



Fabrication of Bio-based Protective Fabrics Functionalized with ZnO/MgO Nanoparticles for Antibacterial and Chemical Detoxification Application

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ABSTRACT

Development of protective fabrics capable of actively neutralizing chemical and biological hazards remains a major challenge, as conventional fabrics mainly provide passive protection and often rely on synthetic materials with limited environmental sustainability. In this study, a multifunctional bio-based protective fabric was developed using banyan aerial root cellulose fibers functionalized with electrospun chitosan/polyvinyl alcohol (CS/PVA) nanofibers incorporating zinc oxide and magnesium oxide nanoparticles. ZnO and MgO nanoparticles were synthesized through a precipitation-based method and deposited onto the natural fiber fabrics using electrospray coating, followed by electrospinning of CS/PVA nanofibers containing nanoparticles to form a uniform nanostructured composite layer. Structural and functional characterization was performed using attenuated total reflection Fourier transform infrared spectroscopy, scanning electron microscopy and ground-state diffuse reflectance spectroscopy to confirm nanoparticle incorporation and coating morphology. The synthesized materials demonstrated excellent antibacterial performance, achieving 99.71 ± 0.18 % inhibition of *Staphylococcus aureus* and 99.56 ± 0.27 % inhibition of *Escherichia coli* for ZnO/MgO coated fabrics, while electrospun CS/PVA–ZnO/MgO nanofiber composites exhibited nearly 100 % antibacterial efficiency. Photocatalytic experiments showed significant methylene blue degradation, with remission function values decreasing from 12.10 for CS/PVA coatings to 2.40 for CS/PVA–ZnO/MgO nanofiber composites after UV irradiation. Additionally, degradation experiments using the nerve agent simulant dimethyl methylphosphonate revealed a detoxification efficiency of 97.13 % under UV exposure. These outcomes show that the synthesized nanostructured fabrics possess strong antibacterial, photocatalytic, and chemical detoxification capabilities, making them promising candidates for advanced protective clothing, antimicrobial medical fabrics, and environmental remediation applications.

Keywords: Antibacterial activity; Sustainability; Methylene blue; Chemical detoxification; Electrospinning.

1. INTRODUCTION

Natural fiber-reinforced composites have gained attention because of their biodegradability, sustainability, and favorable mechanical performance. Hybrid composites reinforced with banyan fibers have been investigated to understand the influence of fiber composition and stacking sequence on composite performance. Surface morphological analysis using scanning electron microscopy (SEM) revealed the structural characteristics and fiber–matrix interactions within the hybrid composites (Thandavamoorthy and Palanivel, 2020). Similarly, natural fiber reinforced hybrid composites containing neem and banyan fibers were examined to evaluate the influence of drilling parameters on surface integrity, where microscopic analysis confirmed the importance of optimized

processing conditions for maintaining composite quality (Raja *et al.* 2022). Banyan fibers from aerial roots of banyan trees have also been studied for their physical and biological characteristics. Structural characterization using Fourier transform infrared spectroscopy (FTIR) and SEM revealed significant chemical functional groups and surface morphological changes after chemical treatment, while the fibers exhibited inherent antimicrobial resistance suitable for hygiene-related applications (Rana and Chopra, 2022).

Further studies have explored banyan fiber reinforced epoxy composites with different fiber orientations to evaluate their structural and chemical properties. Characterization techniques such as FTIR, Field Emission Scanning Electron Microscopy (FESEM) confirmed effective fiber–matrix bonding and

microstructural stability, demonstrating the suitability of banyan fibers for sustainable composite systems (Shyam *et al.* 2021). Hybrid composites reinforced with banyan fibers, using an epoxy matrix and sawdust filler, were also investigated, where structural characterization using SEM revealed improved crystallinity and enhanced fiber–matrix interaction, highlighting their potential for eco-friendly composite development (Raja and Anand, 2022). In addition, banyan fiber-reinforced epoxy composites incorporated with Al_2O_3 particles showed uniform filler dispersion within the matrix as confirmed by SEM analysis, while the composite exhibited antibacterial activity against microbial species (Baskar *et al.* 2025). Similarly, hybrid composites reinforced with flax fibers and aerial root banyan fibers containing graphene filler demonstrated improved structural stability and functional performance, where morphological studies confirmed effective filler distribution within the composite matrix (Ganapathy *et al.* 2024).

Electrospun nanofibers have emerged as promising materials for biomedical and environmental applications because of their high surface area, interconnected porous structure, and ability to incorporate functional nanoparticles. Alginate/PVA/chitosan coaxial nanofibers fabricated through electrospinning demonstrated excellent water absorption capacity and antibacterial activity, while *in vivo* studies confirmed their effectiveness in promoting wound healing and tissue regeneration (Liu *et al.* 2019). Electrospun nanofibers composed of polyvinyl alcohol, polyaniline, and graphene oxide or chitosan have also been developed for environmental remediation applications, where structural characterization using SEM and FTIR confirmed the formation of uniform nanofiber structures capable of removing metal ions from aqueous solutions (El-Sawy *et al.* 2023). Furthermore, chitosan/PVA electrospun nanofibers loaded with photosensitizers demonstrated strong antibacterial activity and enhanced wound healing performance, supported by structural characterization results obtained from SEM, FTIR analyses (Qiu *et al.* 2020; Raja *et al.* 2024).

Nanoparticle incorporation within electrospun nanofibers has further improved their functional properties. For example, ZnO/polyvinylpyrrolidone composite nanofibers fabricated through electrospinning exhibited homogeneous morphology and enhanced surface characteristics suitable for functional applications (Mhetre *et al.* 2023). Electrospun nanofiber membranes containing zinc oxide nanoparticles and bioactive agents demonstrated strong antibacterial activity and enhanced tissue regeneration capabilities (Wang *et al.* 2023). Similarly, one-dimensional core–shell nanostructures composed of polyacrylonitrile and ZnO prepared using electrospinning combined with atomic layer deposition exhibited well-defined nanofiber

coatings with potential applications in sensing and advanced functional materials (Damberga *et al.* 2020). Activated carbon nanofibers decorated with ZnO nanospines also showed strong photocatalytic activity and antimicrobial performance for air purification applications (Kang *et al.* 2022).

Magnesium oxide nanoparticles have gained attention because of its excellent antibacterial, photocatalytic, and biocompatible properties. Electrospun nanofibrous membranes incorporating MgO nanoparticles demonstrated improved antibacterial activity and supported tissue regeneration for biomedical applications (Tao *et al.* 2026; Yuan *et al.* 2025). Similarly, polycaprolactone nanofibers containing MgO and CuO nanoparticles showed enhanced antibacterial performance suitable for advanced filtration systems (Ferreira *et al.* 2022). Mg/MgO nanoparticle-reinforced electrospun membranes have also been developed for guided bone regeneration, where the composite structure promoted cell adhesion and osteogenic activity (Wang *et al.* 2024). In addition, poly (lactic acid) nanofibers incorporated with bioactive glass and MgO nanoparticles demonstrated improved bioactivity and antimicrobial performance for tissue engineering applications (Canales *et al.* 2022). Electrospun nanofiber membranes containing MgO nanoparticles and bioactive molecules further showed enhanced antibacterial properties and osteogenic performance (Dong *et al.* 2023).

