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Multifunctional Cotton Fabrics Coated with Banana Peel-Synthesized ZnO Nanoparticles

Parintip Rattanaburi[1], Paweena Porrawatkul[2,3,*], Rungnapa Pimsen[2,3], Montakarn Tongsom[4], Prawit Nuengmatcha[2,5] and Sunanta Khongsai[6]

[1]*Department of General Science, Faculty of Education, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat 80280, Thailand*
[2]*Center of Excellence in Nanomaterials Chemistry, Faculty of Science and Technology, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat 80280, Thailand*
[3]*Department of Chemistry, Faculty of Science and Technology, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat 80280, Thailand*
[4]*Department of Biology, Faculty of Science and Technology, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat 80280, Thailand*
[5]*Creative Innovation in Science and Technology, Faculty of Science and Technology, Faculty of Science and Technology, Nakhon Si Thammarat Rajabhat University, Nakhon Si Thammarat 80280, Thailand*
[6]*Faculty of Science and Fisheries Technology, Rajamangala University of Technology Srivijaya, Trang 92150, Thailand*

([*]Corresponding author's e-mail: paweena_por@nstru.ac.th)

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Abstract

This research presents an environmentally friendly approach for synthesizing zinc oxide (ZnO) nanoparticles using banana peel extract as a natural reducing and stabilizing agent. The synthesis avoids hazardous chemicals, aligning with green chemistry principles. The ZnO nanoparticles were characterized using XRD, SEM, EDX, TEM, and FTIR techniques, confirming their crystalline structure, uniform morphology, and successful phytochemical interaction. The ZnO nanoparticles were coated onto cotton fabrics via an ultrasonication method, ensuring even deposition. The coated fabrics demonstrated enhanced UV protection with a UV protection factor (UPF) of 82.67, categorized as excellent protection, and retained strong UV-blocking properties even after 20 washing cycles. The fabrics also exhibited significant antibacterial activity, effectively inhibiting Staphylococcus aureus (zone of inhibition: 26.17 mm) and Escherichia coli. This antibacterial performance was attributed to the release of reactive oxygen species (ROS) and Zn^{2+} ions, which disrupt bacterial cell walls. This study highlights the dual functionality of ZnO-coated fabrics in providing UV protection and antibacterial properties while maintaining their durability and eco-friendliness. The findings demonstrate the potential of utilizing green-synthesized nanoparticles in developing multifunctional textiles for applications in healthcare, protective clothing, and environmental sustainability.

Keywords: Antibacterial activity, Banana peel, Cotton fabric, Green synthesis, Multifunctional textiles ZnO nanoparticles, UV protection

Introduction

Cotton fibers, which predominantly consist of 95 % cellulose, are the most commonly used natural fibers. These fibers are ideal for producing comfortable textiles and clothing due to their remarkable flexibility, comfortability, water absorptivity, and air permeability. Notably, the initial studies on functionalized cotton fibers modified with nanoparticles have broadened the use of cotton fabrics in various applications [1], including conductive [2], magnetic [3], photocatalytic [4-6], antimicrobial [7], and super hydrophobic [8-10] textiles. ZnO nanoparticles are semiconductor materials [11] that have been extensively utilized due to their unique physical and chemical properties, including surface effect, quantum size effect, and macroscopic quantum effect [12]. The application of ZnO nanoparticles to textiles has garnered considerable attention due to their advantages, such as UV shielding [13], antibacterial activity [14-17], biocompatibility, biodegradability, and biosafety for environmental applications.

ZnO nanoparticles demonstrate significant antibacterial efficacy against both gram-positive and gram-negative bacteria even in the absence of light, illustrating their enormous potential in combating microbial infections. Studies have shown that ZnO nanoparticles generate reactive oxygen species (ROS) and release Zn^{2+} ions, which contribute to their antimicrobial activity by damaging bacterial cell walls and disrupting cellular functions [18-22]. Moreover, doping ZnO with metallic elements has been reported to enhance its antibacterial efficiency by increasing the electron-hole separation efficiency, thereby improving photocatalytic activity [23-26]. Several studies have demonstrated that metal-doped ZnO nanoparticles, including Ag-ZnO composites, exhibit superior antibacterial performance due to their synergistic effects in ROS generation and Zn^{2+} ion release [27,28]. These enhancements have broadened the application of ZnO nanoparticles in medical textiles and protective clothing [29,30].

