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Advanced Carbon Nanoparticle-Based Filtration Systems for Water Disinfection and Microplastics Removal

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Abstract

Providing clean and safe water is an inherent entitlement of every individual, underscoring the imperative for efficient water disinfection methods. Nevertheless, the increasing prevalence of microplastics in water sources has presented intricate obstacles for current treatment methodologies. Microplastics present significant challenges to both human health and ecosystems, hence requiring the development of novel and inventive solutions. This study suggests introducing a Nanoparticle-Based Water Filtration System (NP-WFS) specifically developed to tackle the combined issue of water disinfection and microplastic elimination. This technique presents a viable alternative to traditional methods by utilizing the distinctive characteristics of Carbon Nanoparticles (CNP) in conjunction with a precisely engineered membrane. At a wavelength of 450 nm, there was a noticeable absorption peak with an absorbance of 1.81%. This discovery demonstrates the existence of CNP. The peak suggests the presence of microplastic particles at 2901.4 cm-1, which coincides with the value found in the untreated water sample. The continuous range of 2798.6 cm-1 in the microfilm indicates that the CNP-infused microfilm effectively collects minuscule plastic beads. This finding implies that the CNP microfilm successfully captured the microorganisms and microplastics. These results serve as evidence of the efficacy of the NP-WFS in the field of water purification. Compared to conventional approaches, NP-WFS demonstrates superior performance in removing microplastics and establishes a novel benchmark for water disinfection. This initiative effectively tackles pressing concerns about water safety, safeguarding ecosystems, and human well-being. This study advances water filtration technology, offering a viable solution to sustainably address the ever-changing waterborne issues.

Keywords: *Water Filtration, carbon nanoparticles, Disinfection, Microplastics Removal.*

Introduction

Water is widely recognized as a fundamental resource that is crucial in supporting life and the natural environment. Providing clean and safe drinking water is an inherent entitlement of every individual. Yet, it continues to pose a significant obstacle for numerous populations across the globe as a result of escalating levels of pollution stemming from various sources such as contaminants, diseases, and microplastics [1]. The increasing apprehension regarding waterborne illnesses, hazardous substances, and the buildup of microplastics in aquatic environments has prompted scholarly investigation and advancements in water treatment methodologies. Advanced filtering systems utilizing nanoparticles have emerged as a state-of-the-art approach in pursuing effective and environmentally-friendly methods for water disinfection and eliminating microplastics [2].

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The issue of water source contamination has emerged as a significant global concern, carrying extensive implications for public health and the environment. Pathogenic microorganisms, including bacteria, viruses, and protozoa, provide an ongoing and significant risk, resulting in waterborne diseases that impact a substantial number of individuals yearly. Furthermore, the discharge of industrial pollutants, heavy metals, and new contaminants into aquatic environments exacerbates the issue, diminishing the efficacy of current water treatment approaches [3].

In recent years, there has been a growing worry regarding microplastics, which are minute plastic particles measuring less than 5 mm in size. The particles mentioned above, which have emerged from diverse origins, including plastic debris, textiles, and cosmetics, have successfully invaded aquatic ecosystems and are presently ubiquitous in surface water and groundwater. Microplastics present a dual threat, as they not only endanger aquatic organisms but also can infiltrate the food web, raising health apprehensions for human beings [4].

In response to these issues, the discipline of nanotechnology has arisen as a viable route for the treatment and purification of water. Nanoparticles, which typically possess dimensions within the 1 to 100 nanometers range, have distinctive physical, chemical, and biological characteristics that render them exceptionally efficient in water pollution removal [5]. These characteristics encompass their significant surface area-to-volume ratio, elevated reactivity, and adjustable surface functions. Nanoparticle-based filtering systems have numerous advantages compared to conventional techniques [6]. Many processes can effectively eliminate pathogens, including electrostatic attraction, adsorption, and photocatalytic inactivation. Moreover, the inherent adaptability of nanoparticles facilitates the creation of multifaceted materials with the capacity to effectively target a diverse array of pollutants concurrently effectively.

This study aims to conduct a comprehensive investigation into the utilization of modern filtration systems based on nanoparticles for water disinfection and the removal of microplastics. This study aims to provide an overview of the fundamental principles underlying nanoparticle-based water treatment. Specifically, it will delve into the various types of nanoparticles typically utilized in this field, the methods employed for their synthesis, and the mechanisms by which they effectively combat contaminants.