Several research works have also focused on synthesis and functional applications of MgO nanoparticles. MgO nanoparticles synthesized using polyanionic cellulose as a stabilizing agent exhibited strong photocatalytic activity for dye degradation, as confirmed through structural characterization using FTIR, and SEM analyses (Barzegar *et al.* 2024). Green synthesis approaches using plant extracts have also been employed to produce MgO and Ag/MgO nanocomposites, which demonstrated enhanced photocatalytic degradation of organic dyes and strong antibacterial activity (Panchal *et al.* 2022). Furthermore, Cu and Zn co-doped MgO nanoparticles exhibited tunable optical properties and improved photocatalytic performance for environmental remediation applications (Abbas *et al.* 2025; Trier *et al.* 2025). Similarly, CuO/MgO nanocomposite thin films prepared through a sol–gel process showed enhanced photocatalytic degradation of methylene blue dye (Rouabah *et al.* 2023).

In the present work, a novel multifunctional bio-based protective material was developed by integrating banyan aerial root cellulose fibers with electrospun chitosan/polyvinyl alcohol nanofibers containing ZnO–MgO nanoparticles, forming a hierarchical hybrid structure for simultaneous adsorption, antibacterial activity, and catalytic degradation of hazardous agents. The study uniquely combines electrospinning and electrospray nanoparticle deposition to achieve uniform

nanostructured coatings on natural fibers. The resulting system demonstrates near-complete antibacterial efficiency and high degradation of chemical simulants while maintaining coating stability after washing, highlighting its potential for next-generation sustainable protective fabrics and environmental remediation materials.

2. MATERIALS AND METHODS

2.1 Materials

Banyan aerial root fiber fabric used as the natural cellulose substrate in this study had an areal density of approximately 315 g m^{-2} and was fabricated from 100 % banyan aerial root natural yarns originating from Tamil Nadu, supplied by Go Green Products, Chennai, India. Chitosan (CS) with a high molecular weight of 310,000–375,000 Da and polyvinyl alcohol (PVA) with an average molecular weight of ~900 kDa were obtained in powder forms from Star Scientific Erode and used as polymeric materials for electrospinning. Zinc oxide precursor chemicals required for nanoparticle preparation were procured from Matrices Enterprises, Nagercoil, Tamil Nadu. Thermal treatment and drying of the samples were performed using a Memmert UNE 800 laboratory oven. Photocatalytic degradation experiments were conducted under irradiation from a 15 W ultraviolet blacklight lamp. For the evaluation of chemical degradation performance, diethyl and dimethyl methylphosphonate supplied by Sigma-Aldrich were used as model organophosphate simulants.

2.2 ZnO and MgO Nanoparticles Synthesis

Zinc nitrate hexahydrate (0.1 M) solution was prepared by dissolving 2.975 g of $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ powder in 100 mL of distilled water. About 10 mL of banyan aerial root extract was incrementally added via a burette to the zinc nitrate solution, which was agitated magnetically at 800 rpm at 55–65°C for two hours. The pH was subsequently adjusted to 12 by adding 1 M NaOH solution, after which the synthesis continued under identical conditions for an additional hour. The mixture was permitted to rest for 30 mins before centrifugation at 10,000 rpm for 10 mins. Subsequent to the removal of the supernatant liquid, the pellets were washed through re-dispersions in distilled water and thereafter subjected to centrifugation. The rinsing procedure was conducted thrice. The pellets were subsequently dried in an oven at 50°C for 24 hours and stored in an airtight container for subsequent analysis (Taher *et al.* 2026).

The eco-friendly synthesis of MgO was carried out by mixing a 0.1 M $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ solution with banyan aerial root extract, under continuous stirring at 60–80°C maintaining pH between 8 and 12. The reaction

was permitted to continue for 4–6 hours. The color of the solution changed from light yellow to brown, indicating the formation of magnesium hydroxide precipitate (Al-Wasidi *et al.* 2024). The precipitate was thoroughly rinsed with purified water and centrifuged at 10,000 rpm for 15 minutes to eliminate contaminants. The purified product was dried at 60–70°C and calcined at 400–500°C for 2–3 hours to yield MgO nanoparticles (Qaisar *et al.* 2026).

2.3 Fabric Preprocessing

Prior to functionalization, banyan aerial root fiber fabrics (5 cm × 5 cm) were pretreated to eliminate surface impurities such as waxes and oils (Muniyasamy *et al.* 2025). The samples were initially immersed in a 5 % non-ionic detergent solution and maintained at 70°C. Subsequently, the fabrics were thoroughly rinsed with DI water at 80°C to remove residual detergent. Finally, cleaned fabrics were oven-dried at 100°C for 1 hour to obtain moisture-free substrates for further modification.

2.4 Electrospay Deposition

Nanoparticle coating on banyan aerial root fabrics was carried out using an electrospay technique with ethanolic suspensions of ZnO and ZnO/MgO nanoparticles (0.5 % w/v). The suspension was deposited onto pretreated fabrics using a Fluidnatek® LE-50 electrospinning system with 0–30 kV power supply, while a syringe pump ensured controlled flow to maintain a stable spraying jet.

Table 1. Parameters of ZnO/MgO deposition

Temperature	19 - 20°C
Humidity	59-65 %
Type of collector	Static
Deposition time	30 min
Inner needle diameter	0.60 mm
Needle-to-collector distance	150 mm
Feed rate	5 mL/h
Applied voltage	10 kV

2.5 Preparation of CS/PVA Nanoparticle Solutions

A homogeneous CS/PVA polymer solution was prepared in 50% (v/v) acetic acid under continuous stirring for 8 hours, followed by centrifugation at 5000 rpm for 30 min. Subsequently, 0.5% (w/v) ZnO nanoparticles or a mixture of 0.5% ZnO and 0.5% MgO nanoparticles was added to the solution and stirred overnight to obtain a uniform electrospinning solution.

2.6 Electrospinning

The prepared Chitosan /PVA, Chitosan /PVA–ZnO, and Chitosan /PVA–ZnO/MgO polymer solutions were electrospun using NF-103 electrospinning system. The generated nanofibers were directly deposited onto the pretreated banyan aerial root fiber fabrics, forming a uniform nanofibrous coating layer on the natural fabric substrate (Fig. 1).

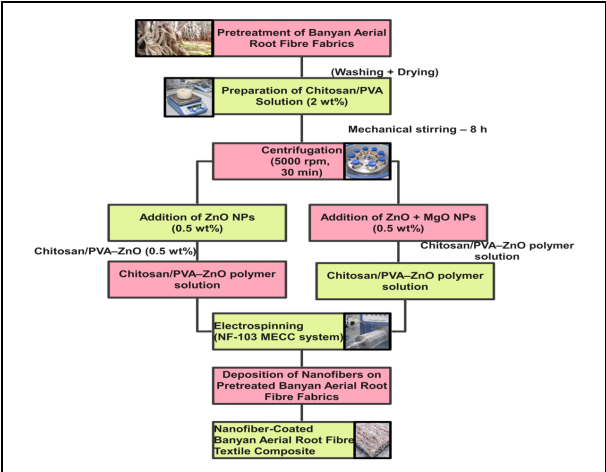


Fig. 1: Electrospinning deposition on banyan root fibers

Table 2. Electrospinning process parameters

Temperature	19 - 20°C
Humidity	59-65 %
Type of collector	Static
Processing parameters	Optimized values
Head transverse distance	50 mm/s
Head transverse speed	150 mm
Deposition time	2 hours
Needle diameter	0.41 mm
Feed rate	4 mL/hour
Applied voltage	29 kV

2.7 Material Characterization

2.7.1 Scanning Electron Microscopy (SEM)

The surface morphology of nanoparticle-coated banyan aerial root fibers and fibers coated with doped nanofibers were examined using scanning electron microscopy (Gemini, Zeiss). Prior to imaging, specimens was sputter-coated with thin Au/Pd layer (~20 nm) to improve conductivity, and the microstructural analysis was performed at an accelerating voltage of 10 kV (Raja *et al.* 2022).