In addition to antibacterial properties, ZnO nanoparticles have been widely explored for their UV-blocking capabilities. The high-energy bandgap of ZnO (approximately 3.37 eV) allows it to effectively absorb and scatter UV radiation, making it a preferred material for UV-protective coatings on textiles [31,32]. The incorporation of ZnO nanoparticles into cotton fabrics not only enhances UV shielding but also maintains the fabric’s breathability and mechanical properties, making it an ideal candidate for multifunctional textiles [33]. Notably, green synthesis approaches utilizing plant extracts, such as banana peel extract, provide an eco-friendly and sustainable route for ZnO nanoparticle production, eliminating the need for hazardous chemicals [34,35]. This biosynthesis method leverages phytochemicals as reducing and stabilizing agents, contributing to the formation of ZnO nanoparticles with high stability and biocompatibility.

Overall, the application of ZnO nanoparticles in textiles represents a promising avenue for developing sustainable, multifunctional fabrics with enhanced antibacterial and UV-protective properties. The present study aims to build upon these advancements by exploring the biosynthesis of ZnO nanoparticles using banana peel extract and evaluating their efficacy in antibacterial and UV-protective applications on cotton fabrics.

Recently, the phytochemical synthesis of metal oxide nanoparticles has garnered significant attention because of their eco-friendliness, affordability, lack of toxicity to people, and bio-inspiration. ZnO nanoparticles are synthesized by employing plant-derived phytocompounds as reducing and capping agents. However, there are no reports available on the biosurfactant-based synthesis of ZnO nanoparticles, and hence their thermal and UV protection properties, photocatalytic activity, and antibacterial activity were analyzed. In general, the synthesis of metal oxide nanomaterials can be realized through various methods, including hydrothermal [36], thermal decomposition [37], microwave-assisted [38], co-precipitation [39], ultrasonic hydrothermal [40], electrochemical [41], and sol-gel methods [42]. All these methods involve the use of toxic chemicals and solvents, which are detrimental to human health and the environment. Recently, green synthesis of ZnO NPs composites, particularly using plants, has gained significant consideration due to its low cost and facile synthesis process. Plants contain various chemical compositions, including alkaloids, flavonoids, terpenoids, carotenoids, tannins, and chlorophylls. The chemical components in plants can function as reducing and capping agents for the synthesis of ZnO NPs [43,44].

Accordingly, the present study reports on the biosynthesis of ZnO nanoparticles (ZnO NPs) using banana peel (*Musa acuminata*) extract as a reducing agent. The physicochemical characteristics of the synthesized ZnO NPs were ascertained through various techniques, including powder X-ray diffraction, Fourier transform infrared spectroscopy, scanning electron microscopy, energy-dispersive X-ray, and transmission electron microscopy. The water-wash durability and UV protection characteristics of the cotton fabric were examined following modification with this synthetic ZnO NPs coating. Furthermore, the antibacterial activities of the synthesized products were tested on *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) bacteria.

Materials and methods

All the analytical reagents used in the analysis were purchased from Merck and were of analytical grade. The nutrient agar for bacterial culture, Mueller-Hinton broth, and antimicrobial activity agar were provided by Hi-Media, Mumbai, India. Cotton fabric (100 %, 220 g/m^2) was purchased from Chok-dee Textiles Company, Nakhon Si Thammarat, Thailand.

Preparation of banana peel extracts

The banana peels of *Musa acuminata* were collected from the Tungsong district, Nakhon Si Thammarat province. The banana peels were washed and cut into small pieces. Subsequently, these were dried in an oven at 50 °C until the banana peel was completely dry. A quantity of 50 g of dry banana peel was refluxed in DI water for 30 min. The extract solution was then filtered through filter paper No. 1. The solvent was removed from the filtrate using an evaporator, resulting in the banana peel extract (BPE), which is used as both a reducing agent and stabilizing agent in the subsequent steps.

Green synthesis of zinc oxide nanoparticles

To synthesize the ZnO NPs, 2 g of zinc nitrate was mixed with 42.5 mL of peel extract solution. These mixtures were stirred for 30 min and subsequently placed in a water bath at 60 °C for 60 min. The mixtures were dried at 150 °C and calcined at 400 °C for 1 h.

Characterization of biosynthesized ZnO nanoparticles

The ZnO NPs were visually observed, and their maximum absorbance was measured using UV-visible spectrophotometry in the range of 200 - 800 nm. Their morphology and composition were analyzed using a scanning electron microscope (SEM). The crystallographic structure and particle sizes of ZnO NPs were examined using an X-ray diffractometer (XRD). Furthermore, the elemental distribution on the surface of the samples was analyzed through energy-dispersive X-ray spectroscopy (EDX). The green synthesis of ZnO NPs was confirmed through Fourier-transform infrared spectroscopy (FT-IR).

