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ChitoZen: A Biochar ZnO-Chitosan Filter for Microplastic Reduction in Laundry Wastewater

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Keywords

Adsorbent; Biomaterial; Biomass; Environment; Microplastics

Abstract

The washing of synthetic textiles is a major contributor of microplastic fiber (MPF) release into aquatic environments. This study develops an innovative, cost-effective, and environmentally friendly filter based on coconut shell waste–derived biochar modified with ZnO and coated with chitosan (ZnO–Biochar–Chitosan) for MPF reduction. The material was synthesized through biochar impregnation with $Zn(NO_3)_2 \cdot 6H_2O$, pyrolysis at 550 °C and immobilization with chitosan. Filter performance was evaluated using FTIR and UV–Vis spectroscopy. FTIR analysis confirmed successful biochar modification, indicated by the presence of Zn–O functional groups (<800 cm^{-1}), O–H and N–H groups (~3400 cm^{-1}). Positively charged N–H groups enable electrostatic interactions with negatively charged MPFs in laundry wastewater. UV–Vis results showed a decrease in absorbance from 3.718 to 1.305 at 219 nm after 5 minutes of contact time, corresponding to adsorption efficiency of 64.9%. These results demonstrate the potential of ChitoZen as a household-scale MPF filtration system.

INTRODUCTION

Microplastics have emerged as one of the pollutants receiving widespread attention in recent years. It is estimated that approximately 82,000–578,000 tons of microplastics were present on the ocean surface between 2000 and 2019 (Isobe et al., 2021), and this amount is projected to continue increasing. If microplastic emissions persist following historical trends, their accumulation on the ocean surface is expected to reach 2.65 million tons by 2050 (Lebreton et al., 2019). These plastic fragments, measuring less than 5 mm in size, exhibit high resistance to degradation and tend to accumulate in aquatic ecosystems. Their presence in aquatic environments, combined with their small size, makes microplastics easily ingested by marine organism, particularly fish. Through daily consumption, the accumulation of microplastics in fish has the potential to enter the human digestive system, leading to oxidative stress, cytotoxic effects, and translocation to other body tissues (Alberghini et al., 2023). Furthermore, toxic compounds and pathogenic microorganisms adsorbed onto microplastics increase the potential risks to human health.

Microplastics are commonly found in various forms, including spheres, foams, granules, films, fragments, pellets, and fibers (Gan et al., 2023). Among these, microplastic fibers (MPFs) raise particular concern due to their widespread distribution in both aquatic environments and the atmosphere. One of the primary sources of microplastic fibers is synthetic textile products, such as acrylic, polyamide (PA), polyester (PET), recycled polyester (RPET), and polypropylene (PP). The most significant contributor to the release of microplastic fibers into the environment is the washing of synthetic clothing in households (Akyildiz et al., 2024), with an estimated 6,000,000 –17,700,000 MPFs released from

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every 5 kg of laundry, depending on the type of detergent used (Falco et al., 2018). This issue is further exacerbated by the high global consumption of textile fibers, which is projected to reach 160 million tons by 2030 (Textile Exchange, 2024).

To reduce MPF emissions into the environment, one mitigation approach that has been developed is the use of physical filters in household washing machines. Although these filters have been shown to reduce the number of fibers released, commercially available filters still have several limitations. Most existing filters exhibit low efficiency in retaining microplastic fibers released from clothing during washing due to their relatively large pore sizes (Napper et al., 2020), allowing very small MPFs to pass through unfiltered. In addition, the use of detergents and fabric softeners can lead to clogging of the filters, thereby reducing their efficiency over time.

One approach to addressing this issue is the development of biomass-based filters, particularly biochar, which is known for its porous structure, high surface area, and environmental friendliness (Li & Tasnady, 2023). One of the key factors determining the effectiveness of biochar as an adsorbent is the selection of its feedstock (Muhammad, 2019). Coconut shell waste is considered a highly promising raw material due to its abundance, economic value, and alignment with the waste to resource concept. Data indicate that Indonesia has approximately 3.29 million hectares of coconut plantations (Direktorat Statistik Tanaman Pangan Hortikultura dan Perkebunan, 2025). In addition, coconut production, presented in the form of copra, reached a total of 2.7 million tons in 2024, demonstrating a substantial national supply. The processing of coconuts into copra inevitably generates coconut shell waste, indicating that the production trend in 2024 corresponds with the availability of this by-product. The abundance of coconut shell waste thus presents significant potential as a feedstock for biochar production.