2.7.2 ATR-FTIR Analysis

The structure of nanoparticles and modified banyan aerial root fabrics was examined using ATR-FTIR spectroscopy (IRAffinity-1S, Shimadzu, Japan). The spectra were recorded in the 4000–400 cm⁻¹ range with 8 cm⁻¹ resolution and 45 scans.

2.7.3 Ground-state Diffuse Reflectance (GSDR) Spectroscopy

The reflectance spectra were recorded in 200–800 nm wavelength range, and the optical responses were evaluated using Kubelka–Munk remission function to analyze the absorption characteristics of the coated fabrics:

$$\frac{K}{S} = \frac{[1-R]^2}{2 \times R} \quad \dots (1)$$

2.8 Evaluation of Properties

The antibacterial performance of nanoparticle-coated and electrospun nanofiber-modified banyan aerial root fabrics was evaluated using the absorption method based on JIS L 1902:2002 standards. *Staphylococcus aureus* (ATCC 6538) and *Escherichia coli* (ATCC 434) were used as model Gram-positive and Gram-negative bacteria, respectively. Bacterial suspensions were prepared in Tryptic Soy Broth and incubated at 36 °C for 24 hours, followed by dilution to obtain the required cell concentration. The fabric samples were inoculated and incubated at 36 °C for 24 hours, after which the viable bacterial cells were recovered using a physiological saline solution containing NaCl and Tween-20. The viable bacteria were quantified using the serial dilution plate count technique, and all experiments were conducted in triplicate to ensure reproducibility (Raja *et al.* 2024).

2.8.1 Methylene Blue (MB) Dye Degradation

The photocatalytic activity of ZnO and MgO nanoparticle-coated banyan aerial root fabrics was evaluated using methylene blue as model dye. A 500 µL MB solution (1 g/L) was applied to the fabric surface, equilibrated in the dark for 30 mins, and then UV-irradiated for 24 hours, with degradation monitored hourly using GSDR spectroscopy.

2.8.2 Dimethyl Methylphosphonate (DMMP) Degradation

The degradation behavior of DMMP was evaluated using banyan aerial root fabrics with CS/PVA nanofibers containing ZnO and MgO nanoparticles. The specimens (1.5 × 1.5 cm) were placed in vials, and 20 µL of DMMP solution were deposited on the surface. After sealing, the samples were equilibrated at dark for 10 mins and then exposed to UV irradiation for different durations up to 24 hours. The degradation products were quantified using gas chromatography–mass spectrometry (GC–MS, Bruker SCION 456-GC SQ), employing diethyl

methylphosphonate as an internal standard for accurate calibration and analysis.

3.RESULTS AND DISCUSSION

3.1 IR spectra

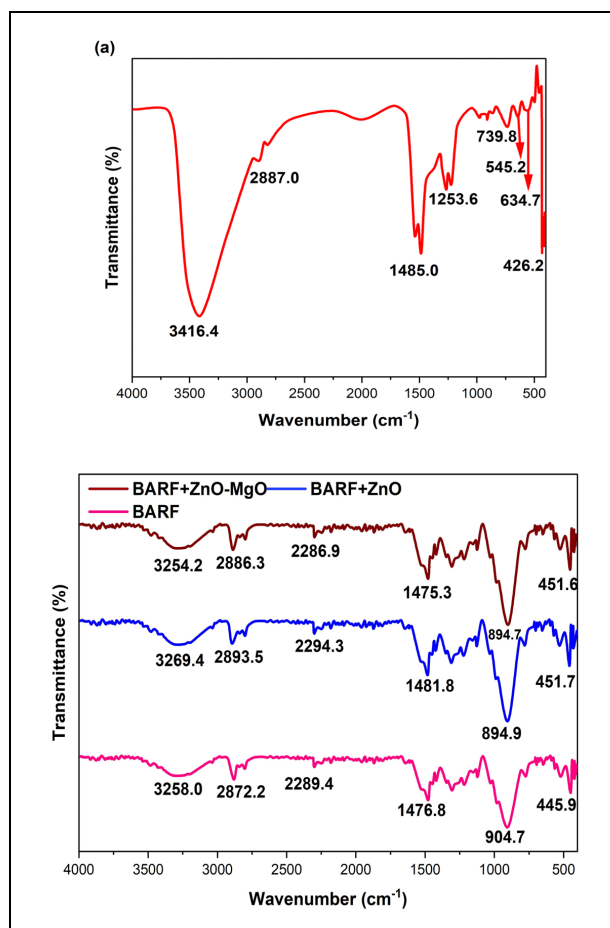
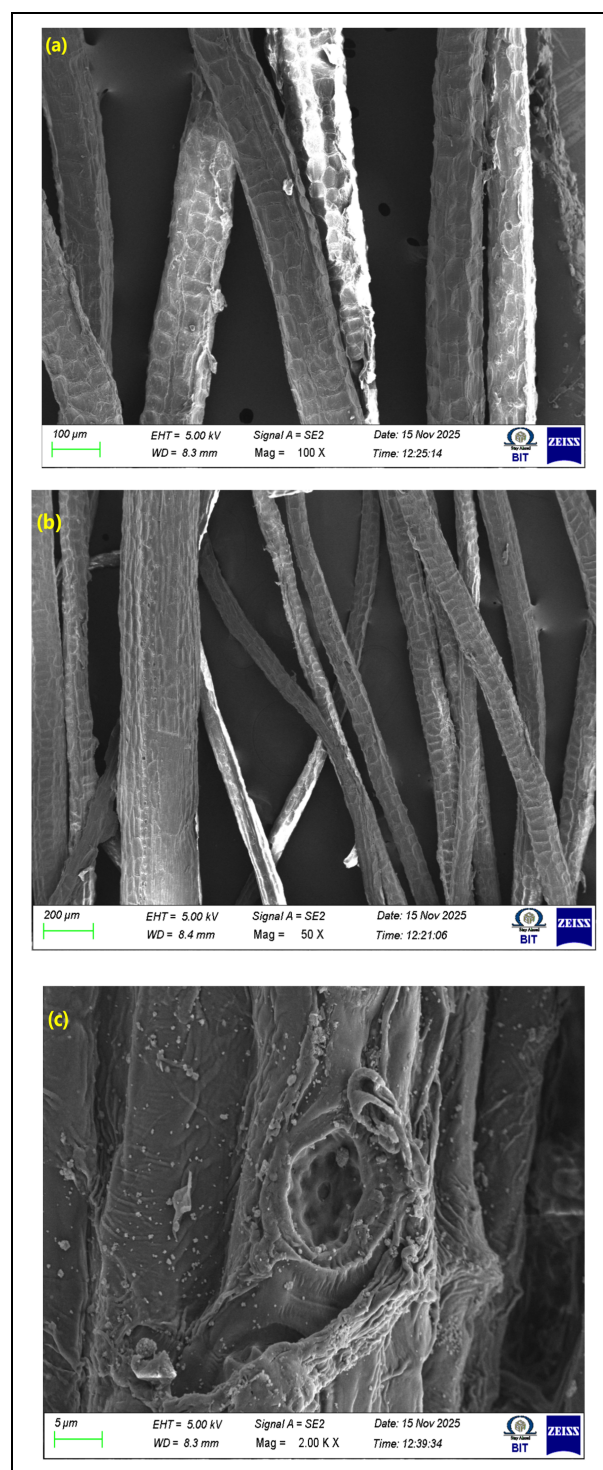


