD system. Variations in flow rate can influence contact time between microplastics and biosorbent materials, directly affecting removal performance. Temperature changes may impact both adsorption capacity and enzymatic activity within the system. Similarly, pH conditions can alter enzyme stability and the surface charge of adsorbent materials. Optimization of these parameters is essential to ensure consistent and efficient system operation under different environmental conditions (Wang et al., 2021). The development of the BLUEPOD system represents a significant advancement in microplastic remediation technology. The combination of adsorption and enzymatic oxidation provides both removal and transformation of pollutants within a single system. This approach improves treatment efficiency while maintaining environmental sustainability. The system design also allows flexibility and scalability for various aquatic applications. These characteristics highlight the potential of BLUEPOD as a practical solution for addressing microplastic pollution challenges (Zandieh et al., 2024).

The future development of microplastic treatment technologies should focus on improving system durability and operational efficiency. Advances in material science and enzyme stabilization techniques can enhance long-term performance of biosorbent systems. The integration of such technologies with existing water treatment infrastructure may provide more effective solutions for pollution control. Continuous innovation is necessary to address the evolving challenges of microplastic contamination. These efforts will contribute to the development of sustainable and scalable environmental remediation strategies (Khatua et al., 2024).

4. Conclusions

The results of this study demonstrate that the BLUEPOD system is an effective and innovative approach for microplastic removal in aquatic environments. The integration of activated carbon and immobilized laccase enzyme enables a dual-function mechanism involving adsorption and enzymatic oxidation. This combined mechanism significantly improves removal efficiency compared to conventional single-treatment systems. The system achieved high removal performance under both batch and continuous-flow conditions. These findings indicate that BLUEPOD has strong potential as a reliable solution for addressing microplastic pollution.

The adsorption process facilitated by activated carbon plays an important role in capturing microplastic particles from aqueous media. The porous structure and high surface area of activated carbon allow rapid interaction with pollutants. This process is particularly effective during the initial stage of treatment when active sites are abundant. As the system operates, adsorption gradually approaches equilibrium due to site saturation. The efficiency of this process confirms the importance of adsorption as the primary removal mechanism.

Acknowledgement

The authors gratefully acknowledge the financial support, laboratory facilities, and technical assistance provided by their institution and collaborators, which enabled this research to be completed successfully and contributed significantly to its outcomes.

Author Contribution

Conceptualization, F.D. and B.N.; Methodology, F.D. and S.S.; Software, F.D.; Validation, F.D., B.N. and S.S.; Formal Analysis, F.D.; Investigation, B.N.; Resources, S.S.; Data Curation, F.D.; Writing – Original Draft Preparation, F.D.; Writing – Review & Editing, F.D. and B.N.; Visualization, F.D.; Supervision, F.D.; Project Administration, S.S.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

Not available.

Data Availability Statement

Not available.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author(s) used a generative AI tool to assist in paraphrasing certain sections for clarity and Grammarly to assist in improving the grammar and academic tone of the manuscript. After using these tools, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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