Furthermore, coconut shells contain chemical components such as cellulose (34%), hemicellulose (21%), and lignin (27%) (Afrah et al., 2022). These lignocellulosic components play a crucial role in determining the quality of the resulting biochar. The faster decomposition rate of cellulose contributes to the development of a more porous biochar structure, thereby increasing its specific surface area and enhancing its effectiveness as an adsorbent. Meanwhile, a higher lignin decomposition rate leads to biochar with increased carbon content (Ajien et al., 2023).

However, biochar produced through simple pyrolysis generally exhibits low surface area or may even be non-porous, resulting in limited adsorption capacity (Jung et al., 2019). Therefore, an activation process is required. Several studies have explored chemical activation methods, for instance using metal oxides (Wang et al., 2025). In their study, modification was carried out using $Zn(NO_3)_2 \cdot 6H_2O$ as a precursor for the formation of ZnO nanoparticles. Upon heating, this compound releases NO_2 and H_2O, leaving ZnO deposits on the surface of the biochar, which help maintain and enhance its pore structure.

In addition, the performance of biochar in adsorbing microplastics can be enhanced through surface modification with amine functional groups. Positively charged amino groups ($-NH_3^+$) can interact electrostatically with negatively charged microplastics present in laundry wastewater. Microplastics, particularly those released during the washing of synthetic textiles, generally carry a negative charge due to the use of household detergents containing anionic surfactants. These surfactants can adsorb onto the surface of microplastics, thereby increasing their negative surface charge. This approach, utilizing coconut shell biochar modified with ZnO and chitosan, is expected to produce an effective laundry wastewater filter aimed at preventing the release of microplastics into aquatic environments.

RESEARCH METHODS

This study was conducted through several stages, including literature review, synthesis of biochar–ZnO, synthesis of chitosan from green mussel shells, immobilization of chitosan onto biochar–ZnO, analysis using FTIR, fabrication of the filter prototype, filter performance testing using laundry wastewater samples at specific time intervals, and analysis using UV–Vis spectroscopy. All stages of this research were carried out at the laboratory scale.

The study was conducted using both quantitative and qualitative approaches. Accordingly, the data obtained as outputs of this research consist of quantitative data, including UV–Vis absorbance measurements of laundry wastewater samples before filtration and after 5 minutes of filtration, as well as qualitative data derived from functional group identification using FTIR. In addition, secondary data from literature studies were utilized as supporting information for comparative analysis.

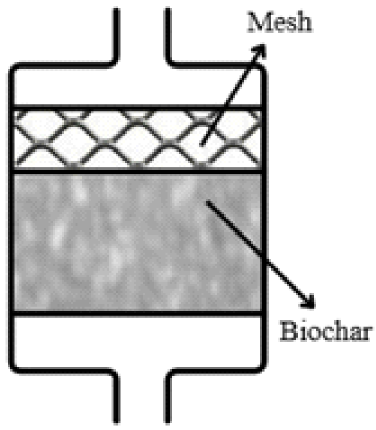
This study employs three types of variables: independent, dependent, and control variables. The independent variable is the sample concentration. The dependent variables include the type of material and the type of material modification. Meanwhile, the control variable is the efficiency of microplastic removal at a specified time.

ZnO and chitosan-modified biochar was prepared through two main stages: ZnO dispersion onto biochar and chitosan coating of the biochar. In the first stage, ZnO dispersion onto biochar, the raw material was prepared and dispersed prior to pyrolysis to produce ZnO distributed on the biochar matrix. Before ZnO dispersion, coconut shell powder was sieved to obtain a uniform particle size. The powder was then immersed in a solution containing 0.012 mol of $Zn(NO_3)_2$ $6H_2O$ and stirred gently to ensure adequate contact between the powder and Zn^{2+} ions. The mixture was subsequently left to age overnight at room temperature to facilitate the adsorption of Zn ions onto the surface and pores of the biochar precursor. After the soaking period, an initial drying stage was carried out at 105°C until completely dry to facilitate handling prior to pyrolysis. The pyrolysis process was conducted in a tube furnace at a temperature of 500 °C, maintained for 2 hours, and then allowed to cool naturally to room temperature overnight.