Fig. 2: ATR-FTIR of (a) ZnO nanoparticles and (b) BARF, BARF + ZnO and BARF + ZnO-MgO

The ATR-FTIR spectrum of ZnO nanoparticles is presented in Fig. 2 (a). The broad peak around 3416.4 cm^{-1} is due to the stretching vibration of hydroxyl (O–H) groups and adsorbed moisture on nanoparticle surface. The peak at 1485.0 cm^{-1} is attributed to bending vibration of surface hydroxyl groups, associated with physically adsorbed molecules. Additionally, the characteristic Zn–O stretching peak detected at approximately 426 cm^{-1} confirms the successful formation of zinc oxide nanoparticles. The ATR-FTIR spectra of pristine banyan aerial root fabric (BARF) and nanoparticle-coated samples (ZnO and ZnO/MgO) are presented in Fig. 2 (b). The pristine BARF exhibits typical lignocellulosic peaks, where the broad peak at 3258.0 cm^{-1} corresponds to O–H stretching of hydroxyl groups and absorbed moisture. The peak at 2872.2 cm^{-1} is assigned to C–H stretching of cellulose and hemicellulose, while the one at 2289.4 cm^{-1} is associated with lignin aromatic vibrations. The peak

at 1476.8 cm^{-1} represents C–H bending in cellulose, and the other at 904.7 cm^{-1} corresponds to polysaccharide-related C–O and O–H vibrations.

Upon ZnO coating, slight peak shifts to 3269.4 , 2893.5 , 2294.3 , and 1481.8 cm^{-1} are observed, indicating interaction among ZnO nanoparticles and cellulose matrix. The appearance of a peak at 451.7 cm^{-1} , attributed to Zn–O stretching, confirms successful deposition of ZnO nanoparticles.



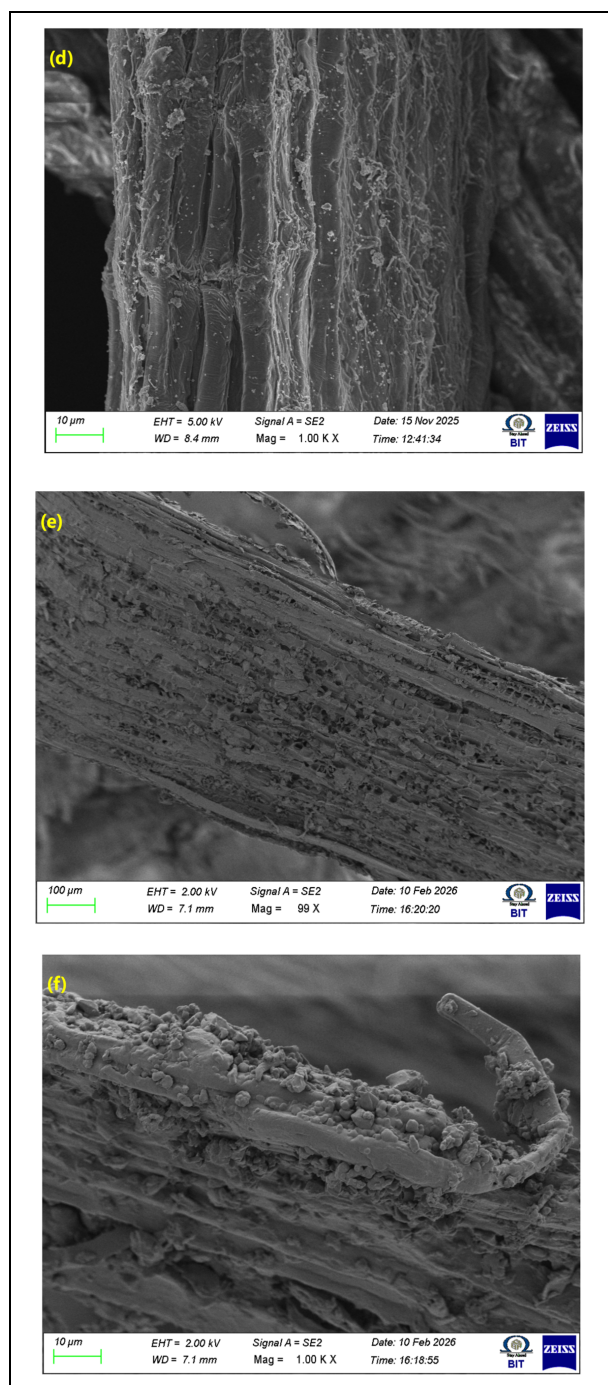


Fig. 3: SEM images of (a) ZnO-coated banyan fibers, (b) ZnO/MgO-coated banyan fibers, (c) ZnO nanoparticle composites, (d) ZnO/MgO nanoparticle composites, (e) ZnO surface distribution and (f) ZnO/MgO surface distribution

For the ZnO/MgO-coated BARF, characteristic peaks are located at 3254.2, 2886.3, 2286.9, and 1475.3 cm^{-1} , showing further spectral shifts due to synergistic interaction between ZnO, MgO, and cellulose functional groups. The peak at 451.6 cm^{-1} corresponds to metal–oxygen (Zn–O/Mg–O) vibrations, confirming the incorporation of hybrid nanoparticles. The variation in O–H stretching intensity suggests enhanced hydrogen

bonding between cellulose hydroxyl groups and metal oxide nanoparticles, leading to improved interfacial adhesion and coating stability.

3.2 Morphology of the Coated Fabric Samples

Following nanoparticle synthesis, ZnO and ZnO/MgO nanoparticles were deposited onto the banyan aerial root fabric surface using an electrospray coating technique. Ethanolic nanoparticle suspensions with concentration of 0.5 % (w/v) was prepared and uniformly sprayed onto the fabric under optimized operating conditions, including an applied voltage of 10 kV. These controlled parameters enabled formation of uniform nanoparticle coating on natural fiber substrate.

The SEM micrographs of banyan aerial root fabrics coated with ZnO nanoparticles (Fig. 3a, c, e) and ZnO/MgO nanoparticles (Fig. 3b, d, f) demonstrate that the electrospray deposition technique produced a uniform and well-dispersed nanoparticle layer across the fiber surface. The images reveal the presence of both ZnO and MgO nanoparticles distributed along the fabric structure, with only minor particle agglomeration. A comparatively higher nanoparticle density is evident on fabrics treated with the combined ZnO/MgO system, indicating effective deposition of both nanomaterials. These observations confirm that the electrospray process successfully immobilized ZnO and MgO nanoparticles onto the banyan aerial root fabric surface, resulting in a homogeneously coated fibrous substrate. Similarly, previous studies reported electrospun ZnO nanofiber networks integrated with thin-film structures for advanced functional applications. The SEM and structural analyses confirmed the formation of uniform ZnO nanofibers with nanoscale diameters. The nanofiber network enhanced the interfacial properties and improved the overall performance of the developed system (Hernández-Hernández *et al.* 2025).