Coating of ZnO NPs on cotton fabrics

The green-synthesized ZnO NPs were coated on cotton fabric by utilizing an ultrasonication method. Herein, 2 g of ZnO NPs were dispersed in 200 mL of DI water and sonicated for 10 min using a fixed power sonicator (frequency: 20 kHz; power: 250 W). Later, NH_4OH was added dropwise until it attained a pH of 8 to align with the alkalinity of the cotton fabric. Sonication was then continued for 10 min with NH_3 usage being permitted [45]. The cotton fabric (3×3 cm^2) was immersed in the solution and sonicated for 30 min. Then, the coated cotton was taken out of the solution, washed with DI water, and left to dry at 80 °C before characterization.

UV protection factor analysis

The efficacy of ZnO NPs-coated cotton fabric in ultraviolet (UV) blocking was verified through UV protection factor (UPF) calculations, which achieved a near-complete UV blocking capability. The UPF value and percent UV transmission were derived from the transmission data using the formulas given below, with the mean % transmission in the UV range (280 - 400 nm) used for calculation (AATCC Test Method 183 - 2004) [46].

$$UPF = \frac{\sum_{280}^{400} E_\lambda S_\lambda \Delta_\lambda}{\sum_{280}^{400} E_\lambda S_\lambda T_\lambda \Delta_\lambda}$$

here, E_λ denotes the relative erythemal spectral effectiveness, S_λ represents the solar spectral irradiance in $Wm^{-2}nm^{-1}$, and T_λ signifies the spectral transmission of the specimen obtained from UV spectrophotometric experiments.

Results and discussion

Green synthesis and characterization of ZnO nanoparticles

ZnO nanoparticles were synthesized using the bio-mediated method, where BPE functions as both a reducing and stabilizing agent to create ZnO nanoparticles without relying on any environmentally dangerous substances. **Figure 1(a)** depicts the experimental system for the synthesis of ZnO nanoparticles. **Figure 1(b)** presents a potential reaction pathway for the environmentally friendly synthesis of ZnO utilizing BPE, where ligation occurs between the zinc precursor and the functional components of the banana peel. The organic compounds in banana peel extract act as reducing agents. Notably, these extract constituents, which include hydroxyl aromatic ring groups, combine with Zn^{2+} ions to produce complex ligands. Nanoparticles are generated and stabilized through nucleation, shaping, and growth processes. The ZnO nanoparticles are subsequently released when the organic solution mixture is calcined at 400 °C, causing a direct breakdown [47,48].

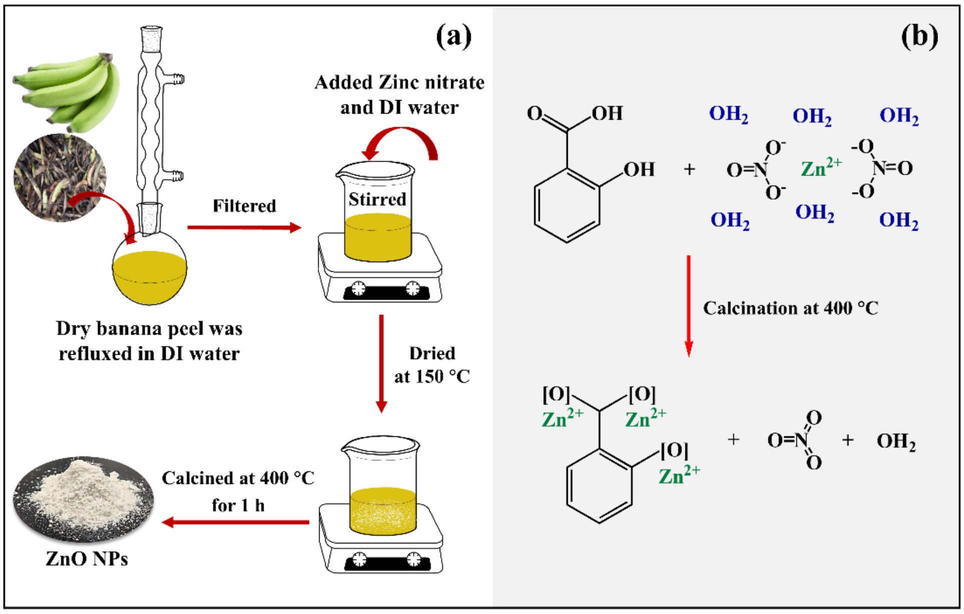

Figure 1 (a) Schematic representation of green synthesized ZnO NPs and (b) probable mechanism of zinc oxide nanoparticles (ZnO-NPs) formation using banana peel extract.