The primary contributions are given below:

- Development of an innovative Nanoparticle-Based Water Filtration System (NP-WFS) for efficient water disinfection and microplastic removal.
- Advancement in water treatment technology through the application of CNP and a custom-designed membrane.
- Mitigating health risks associated with microplastic contamination ensures water safety for humans and wildlife.
- Contribution to sustainable water management practices by addressing emerging waterborne challenges and environmental threats.

The following sections are arranged in the following manner: Section 2 presents a comprehensive review of the current research on water filtration using nanoparticles. Section 3 provides a Nanoparticle-Based Water Filtration System (NP-WFS) to address the dual challenge of water disinfection and microplastic removal. Section 4 presents the results and discussion. Section 5 provides the conclusion and scope for further research.

Related Works

The review will delve into recent advancements in nanoparticle-based technologies, highlighting their efficacy in removing pathogenic microorganisms, organic pollutants, heavy metals, and microplastics from water. It will also discuss the challenges and limitations associated with implementing these systems, including issues related to nanoparticle stability, toxicity, and scalability.

The planned technique for the study by Fox (2021) involves characterizing the microplastics in the water column of Western Lake Superior [7]. This was achieved by taking water samples at various depths and places, filtering them, and then analyzing the results using microscopic and spectroscopic methods. The identification and measurement of the microplastics found in the lake water were made possible by applying this technology. The study's output values provided thorough information on the kinds, sizes, and concentrations of microplastics in Lake Superior, offering important knowledge for comprehending the effects of microplastics on freshwater ecosystems. The benefits of this strategy are seen in how it advances our understanding of microplastic contamination in a particular area and ecosystem. However, it can be constrained by the requirement for specific tools and knowledge.

Research on the identification and elimination of microplastics from freshwater and wastewater systems was carried out by Nkosi (2022)—the suggested process comprised of cutting-edge detection techniques and effective removal technologies. Field tests and laboratory studies were used to implement this methodology to confirm the efficacy of the created detection and removal approaches [8]. Innovative methods and techniques for locating and reducing microplastic pollution in aquatic systems were incorporated into the result values. The research's merits lay in its ability to address a severe environmental problem, but scaling up the technique for real-world use may present difficulties.

In the work by Dung et al. (2019), the suggested approach focused on creating ceramic filters with silver nanoparticles using an in-situ reduction process [9]. The efficacy of these filters in disinfecting water was then evaluated. Silver nanoparticles were synthesized, added to ceramic filters, and tested using bacterial and water quality indicators as endpoints. The output values included the creation of a unique water disinfection technique employing ceramic filters containing silver nanoparticles, which might have considerable benefits for water treatment in environments with limited resources. The cost and scalability of the production process, meanwhile, may be drawbacks.

To disinfect drinking water, Msoka, Jacob, and Mahadhy (2023) created a filter system employing modified silica sand with silver nanoparticles. The suggested approach incorporated silver nanoparticles with silica sand into a filter system [10]. Implementation included testing the filter system's effectiveness at eliminating germs from water in a lab. One of the outcome values was a viable and perhaps economical method for disinfecting drinking water. The use of materials that are easily accessible has advantages, but it may be difficult to optimize the filter's efficiency for different types of water.

Wafy et al. (2023) concentrated on using a sturdy ceramic filter covered with silver nanoparticles made utilizing actinomycetes for water disinfection [11]. The suggested procedure includes creating silver nanoparticles from actinomycetes, coating a ceramic filter, and testing the filter's efficacy at sanitizing water. Testing for microorganisms and water quality was required for implementation. The final product was a durable ceramic filter with antibacterial qualities that could be used to purify water. Natural antibacterial agents have benefits; however, scalability issues may exist.

To filter microplastics from polluted water, Kamaraj et al. (2023) created a microfilm made of CNP [12]—the suggested process comprised creating the microfilm and using it to purify water. After implementation, testing in the lab was done to see how well the film removed microplastics. The output values included a cutting-edge filtration system created to eliminate microplastics, which might lessen a rising environmental threat. However, there could be difficulties in modifying the technology for widespread application.

For portable water purification, Tavakoli et al. (2023) created silver nanoparticles loaded on silica nanoparticles and activated carbon [13]. The suggested process includes creating nanoparticles from scratch and incorporating them into a composite material. Evaluation of the composite's efficacy in water treatment was required throughout implementation. A flexible and potentially transportable water treatment solution was one of the result values.