3.3 ZnO/MgO Doped CS/PVA Nanofiber Coating

Electrospinning was employed to generate CS/PVA nanofibers incorporated with ZnO and ZnO/MgO nanoparticles, which were directly deposited onto the banyan aerial root fabric surface. The polymer solutions containing 0.5 % (w/v) ZnO or ZnO/MgO nanoparticles were electrospun under optimized conditions. The structural characterization of the developed materials are illustrated in Fig. 4.

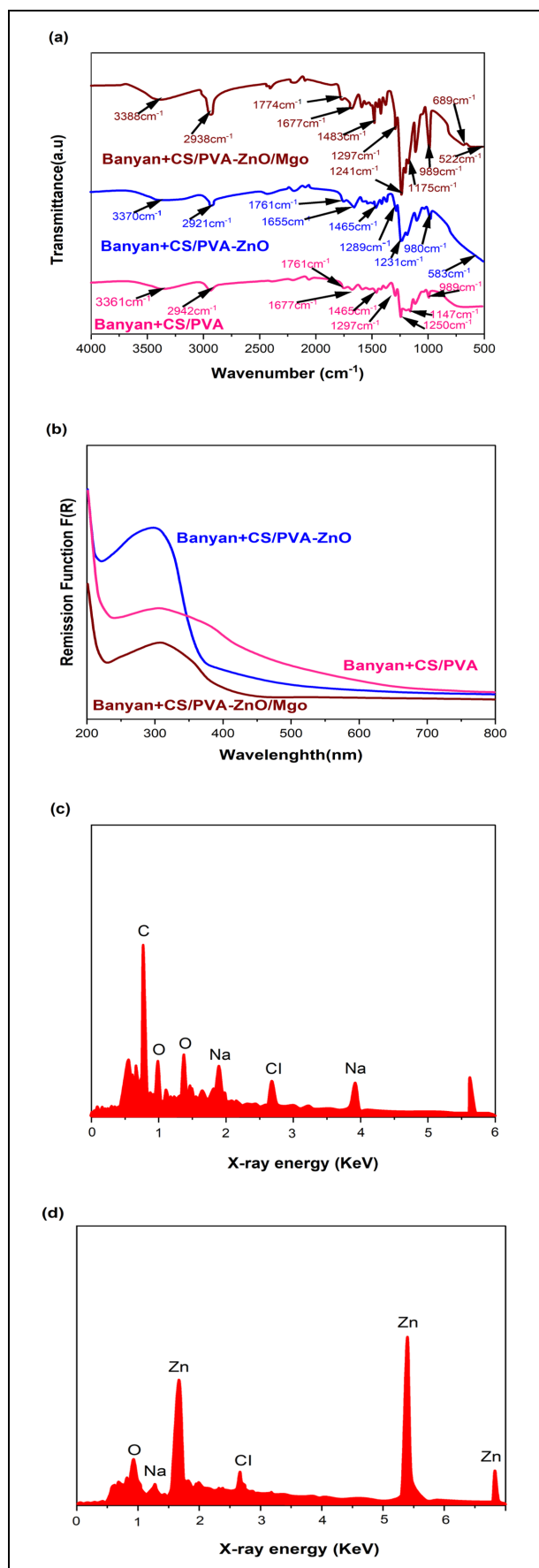


Fig. 4: (a) ATR-FTIR of coated banyan fabrics, (b) GSDR spectra of functionalized banyan fabrics, (c) EDX spectrum of CS/PVA coating, (d) EDX spectrum of ZnO nanocomposite and (e) EDX spectrum of ZnO/MgO nanocomposite

The ATR-FTIR spectra of banyan aerial root fabrics coated with Chitosan /PVA nanofibers and those containing ZnO and ZnO/MgO nanoparticles are presented in Fig. 4a. The CS/PVA-coated fabrics display characteristic peaks of cellulosic fibers together with peaks associated with chitosan and polyvinyl alcohol. The broad peak near 3300 cm⁻¹ corresponds to N–H and O–H stretching vibrations, while the peak around 1550 cm⁻¹ is attributed to amide II (N–H bending) of chitosan. The peaks near 1145–1060 cm⁻¹ arise from C–O–C stretching vibrations of PVA. After incorporation of ZnO nanoparticles, the peak 411 cm⁻¹, corresponding to Zn–O vibrations, confirms nanoparticle presence. For samples containing ZnO/MgO nanoparticles, an additional peak near 550 cm⁻¹ associated with Mg–O vibrations is observed. Moreover, the increased intensity of O–H peak around 3311 cm⁻¹ suggests the formation of hydrogen bonding interactions among cellulose hydroxyl groups and MgO nanoparticles, indicating stronger attachment of the nanoparticles to fiber surface. A previous study demonstrated the fabrication of nanofibers using polycaprolactone and polyvinylpyrrolidone incorporated with scandium oxide–magnesium oxide nanoparticles. The ATR-FTIR showed peaks at ~1720 cm⁻¹ and ~1660 cm⁻¹, confirming the polymer structure and successful nanoparticle incorporation (Liu *et al.* 2023).

The GSDR spectra of banyan aerial root fabrics with CS/PVA nanofibers and nanoparticle-doped nanofibers are presented in Fig. 4 (b). The spectra of samples containing ZnO and ZnO/MgO nanoparticles show distinct absorption band near 300 nm, which is characteristic of metal oxide nanoparticles and confirms their successful incorporation into the nanofibrous coating. Furthermore, the absorption intensity slightly decreases in samples containing both ZnO and MgO nanoparticles compared to those containing only ZnO. This reduction is attributed to the higher reflectance of

inorganic oxide nanoparticles, as their presence increases light scattering and reflectivity, thereby reducing the overall absorption intensity in the UV region.

The EDX spectra of banyan aerial root fabrics with CS/PVA nanofibers and nanoparticle-doped nanofibers are presented in Fig. 4 (c–e). The elemental analysis of the CS/PVA-coated fabrics primarily shows carbon (C) and oxygen (O), corresponding to the polymer matrix and natural cellulose fibers. In contrast, the samples containing nanoparticles exhibit additional peaks corresponding to zinc (Zn) and magnesium (Mg), confirming the successful incorporation of ZnO and MgO nanoparticles within the electrospun nanofiber coating on the fabric surface.

The GSDR, ATR-FTIR, FESEM, and EDX analyses collectively confirmed successful fabrication of nanoscale electrospun CS/PVA and their uniform deposition onto the banyan aerial root fabric surface, as well as the effective incorporation of ZnO and MgO nanoparticles within the nanofibrous structure. The electrospinning process enhances the interaction and adhesion between nanoparticles and the fibrous substrate, resulting in improved nanoparticle immobilization on the fabrics surface. Strong nanoparticle adsorption is advantageous because it enhances the durability and stability of the introduced functionalities, thereby improving the long-term performance of the functionalized fabrics material.

3.4 Assessment of Functional Properties

3.4.1 Antibacterial Activity

Metal oxide nanoparticles like ZnO and MgO are widely recognized for their antibacterial properties, mainly due to their photocatalytic activity. Under irradiation, these nanoparticles generate oxygen species (ROS), damaging essential components like proteins, cell membranes, lipids, RNA, and DNA, leading to cell death. The antibacterial activity of banyan aerial root fabrics functionalized with ZnO and MgO nanoparticles by electrospray deposition was evaluated, and the results are summarized in Table 3.