SEM and EDX analysis

The surface morphology of ZnO NPs was determined using scanning electron microscopy. The SEM images depicted in **Figure 2(a)** reveal the spherical form of ZnO NPs. The Zn, O, and C element peaks in the energy-dispersive X-ray (EDX) spectrum of ZnO nanoparticles (NPs) verified the ZnO composition and the absence of contaminants in the generated samples. These EDX patterns of ZnO NPs show a zinc content of 78.1 %, a carbon content of 5.4 %, and an oxygen content of 16.5 %. **Figure 2(b)** displays the EDX spectrum of ZnO NPs.

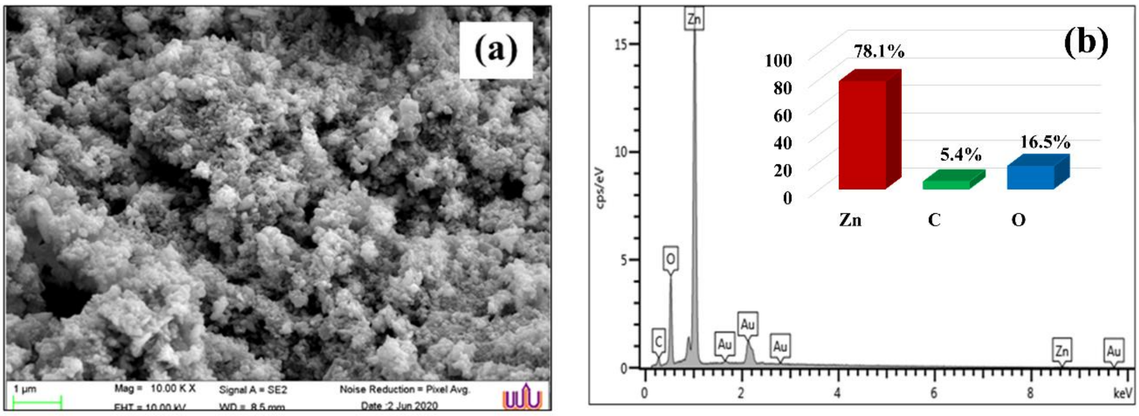

Figure 2 SEM image of (a) ZnO NPs (b) EDX spectrum of ZnO NPs.

X-ray diffraction analysis of ZnO nanoparticles

Figure 3 displays the XRD pattern, demonstrating the crystalline nature of green-synthesized ZnO NPs. The spectrum represents the XRD profile of the ZnO NPs synthesized through biogenic methods. The particle size is estimated using the Debye–Scherrer formula as represented in Eq. (1):

$$\text{Particle Size} = (0.9\times\lambda)/(d\cos\theta) \qquad (1)$$

where λ = 1.54060 Å, $0.9\times\lambda$ = 1.38654 Å, $\theta = 2\theta/2$, and *d* represents the full width at half maximum intensity of the peak.

According to the aforementioned equation, the calculated mean size of the green-synthesized ZnO NPs is 51.32 nm. The XRD peaks were observed at 2θ values of 31.82, 34.45, 36.39, 47.45, 56.69, 62.89, 67.94 and 77.12 °, which correspond to the lattice planes (100), (002), (101), (102) (200), (112), (201) (004), and (202), respectively. Notably, the peak patterns were indexed to the hexagonal wurtzite phase of ZnO, and the observed pattern matches the ICDD/JCPDS no. 36 - 1,451 [49]. Moreover, biogenic ZnO often contains internal strain, oxygen vacancies, or crystal defects introduced during the synthesis process. The presence of biomolecules (e.g., flavonoids, polyphenols) from plant extracts can disrupt the crystallization process, leading to lattice distortions and broader XRD peaks [50].