The second stage involves coating the ZnO-modified biochar with chitosan, aiming to introduce positively charged NH_3^+ functional groups that enhance surface functionality and improve adsorption interactions with micro-plastics. First, a chitosan solution was prepared by dissolving approximately 2.0 g of chitosan in 250 mL of 2% acetic acid. Due to the slow solubility of chitosan, the dissolution process was carried out under continuous stirring with heating at 60 °C until a homogeneous solution was obtained. After achieving homogeneity, 2 g of ZnO-modified biochar was gradually added while stirring to ensure proper particle dispersion and maximum surface contact. The mixture was then heated in a water bath at 60 °C for 30 minutes to accelerate the initial reaction. Subsequently, the pH was gradually increased using a dilute NaOH solution until basic conditions were reached (pH 8-9). This step promotes the polymerization or solidification of the chitosan layer and enhances its adhesion to the biochar surface. After completion of the reaction, the material was separated by centrifugation. The modified biochar was then transferred into a beaker through decantation and mixed with laundry wastewater. The mixture was stirred using a stirrer for 5 minutes. Characterization was conducted using FTIR, which indicated the appearance of N–H and C–N bands, as well as peak shifts, confirming the interaction between chitosan and the biochar surface.

Material characterization and filtration efficiency analysis were conducted using FTIR and UV–Vis spectrophotometry. FTIR was employed to identify functional groups and to evaluate the success of surface modification through the appearance or shifts of absorption peaks at specific wavenumbers, while UV–Vis spectrophotometry (200–300 nm range) was used to compare the spectra of laundry wastewater samples before and after filtration, with a focus on changes in absorbance intensity associated with turbidity levels. In a reference study by Tziourrou et al. (2023), which examined variations in absorbance related to the presence and interaction of microplastics in bioreactor systems containing plastics (LDPE, PET), the absorbance spectra of each sample exhibited several shoulders and peaks: a shoulder at 275 nm for R1 (seawater), R2 (activated sludge), and R3 (freshwater algae); an additional shoulder at 420 nm for R2; shoulders at 225 nm and 330 nm for R3; and peaks at 675 nm for R2 and 687 nm for R3. These findings suggest that the presence of microplastics can be indicated by characteristic absorption bands, particularly within the 200–300 nm range. As a comparison, Fan et al. (2022) reported that PET microplastics exhibit absorption at approximately 266 nm. It should be noted that UV–Vis measurements primarily reflect overall turbidity or particulate changes and are not capable of specifically identifying microplastic polymer types. Therefore, filtration analysis is interpreted through spectral comparison before and after filtration, along with the calculation of absorbance reduction percentage as an indicator of particle removal efficiency.

The filtration prototype was designed with a layered structure to enhance the effectiveness of microplastic removal from laundry wastewater. The first layer consists of a mesh acting as a pre-filter, which functions to remove larger particles and prevent clogging in the subsequent layers. The second layer is composed of biochar–ZnO–chitosan adsorbent compacted using a natural binder, namely starch. At this stage, microplastics are physically retained and trapped within the modified biochar layer. The third layer, in the form of a net, functions to maintain the position of the mesh and the biochar–ZnO–chitosan layer, ensuring stability during the filtration process. All layers are placed within a cylindrical PVC pipe, with the lower end designed to taper downward in order to regulate the flow of filtered water.



Source: Processed Primary Data, (2025)

Figure 1

ChitoZen Filter Prototype

The efficiency of particle removal or signal reduction (absorbance/concentration/spectral area) is expressed by the following equation:

$$\text{Efficiency } (\%) = (A_0 - A_t)/A_0 \times 100\% \quad (1)$$

Where A_0 represents the initial absorbance value (i.e., the absorbance of the sample before filtration), and A_t represents the absorbance value after filtration. This equation calculates the percentage reduction in signal between the initial value prior to filtration treatment and the value after filtration, thereby indicating the effectiveness of the filtration process in reducing absorbance at the peak wavelength.

RESULTS AND DISCUSSION

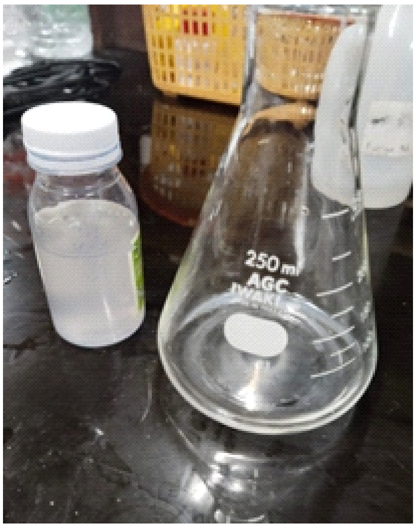
The synthesized ZnO-modified biochar exhibited a grayish-white color, granular form, and a fine sand-like texture, and was insoluble in water. The grayish-white coloration indicates the presence of ZnO dispersed on the surface of the biochar, consistent with the typical characteristics of ZnO-based materials, which are generally white in appearance.