Table 3. Antibacterial activity of ZnO/MgO-coated banyan fibers

Sample	<i>Staphylococcus aureus</i>	<i>Escherichia coli</i>
Banyan aerial root	79.84 ± 4.92	88.67 ± 4.18
Banyan aerial root + ZnO	99.32 ± 0.41	99.08 ± 0.53
Banyan aerial root+ ZnO-MgO	99.71 ± 0.18	99.56 ± 0.27

The results presented in Table 3 indicate that all tested samples exhibited bacteriostatic effects against both bacterial strains. The untreated banyan aerial root fabric showed a certain level of antimicrobial activity, which can be attributed to the natural lignocellulosic composition and the presence of phenolic compounds in lignin. However, addition of ZnO and MgO nanoparticles significantly raised antibacterial efficiency of fabrics, particularly against Gram-positive bacteria. The improved activity is mainly associated with photocatalytic behavior of the metal oxide nanoparticles and ability to generate reactive oxygen species. Nevertheless, no clear distinction could be established between the antibacterial effectiveness of ZnO alone and the combined ZnO/MgO system, as the measured values were almost similar.

For the electrospun nanofiber coating on banyan aerial root fabrics, chitosan (CS) was selected as the primary polymer because of their well-known antimicrobial properties and biocompatibility. Chitosan exhibits antibacterial activity through several mechanisms, including its chelating ability and interaction with microbial DNA, which interferes with mRNA transcription and protein synthesis. Additionally, electrostatic interaction among positively charged chitosan molecules and negatively charged bacterial cell membranes leads to membrane disruption and leakage of intracellular components, ultimately causing cell death. These antimicrobial characteristics of chitosan has widely been reported. The antibacterial performance of banyan aerial root fabrics with CS/PVA electrospun nanofibers is summarized in Table 4.

Table 4. Antibacterial activity of CS/PVA nanofiber composites

Sample	<i>Escherichia coli</i>	<i>Staphylococcus aureus</i>
Banyan aerial root +CS/PVA	99.97 ± 0.01	99.94 ± 0.02
Banyan aerial root +CS/PVA- ZnO	99.98 ± 0.01	99.95 ± 0.02
Banyan aerial root + CS /PVA – ZnO/ MgO	100.0 ± 0.0	99.96 ± 0.01

The results presented in Table 4 show that all coated samples exhibited strong bacterial activity against both Gram-positive (*Staphylococcus aureus*) and Gram-negative (*Escherichia coli*) bacteria. The antibacterial performance of fabrics were mainly attributed to intrinsic antimicrobial nature of chitosan, which effectively inhibited bacterial growth. No difference was observed among fabrics coated with CS/PVA nanofibers alone and those containing ZnO and MgO nanoparticles,

suggesting that chitosan itself provided sufficient antibacterial functionality. Nevertheless, the presence of nanoparticles may contribute to long-term antibacterial stability under prolonged use or washing conditions. When compared with the electrosprayed samples, the fabrics coated with electrosprayed CS/PVA nanofibers demonstrated superior antibacterial performance, indicating that the nanofiber coating strategy was more effective in enhancing the antimicrobial properties of developed fabrics material.

3.4.2 MB Degradation

In addition to antibacterial performance, the chemical decontamination capability of the functionalized banyan aerial root fabrics was evaluated using MB as a model compound for photocatalytic degradation. A 500 μL MB solution was applied to all fabric specimens and kept at dark for 30 mins. Subsequently, the samples were exposed to UV irradiation for 1 day, and the degradation process was monitored by GSDR spectroscopy. Measurements were recorded hourly up to 10 hours, with a final observation at 24 hours. The photocatalytic performance of fabrics coated with ZnO and ZnO/MgO nanoparticles by electrospray deposition is presented at Fig. 5 (b–d), while results for CS/PVA nanofiber-coated fabrics containing nanoparticles are shown in Fig. 6 (b–d), with the MB solution spectrum used as control. A previous study reported the synthesis of Co- and Ni-doped magnesium oxide nanoparticles through a coprecipitation method. Structural and optical analyses confirmed the formation of doped MgO nanostructures. The developed nanoparticles showed high photocatalytic efficiency for methylene blue dye degradation (Arif *et al.* 2025).

The UV–visible spectrum of methylene blue (MB) displays characteristic absorption bands at approximately 491 and 567 nm, which are typical for this dye. When comparing the spectra of untreated banyan aerial root fabrics with those of nanoparticle-functionalized fabrics, a noticeably faster reduction in intensity of MB absorption bands is observed for samples containing ZnO and ZnO/MgO nanoparticles. This behavior indicates that presence of metal oxide nanoparticles enhances photocatalytic degradation of dye, demonstrating the improved catalytic activity of the functionalized fabrics under UV irradiation.

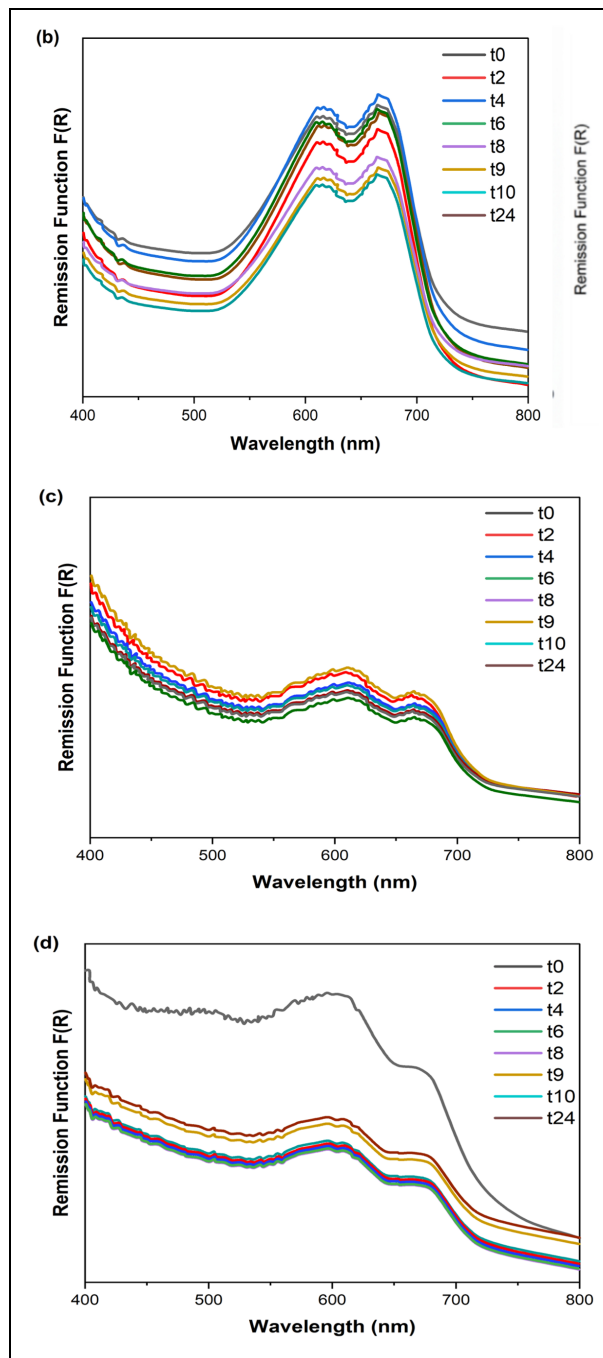
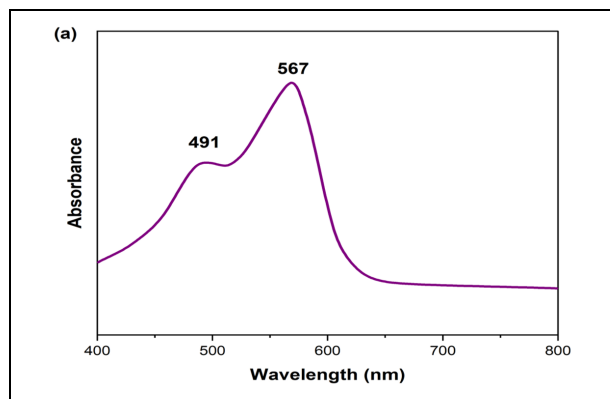