The flexibility of the composite material is a benefit, but applying the technology in various situations may provide practical difficulties.

Ultimately, this review aims to shed light on the immense potential of advanced nanoparticle-based filtration systems as a sustainable and innovative solution for achieving safe drinking water and protecting aquatic ecosystems. Through a comprehensive understanding of the principles and applications of these technologies, we can move closer to realizing the goal of providing clean and accessible water resources for all.

Proposed Nanoparticle-Based Water Filtration System (NP-WFS)

The proposed NP-WFS is a novel water treatment methodology developed to address the concurrent issues of water disinfection and microplastic elimination. The technology mentioned above integrates the utilization of nanoparticles alongside a specific filtering medium to accomplish the aims mentioned above inside a unified procedure.

Materials and Methods

The fresh foliage of Commelina Maculata and silica sand were obtained from separate locations in Tanzania. The plant material was collected from the Mwalimu JK Nyerere campus of the University of Dar es Salaam (UDSM). On the other hand, the silica sand was obtained from the coastline at Kigamboni in Dar es Salaam. A customized glass section, with dimensions of 1.5 cm in diameter and 25 cm in length, has been produced at the UDSM Central Science Workshop. All compounds employed in the current study have been of analytical quality, obtained from Sigma-Aldrich, and used without additional processing and purifying. Fig. 1 shows the process flow of the proposed NP-WFS framework.

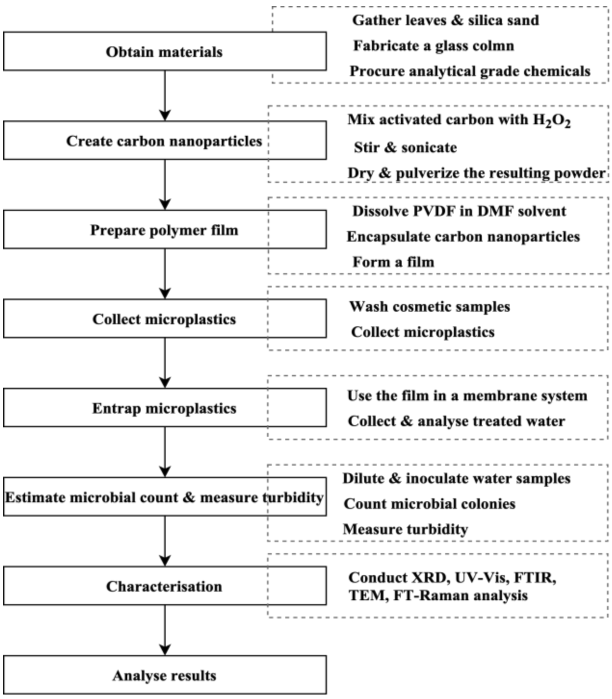

Figure 1: Process flow of the proposed NP-WFS framework

Preparation of Carbon Nanoparticles

A mixture has been created to generate carbon nanoparticles by combining 10 grams of activated carbon with 170 milliliters of H_2O_2. After 25 minutes of magnetic stirring, the mixture was exposed, followed by placement in a sonicator operating in pulse mode for 120 minutes. The solution remained unchanged for the whole of the night. On the subsequent day, the liquid portion was carefully poured out, and the solution in suspension was exposed to a temperature of 100°C in a hot air oven for 10 minutes. The procedure mentioned above was iterated until a desiccated particulate substance was attained. The dry powder was subjected to coarse pulverization using a mortar and pestle before storage.

A well-regulated oxidative procedure synthesized CNP. The primary chemical process entailed in this study is the oxidation of Activated Carbon (AC) using H_2O_2, as represented by the equation below:

$$AC + H_2O_2 = CN + H_2 \quad (1)$$

Using magnetic stirring and sonication techniques facilitated the dispersion and de-agglomeration processes of the CNP. The heat drying process conducted at a temperature of 100°C effectively helped eliminate any remaining water content, producing a powdered substance devoid of moisture.