Source: Processed Primary Data, (2025)

Figure 2
Synthesis Results of Biochar Modified with ZnO and Chitosan

Source: Processed Primary Data, (2025)

Figure 3
Synthesis Results of Chitosan form Green Mussel Shells



Source: Processed Primary Data, (2025)

Figure 4
Comparison of Samples Before Filtration (Left) and After Filtration (Right)

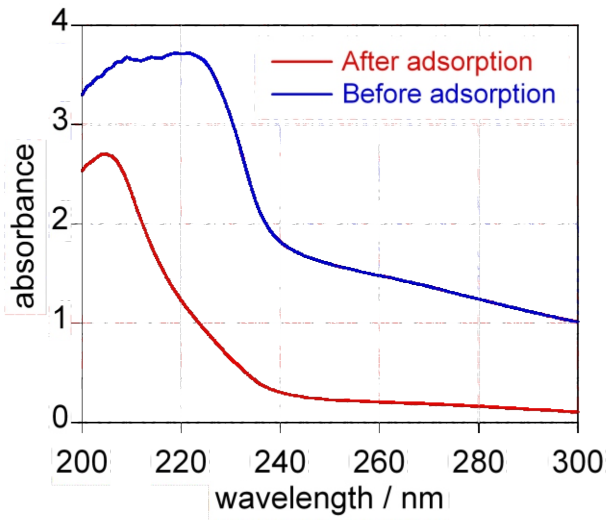
This morphology also confirms the presence of a porous structure commonly found in coconut shell-derived biochar. Meanwhile, chitosan obtained from green mussel shell waste appeared as a light brown powder with a characteristic odor. Prior to UV–Vis spectrophotometric analysis, the laundry wastewater that had been stirred with biochar–ZnO–chitosan was first filtered. This filtration step was intended to remove solid biochar particles that could interfere with spectral measurements, thereby producing a filtrate with sufficient clarity for analysis. UV–Vis spectrophotometry was selected as the characterization method due to its ability to detect changes in absorbance intensity associated with the presence of microplastic particles within specific wavelength ranges. Therefore, the measurement results can represent the effectiveness of microplastic adsorption by the biochar–ZnO–chitosan adsorbent.

Ultraviolet–Visible (UV–Vis) spectrophotometric analysis was conducted to evaluate the effectiveness of the ZnO–biochar–chitosan composite material as an adsorbent for removing contaminants from laundry wastewater suspected of containing microplastics. The spectral analysis results showed a significant difference in absorbance between samples before and after adsorption treatment, quantitatively demonstrating the success of the adsorption process.

The maximum absorption peak (λmax) of the sample before filtration was identified at 219 nm, with an initial absorbance (A_0) of 3.718. After 5 minutes of contact with the adsorbent, the absorbance at the same wavelength decreased significantly to 1.305. This reduction corresponds to a high adsorption efficiency of 64.9%. The maximum absorption peak (λmax) of the sample before filtration was identified at 219 nm, with an initial absorbance (A_0) of 3.718. After 5 minutes of contact with the adsorbent, the absorbance at the same wavelength decreased significantly to 1.305. This reduction corresponds to a high adsorption efficiency of 64.9%. The high efficiency achieved within a very short contact time (5 minutes) indicates rapid adsorption kinetics and highly efficient mass transfer, highlighting the strong potential of this composite material for rapid wastewater treatment applications.

Further analysis of the spectra revealed a shift in the absorption peak (spectral shift) after the adsorption process. The maximum absorption peak of the sample after filtration shifted to a new λmax at 204 nm (with an absorbance of 2.703). This shift, known as a hypsochromic shift (blue shift), indicates a change in the chromophore composition within the solution.This phenomenon suggests that the dominant chromophores responsible for the strong absorption at 219 nm were selectively and effectively removed. The remaining solution is now dominated by species with lower concentrations or weaker absorbance at shorter wavelengths.