Fig. 5: Absorbance of (a) MB solution (control), (b) Untreated banyan aerial root fabric, (c) ZnO-coated banyan aerial root fabric and (d) ZnO/MgO-coated banyan aerial root fabric

The GSDR spectra of banyan aerial root fabrics with CS/PVA nanofibers and nanoparticle-doped nanofibers reveal that the characteristic methylene blue absorption bands at 491 and 664 nm decrease more rapidly in samples containing ZnO and ZnO/MgO nanoparticles. After 2 hour of UV irradiation, remission function values at 567 nm were approximately 12.10 for CS/PVA-coated fabrics, 6.07 for CS/PVA–ZnO, and 2.40 for CS/PVA–ZnO/MgO samples, indicating significantly enhanced dye degradation at presence of nanoparticles.

This behavior is attributed to photocatalytic activity of ZnO and MgO, which accelerates dye decomposition rather than simple adsorption. Moreover, the combined ZnO/MgO system exhibited stronger degradation performance, likely due to a synergistic interaction between the two oxides. The nanofiber-coated fabrics demonstrated superior performance compared to electrosprayed samples, mainly because the electrospun nanofibrous structure provides a higher surface area and finer pore network, enabling improved adsorption, catalytic interaction, and trapping of dye molecules within the fibrous matrix.

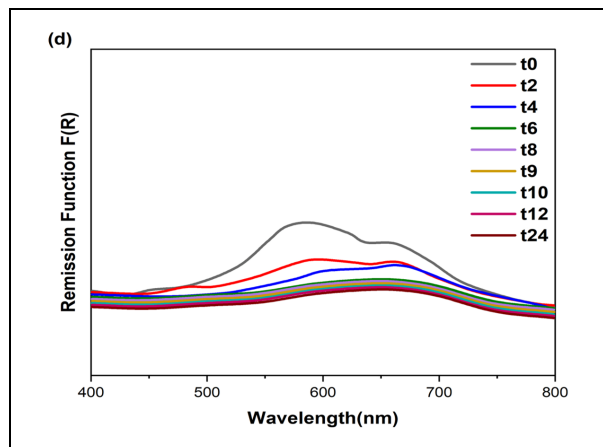
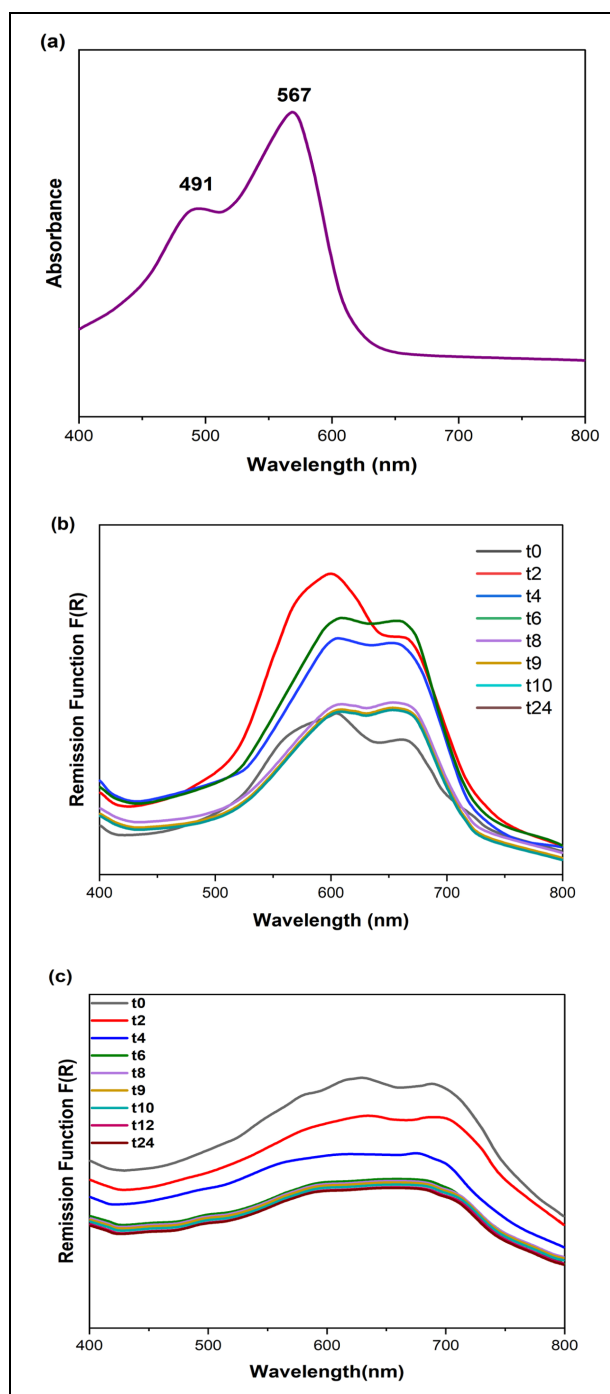


Fig. 6: Absorbance of (a) MB solution (control), (b) CS/PVA nanofiber-functionalized banyan fabric, (c) ZnO-doped nanofiber-coated banyan fabric, (d) ZnO/MgO-doped nanofiber-coated banyan fabric

The photocatalytic degradation of MB by ZnO and MgO nanoparticles has been widely reported. Zinc oxide is considered an effective photocatalyst due to its chemical stability, relatively low toxicity and low cost. Furthermore, ZnO possesses a suitable optical band gap energy (~ 3.2 eV), enabling efficient activation under ultraviolet radiation for pollutant degradation. However, because of wide band gap, ZnO mainly absorbs UV light, which constitutes only small fraction of solar spectrum. In addition, ZnO nanoparticles often show high recombination rate of photogenerated electron-hole pairs, which can limit their overall photocatalytic efficiency.

In contrast, MgO nanoparticles exhibit light absorption extending toward the visible region, and their incorporation with ZnO nanoparticles can broaden the overall light absorption capability of system. The formation of ZnO–MgO semiconductor heterojunction facilitates reduced electron-hole recombination and improved charge carrier separation, while also slightly modifying the effective band gap of the composite structure. These effects enhance the photocatalytic efficiency of the material by promoting more effective generation and utilization of reactive species during irradiation. Therefore, the integration of MgO with ZnO nanoparticles can significantly improve overall photocatalytic efficiency of developed system.