Preparation of Polymer Film Conjugated with Carbon Nanoparticles

Polyvinylidene Fluoride (PVDF) was dissolved by adding it to a 20 ml Dimethylformamide (DMF) solvent. This process was carried out using a magnetic stirrer operating at a temperature of 60°C and a speed of 500 rpm, continuing until full dissolution was seen. During this procedure, CNP entities were enclosed inside the aqueous milieu. The heated solution was carefully transferred onto a glass plate and afterward placed inside a hot air oven, where it was kept at a constant temperature of 60°C for around 20 to 30 minutes. Subsequently, the film was removed. The phenomenon of CNP being enclosed inside the aqueous phase of the solution may be attributed to their hydrophilic characteristics, which are determined by the wetting parameter (θ). The Young-Laplace equation is utilized to explain this particular process and is given as:

$$\cos\theta = \frac{PVDF-SST}{DMF-LST} \quad (2)$$

Solid surface tension (SST) and liquid surface tension (LST) play significant roles in determining the wetting behavior of a liquid on a solid surface. A wetting parameter (θ) near 0° signifies favorable wetting conditions, essential for achieving uniform dispersion of CNP.

Microplastics Sampling

The microplastics were gathered by a laborious process, including washing cosmetic samples containing plastic microbeads. Following this, the samples were air-dried in a shaded environment. The procedure mentioned above resulted in the production of plastic microbeads of a small size, namely measuring 0.5 mm and above. These microbeads were afterward preserved to conduct tests related to the contamination of fake water.

Membrane Entrapping of Microplastics

The CNP-conjugated film was placed into a cross-flow membrane system, whereby manually tainted microplastic water was passed through the system and collected in a separate chamber. The water that was gathered was later examined using Raman spectrometry to conduct a more detailed examination and ascertain its pollution level. The application of Darcy's law may delineate the phenomenon of entrapment, a fundamental principle that elucidates the movement of water within a permeable substance:

$$Q = \frac{k*A}{\mu}\frac{\Delta P}{D} \quad (3)$$

The volumetric flow rate of water is denoted by Q, the permeability of the membrane is represented by k, the cross-sectional area is designated by A, the dynamic viscosity of water is symbolized by μ, the P represents the pressure differential across the membrane$P$, and the th$D$ denotes the thickness of the membrane.

Estimation of Microbial Viable Count and Turbidity

The water samples were subjected to a series of dilutions using sterile distilled water, with dilution factors ranging from 10^{-2} to 10^{-9}. Subsequently, triplicate inoculations of these diluted samples (0.1 ml each) were performed on marine agar and yeast extract media. Following incubation at 37°C, colony counting was carried out. The turbidity measurements were conducted utilizing a nephelometer, with values obtained after the water samples attained ambient temperature. Once the air bubbles had dissipated, the sample was introduced into the turbidimeter tube. Turbidity measurements were then collected directly from the instrument scale or using suitable calibration curves. The quantification of viable microorganisms present in water may be determined by employing the Dilution Factor (DF) in conjunction with the colony count on agar plates. The formula for calculating the DF is as follows:

$$DF = \frac{1}{V * f} \quad (4)$$

The DF is the dilution factor, which is the ratio of the final volume of the sample (f) to the sample inoculated (V). Turbidity measurements were performed utilizing a nephelometer, which quantifies the quantity of particles in water by assessing the intensity of scattered light. The parameter of turbidity (T) is commonly quantified using Nephelometric Turbidity Units (NTU). The following equation may mathematically represent the correlation between turbidity and the intensity of scattered light:

$$T = K * I \quad (5)$$

T is turbidity (NTU), K is the instrument-specific constant, and I is the intensity of light scattered at right angles to the incident light path.

Advantages of Tackling the Dual Challenge

Comprehensive Treatment: The NP-WFS treatment method adopts a comprehensive approach to water treatment by effectively tackling microbiological pollution and microplastics, two prominent issues affecting water quality.

Effectiveness: Using nanoparticles significantly improves the effectiveness of disinfection and microplastic removal procedures, hence establishing a highly effective and dependable system.

Compactness and power conservation: The compactness and power conservation of NP-WFS render it appropriate for a wide range of applications, such as point-of-use systems and community-scale water treatment.

Customization: The selection of nanoparticles and filter medium may be tailored to suit the water quality issues encountered in a given area, hence providing adaptability in the system's design.

Decreased reliance on conventional chemical disinfectants: The utilization of NP-WFS has the potential to decrease reliance on conventional chemical disinfectants, which often incur high costs and have the potential to generate detrimental consequences.

Challenges and Considerations

The present study aims to explore the challenges and considerations associated with the topic at hand.

Cost: The expenses associated with the manufacturing and incorporation of nanoparticles might be significant, thereby impacting the price and availability of NP-WFS, particularly in areas with limited resources.