Fourier Transform Infrared (FTIR) analysis was conducted to verify the successful synthesis of the ZnO–biochar –chitosan composite material through the identification of specific functional groups and interactions among its components. The comparison of vibrational absorption patterns between pure ZnO and the ZnO–biochar–chitosan composite provides strong evidence of successful modification. In the FTIR spectrum of pure ZnO, the dominant absorption band is detected in the wavenumber region below 800 cm^{-1}, which corresponds to the characteristic stretching vibration of Zn–O bonds. The presence of this band in the composite spectrum confirms the incorporation of ZnO into the supporting matrix. Visually, the composite spectrum exhibits increased intensity and complexity of absorption bands compared to pure ZnO, which is attributed to the addition of organic matrices (biochar and



Source: Processed Primary Data, (2025)

Figure 5

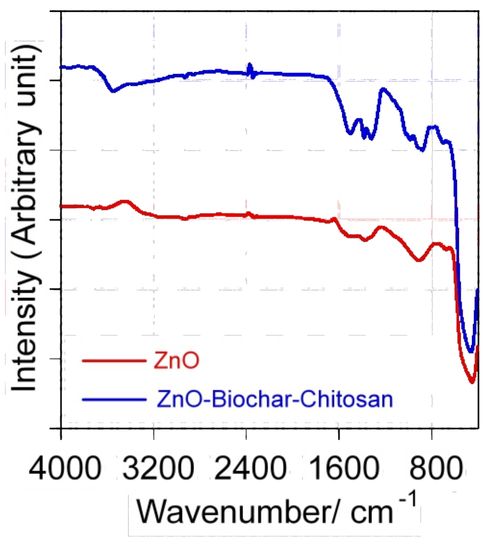
UV–Vis Spectra of Laundry Wastewater Containing Microplastics Before and After Adsorption Using ZnO–Biochar–Chitosan Adsorbent

chitosan) that are rich in various functional groups.

The success of the modification is specifically confirmed by the appearance of new absorption bands in the FTIR spectrum of the ZnO–biochar–chitosan composite, originating from organic functional groups. A broad overlapping band is observed around ~3400 cm^{-1}, indicating the stretching vibrations of hydroxyl (O–H) groups from biochar and chitosan, as well as primary amine (N–H) groups from chitosan. Additionally, a prominent band is identified in the range of ~1650–1600 cm^{-1}, which is commonly associated with N–H bending vibrations of primary amine groups or C=O stretching of amide I, a key characteristic of chitosan. Further evidence of the polysaccharide structure and organic matrix is indicated by bands in the range of ~1100–1000 cm^{-1}, representing the stretching vibrations of C–O and C–N bonds.

The presence of combined functional groups, particularly N–H and O–H, convincingly confirms that chitosan and biochar have been successfully impregnated and integrated with ZnO. In addition to confirming the presence of each component, minor shifts in certain absorption bands in the composite spectrum compared to their original positions suggest the occurrence of chemical interactions, such as hydrogen bonding or coordination interactions, between the reactive functional groups of chitosan and the surface of ZnO nanoparticles or the functional groups of biochar. These interactions are crucial, as they result in a more stable composite material and provide more abundant and well-structured active sites (O–H and N–H), which are essential for enhancing the adsorption efficiency of contaminants in wastewater treatment applications. Therefore, the FTIR results comprehensively validate the successful synthesis of the functional ZnO–biochar–chitosan material.

This study has several limitations. First, the experiments were conducted at a laboratory scale, resulting in a relatively small sample size compared to real field conditions. Second, the identification of microplastics was based solely on UV–Vis spectrophotometry by comparing spectral changes in laundry wastewater samples before and after filtration; thus, it does not allow for specific identification of the polymer types present in the samples. In addition, the use of laundry wastewater samples introduces potential interferences from detergent surfactants, dyes, and other additives, which may affect the analysis.



Source: Processed Primary Data, (2025)

Figure 6

Fourier Transform Infrared (FTIR) Spectra of Pure ZnO and ZnO–Biochar–Chitosan Composite

Therefore, further sample preparation is required, or alternatively, ATR-FTIR can be employed with a simpler preparation method such as KBr-impregnated paper (Kurrey et al., 2020). Accordingly, further characterization using ATR-FTIR is necessary to confirm the presence of characteristic functional groups of microplastic polymers in wastewater samples before and after filtration. In addition, scanning electron microscopy (SEM) is recommended to observe the surface morphology of biochar and to map the distribution of elements such as Zn, O, C, and N on the biochar surface. Future studies utilizing these analytical techniques are expected to provide stronger validation of the interaction mechanisms between biochar and microplastics, as well as to support the potential for larger-scale applications, particularly at the household level, thereby enabling a more comprehensive evaluation of the effectiveness of ZnO- and chitosan-modified biochar in reducing microplastics in laundry wastewater.