The photocatalytic mechanism of banyan aerial root fabrics with CS/PVA nanofibers containing ZnO and MgO nanoparticles can be described based on a Z-scheme heterojunction system, illustrated at Fig. 7. In this mechanism, the interaction between ZnO and MgO promotes the transfer of photogenerated charge carriers and facilitates efficient charge separation, thereby reducing electron-hole recombination. Upon UV irradiation, holes and electrons are generated at both semiconductors, and their migration through the Z-

scheme pathway promotes formation of reactive oxygen species, which are responsible for degradation of organic contaminants.

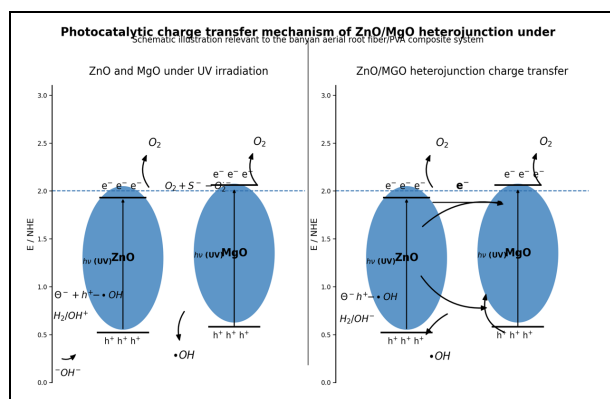


Fig. 7: (a) Type-II heterojunction photocatalytic mechanism and (b) Direct Z-scheme photocatalytic mechanism

Unlike the conventional type-II heterojunction, the Z-scheme mechanism better explains efficient charge separation in ZnO/MgO systems. Under irradiation, electrons in ZnO recombine with holes in MgO, enabling remaining electrons and holes to generate $O_2^{\cdot -}$ and $\cdot OH$ radicals, which actively degrade methylene blue dye through oxidative photocatalytic reactions.

3.4.3 DMMP Degradation

Dimethyl methylphosphonate was employed as nerve agent simulant due to its structural similarity to organophosphate nerve agents while exhibiting significantly lower toxicity. To evaluate chemical detoxification capability, banyan aerial root fabrics coated with CS/PVA nanofibers containing ZnO and MgO nanoparticles, which showed superior antibacterial and photocatalytic performance, were selected. The degradation was monitored using GC–MS analysis at irradiation intervals ranging from 0 to 24 hours under UV exposure, while experiments conducted without fabric samples served as control measurements to assess the degradation efficiency of the functionalized fabric system (Fig. 8).

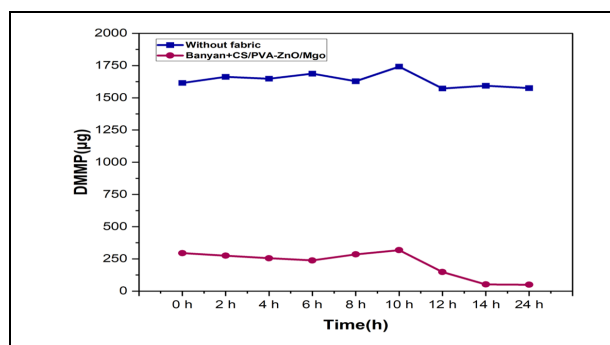


Fig. 8: UV-induced DMMP degradation by ZnO/MgO nanofibers

Fig. 9 demonstrates that banyan aerial root fabrics coated with CS/PVA–ZnO/MgO nanofibers significantly enhanced the degradation of DMMP compared to the control sample. While the control exhibited almost no reduction in DMMP concentration after 24 hours of UV exposure, the functionalized fabric reduced DMMP to 45 μg , corresponding to 97.13 % degradation. These findings highlight the strong detoxification capability of the nanoparticle-coated natural fabric, indicating its promising potential for advanced protective fabrics against biological and chemical hazardous agents.

Dimethyl methylphosphonate is typically adsorbed on oxide surfaces through its phosphoryl oxygen binding to Lewis acid sites, followed by P–OCH₃ bond cleavage *via* reactions with surface hydroxyl groups. This process results in decomposition products such as methanol, dimethyl ether, and surface methoxy species, enabling effective detoxification of organophosphate simulants.

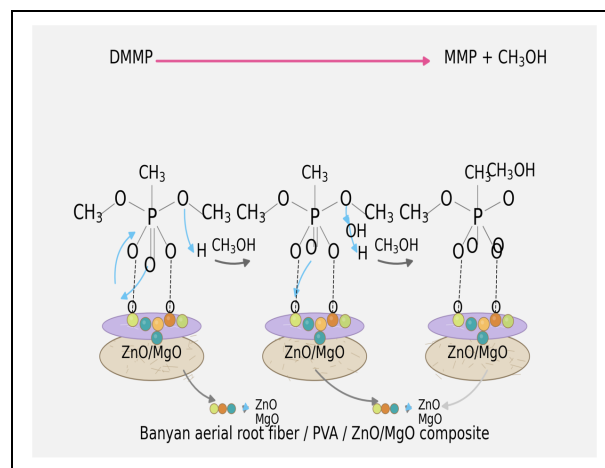


Fig. 9: DMMP decomposition on metal oxide surfaces

These findings represent preliminary evaluations, and additional studies are required to better understand the DMMP degradation mechanisms of the developed materials. Nevertheless, the results demonstrate promising potential for advanced personal protective fabrics, as the functionalized fabrics can actively degrade hazardous chemical agents rather than merely providing passive protection. Furthermore, the incorporation of nanoparticles and electrospun nanofibers enables enhanced functionality without significantly increasing fabric weight, which is highly desirable for practical protective equipment.

4. CONCLUSIONS

Protective fabrics capable of actively neutralizing chemical and biological hazards remain limited, as most conventional fabrics provide only passive filtration and rely on synthetic materials with

lower sustainability. In this work, a multifunctional bio-based protective fabrics was developed using banyan aerial root cellulose fibers functionalized with electrospun chitosan/polyvinyl alcohol (CS/PVA) nanofibers incorporating ZnO and ZnO/MgO nanoparticles. MgO and ZnO nanoparticles were synthesized through a precipitation-based method and deposited onto the natural fiber fabrics using electrospray coating, followed by electrospinning of CS/PVA nanofibers containing nanoparticles to form a hierarchical nanostructured coating. Structural characterization using ATR-FTIR, SEM, EDX, and GSDR spectroscopy confirmed successful nanoparticle incorporation and uniform nanofiber deposition. The functionalized fabrics exhibited excellent antibacterial activity with 99.71 ± 0.18 % inhibition of *Staphylococcus aureus* and 99.56 ± 0.27 % inhibition of *Escherichia coli* for ZnO/MgO-coated fabrics, while CS/PVA–ZnO/MgO nanofiber composites achieved nearly 100 % antibacterial efficiency. Photocatalytic experiments demonstrated significant methylene blue degradation, where remission function values at 567 nm decreased from 12.10 (CS/PVA) to 6.07 (CS/PVA–ZnO) and 2.40 (CS/PVA–ZnO/MgO) after UV irradiation, indicating enhanced catalytic activity. Furthermore, degradation of the nerve-agent simulant dimethyl methylphosphonate reached 97.13 % under UV exposure, confirming strong detoxification capability. These results demonstrate that the developed nanostructured fabrics offer strong antibacterial, photocatalytic, and chemical detoxification performance, making it promising candidate for advanced protective clothing, antimicrobial medical fabrics, and environmental remediation materials.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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