Environmental impact: The management of nanoparticle discharge into the environment and the associated risk of nanoparticle contamination need diligent attention to prevent inadvertent ecological ramifications.

Maintenance: It may be important to regularly maintain and replace nanoparticles and filter medium to ensure the system's constant operation.

In brief, the proposed NP-WFS demonstrates considerable potential as a technology that adeptly tackles the dual issues of water disinfecting and microplastic removal. Using nanoparticles and specific filtering mediums in NP-WFS offers a complete and efficient approach to guaranteeing clean and safe drinking water while simultaneously addressing the detrimental consequences of microplastic pollution. Nonetheless, the successful execution of this initiative necessitates a meticulous evaluation of financial implications, ecological consequences, and upkeep demands.

Results and Discussion

The filtration system utilized a cross-flow membrane filtration system, which had a membrane with a permeability (k) of $3.2 \times 10^{-5} m^2$, a cross-sectional area (A) of $0.04m^2$, and a layer thickness (D) of $0.2\,mm$. The study involved the creation of synthetic water samples containing 50 microplastic particles per milliliter, which varied in size from $0.5\ to\ 2\,mm$. The water flow rate (Q) was maintained at a $0.5\,L/min$. Analytical instruments were employed to evaluate filtration effectiveness using a nephelometer (with a constant K value of $0.3\,NTU/L^2$ for turbidity measurement. Additionally, decreases in microbial counts were quantified within a range spanning from $10^3\ to\ 10^6\ CFU/ml$. Using Ultraviolet-Visible (UV-Vis) spectroscopy, Fourier-Transform Infrared (FTIR) spectroscopy, and Raman Intensity to analyze its structural and optical characteristics, CNP was characterized.

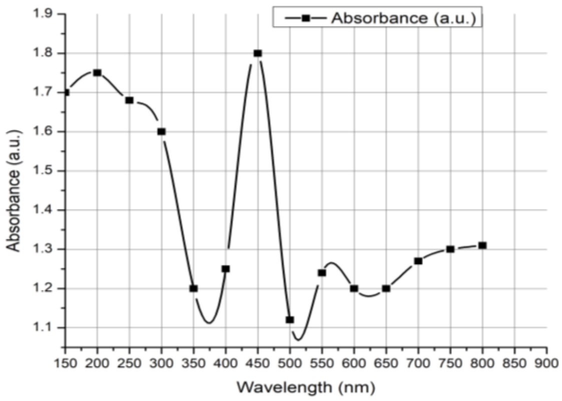

Figure 2: UV-Vis absorption spectra of CNP

Fig. 2 shows the UV-Vis absorption spectra of CNP. The data demonstrates the relationship between the absorbance of CNP and the several wavelengths of incoming UV-Vis light. The data shown indicates a clear trend wherein the absorbance of CNP typically declines as the wavelength increases from 150 nm to 700 nm. The band gap between the ground state and the first excited state in the domain of nanoparticles is significantly influenced by the size of the nanoparticles. This suggests that when the size of a nanoparticle decreases, indicating a decrease in the number of atoms it contains, the absorption peak moves towards the area of lower wavelengths. The absorption peak observed at a wavelength of 200.2 nm can be attributed to the decreased size of the carbon material compared to its regular bulk form. The UV ranges of carbon nanoparticles were observed to be transparent within the 201–285 nm wavelength range. Additionally, many additional peaks were identified at 190 nm and 450 nm wavelengths. A prominent absorption peak was seen at a wavelength of 450 nm, with an absorbance value of 1.81%.

This finding provides evidence for the presence of carbon nanoparticles. Therefore, the existence of a carbon nanoparticle is indicated by both peaks. The presence of many other peaks in the visible range can be attributed to distinct residual chemicals, which are inevitable during the preparation process. However, detecting a peak at 200.2 nm only in samples containing a carbon group suggests that the carbon group was exclusively present in the examined sample. This observation suggests that CNP exhibits a higher efficacy in absorbing shorter wavelengths of light. The provided knowledge is important in comprehending carbon nanoparticles' optical characteristics and prospective uses throughout diverse domains, including materials science and nanotechnology.