Coconut shell-derived biochar serves as the base material of the filter, possessing a porous structure that enables the physical adsorption of microplastic particles. Through a templating effect during pyrolysis, the presence of ZnO dispersed on the surface of the biochar contributes to the formation of microporous structures with high surface area (Thi Luyen et al., 2023). This structure and increased surface area play a crucial role in the adsorption process by providing more active sites for microplastics to interact with the biochar filter. Meanwhile, chitosan immobilized on the biochar surface significantly contributes by providing positively charged amino groups ($-NH_3^+$), which can interact electrostatically with negatively charged microplastics in laundry wastewater (Wang et al., 2025). Microplastics, particularly those released from synthetic textiles during washing, generally carry a negative charge due to the presence of anionic surfactants in household detergents. These surfactants can adsorb onto the surface of microplastics, further increasing their negative surface charge.The synergistic interaction of these three components results in a more effective filtration system for preventing the release of microplastics into aquatic environments.

Coconut shell-derived biochar serves as the base material of the filter, possessing a porous structure that enables the physical adsorption of microplastic particles. Through a templating effect during pyrolysis, the presence of ZnO dispersed on the surface of the biochar contributes to the formation of micro-porous structures with high surface area (Thi Luyen et al., 2023). This structure and surface area play a crucial role in the adsorption process by providing more space for microplastics to interact with the biochar filter. Meanwhile, chitosan immobilized on the biochar surface significantly contributes by providing positively charged amino groups ($-NH_3^+$), which can interact electrostatically with negatively charged microplastics in laundry wastewater (Wang et al., 2025).

Microplastics, particularly those released from textiles during the washing process, generally carry a negative charge due to the use of household detergents containing anionic surfactants. These surfactants can adsorb onto the surface of microplastics, thereby increasing their negative surface charge. The synergistic interaction of these three components provides a more effective filtration system for preventing the release of microplastics into aquatic environments. The novelty of this study lies in the development and application of the ChitoZen filter, based on coconut shell biochar modified with ZnO and chitosan, to prevent the release of microplastics from laundry wastewater. In contrast to previous studies that primarily focus on the removal of metal ions or dissolved organic compounds (e.g., synthetic dyes), ChitoZen is specifically designed to capture microplastic particles through the integration of multiple mechanisms enabled by surface modification. The novelty of this study lies in the development and application of the ChitoZen filter, based on coconut shell biochar modified with ZnO and chitosan, to prevent the release of microplastics from laundry wastewater. In contrast to previous studies that primarily focus on the removal of metal ions or dissolved organic compounds (e.g., synthetic dyes), ChitoZen is specifically designed to capture microplastic particles through the integration of multiple mechanisms enabled by surface modification. From an application perspective, ChitoZen offers added value through the utilization of low-cost, abundant, and sustainable local waste materials, namely coconut shells as a source of biochar and shell waste as a source of chitosan. Furthermore, as a laundry wastewater filtration system, ChitoZen has strong potential for implementation at the household scale, contributing to the prevention of microplastic release into aquatic environments. Ultimately, ChitoZen can provide a tangible contribution to preserving aquatic ecosystems while reducing human health risks associated with microplastic exposure through the food chain.

CONCLUSION

This study demonstrates that the ChitoZen filter, based on coconut shell biochar modified with ZnO and chitosan, is capable of reducing microplastic content in laundry wastewater. This effectiveness is indicated by the decrease in absorbance values in the UV–Vis spectrum within the 200–300 nm wavelength range, as well as the successful material modification confirmed through FTIR analysis. CONCLUSIONThis study demonstrates that the ChitoZen filter, based on coconut shell biochar modified with ZnO and chitosan, is capable of reducing microplastic content in laundry wastewater. This effectiveness is indicated by the decrease in absorbance values in the UV–Vis spectrum within the 200–300 nm wavelength range, as well as the successful material modification confirmed through FTIR analysis.

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