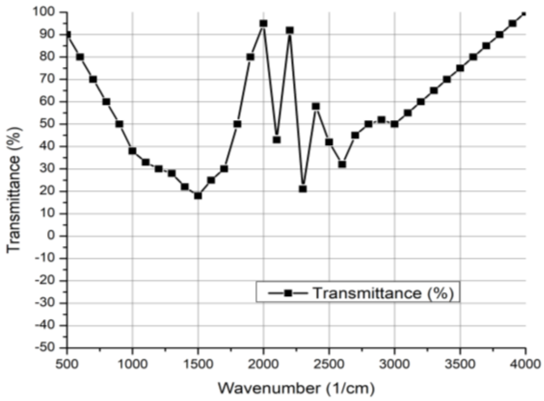

Figure 3: FTIR analysis of CNP

Fig. 2 displays the outcomes of the FTIR spectroscopy examination performed on CNP. The dataset has two distinct columns, namely "Wavenumber ($1/cm$)" and "Transmittance (%)." The Wavenumber, denoted in reciprocal centimeters ($1/cm$), signifies the location within the IR spectrum, whereas the transmittance % indicates the quantity of IR radiation that passes through the sample at each Wavenumber.

The Fig. 2 provides information on CNP's absorbing and transmitting properties throughout a broad spectrum of wavenumbers. As the Wavenumber declines from 4000 cm^{-1} to 400 cm^{-1}, there is a corresponding decrease in the transmittance %. This observation suggests that CNP exhibits a stronger absorption of infrared light at higher wavenumbers. The provided information offers valuable insights into CNP's functional groups and chemical interactions, as distinct wavenumbers are associated with certain molecular vibrational modes. FTIR analysis is a very advantageous technique to identify materials' chemical composition and structure. The data obtained from FTIR analysis plays a crucial role in enhancing our comprehension of the molecular characteristics of CNP. Consequently, this knowledge contributes significantly to exploring possible applications of CNP in diverse scientific and industrial domains.

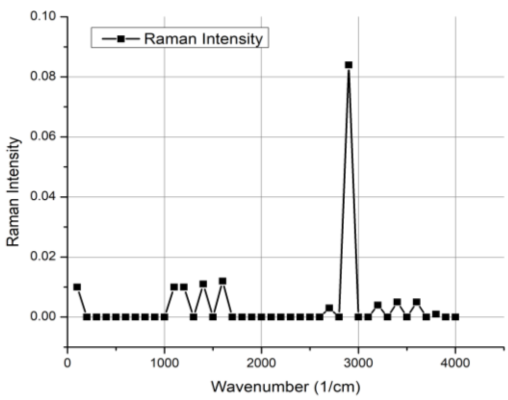

Figure 4: Microplastics available in the CNP film after filtration and post-treatment of water

Fig. 4 illustrates the presence of microplastics within the CNP film. This observation proves that the microfilm containing CNP has effectively captured the microplastics that were originally present in the water sample. The observed peak at 2901.4 cm^{-1}, which aligns with the value identified in the untreated water sample, suggests the existence of microplastic particles. No discernible peak was seen within the specified range in the water that underwent post-treatment. The CNP-infused microfilm effectively captures plastic microscopic beads, as seen by the consistent range of 2798.6 cm^{-1} observed in the film. This observation suggests that the CNP microfilm has successfully captured the microplastics.

This source might be considered a viable option for water treatment while minimizing impacts on the natural system, as the chemicals employed exhibit comparatively lower toxicity levels. The utilization of carbon for secondary water treatment in water treatment facilities has previously been implemented. The utilization of CNP is deemed more effective than conventional carbon or graphene molecules due to their inherent property of zero curvature. The efficiency of CNP can be enhanced by combining them with their counterparts exhibiting negative curvature, resulting in the formation of a structural configuration known as Schwarzites. The enhanced efficiency of this approach may be attributed to the utilization of a three-dimensional structure, which has a pivotal significance.

Conclusion

The introduction of a Nanoparticle-Based Water Filtration System (NP-WFS) has been made in this work to address the twin problems of water disinfection and microplastic removal. By combining a specially designed membrane with the peculiar properties of CNP, this method offers a workable substitute for conventional approaches. A prominent absorption peak was seen at a wavelength of 450 nm, with an absorbance value of 1.81%. This finding provides evidence for the presence of CNP. The observed peak at 2901.4 cm^{-1}, which aligns with the value identified in the untreated water sample, suggests the existence of microplastic particles. The CNP-infused microfilm effectively captures plastic microscopic beads, as seen by the consistent range of 2798.6 cm^{-1} observed in the film. This observation suggests that the CNP microfilm has successfully captured the microbes and microplastics.

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