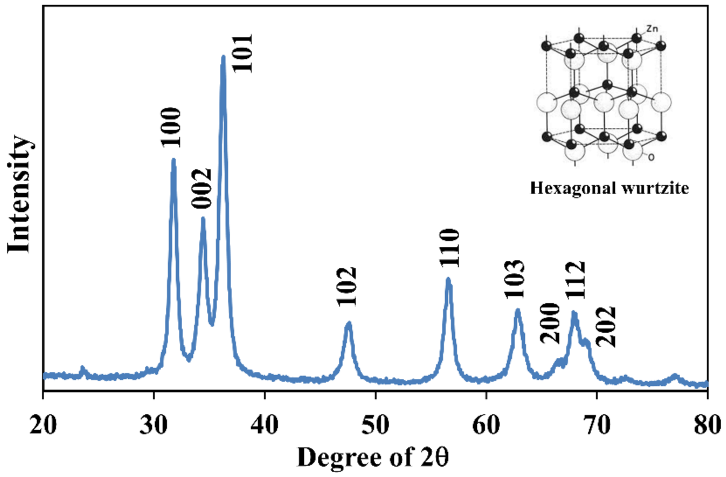

Figure 3 XRD patterns of ZnO NPs synthesis using banana peel extract.

TEM analysis

Furthermore, the morphology of the photocatalyst was examined using TEM. **Figure 4(a)** depicts the TEM image of the green-synthesized ZnO NPs, revealing agglomeration and a spherical to hexagonal nanostructure. Additionally, the distance between crystal planes, or the predicted *d*-spacing in the hexagonal wurtzite structure of ZnO, is closely related to the lattice parameters of the material and is crucial for understanding its crystallographic features and behavior. **Figure 4(b)** presents the high-resolution TEM images [51], which reveal a 0.281 nm lattice corresponding to the (100) plane.

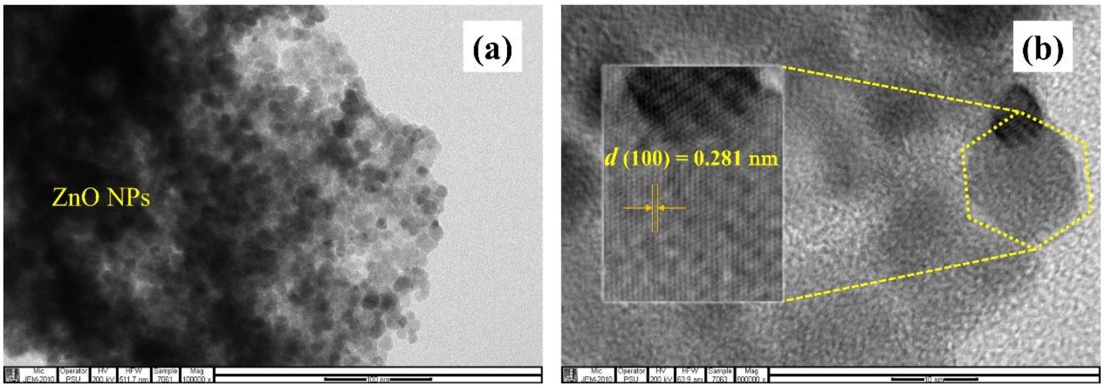

Figure 4 TEM image of ZnO NPs at (a) 100 nm and (b) the fringes at 10 nm scale.

Study of surface morphology of uncoated and coated fabrics

Figure 5 shows the comparison of the surface morphology of uncoated cotton fabric with the ZnO-coated cotton fabric through SEM analysis. The SEM image of the uncoated cotton fabric in **Figures 5(a)** and **5(b)** indicates that the surface of the cotton fiber appears relatively smooth at low magnification, with clear grooves observed at high magnification. The cotton fabrics coated with ZnO NPs after 30 min of sonication time exhibit the surface morphology of cotton fabrics treated with ZnO NPs (**Figures 5(c)** and **5(d)**). The findings confirmed the FTIR result, demonstrating that the ZnO NPs are attached to the cotton fibers. As shown in **Figure 5(e)**, the coating of cotton fabric with ZnO NPs was further verified through EDX analysis and compared with uncoated cotton. Notably, the EDX spectrum of uncoated cotton fabric reveals the presence of only 2 elements, C (52.4 %) and O (47.6 %). Remarkably, the carbon peak in the EDX pattern originates from the cellulosic structure of the cotton fabric [52]. Meanwhile, as shown in **Figure 5(f)**, the ZnO NPs-coated cotton fabric indicated the presence of C (49.4 %), O (40.4 %), and Zn (10.2 %) elements. Furthermore, the cotton fabric coated with ZnO NPs displayed peak of Zn element, suggesting that ZnO NPs had been applied to the cotton fabric. This is consistent with the XRD and FTIR analyses.

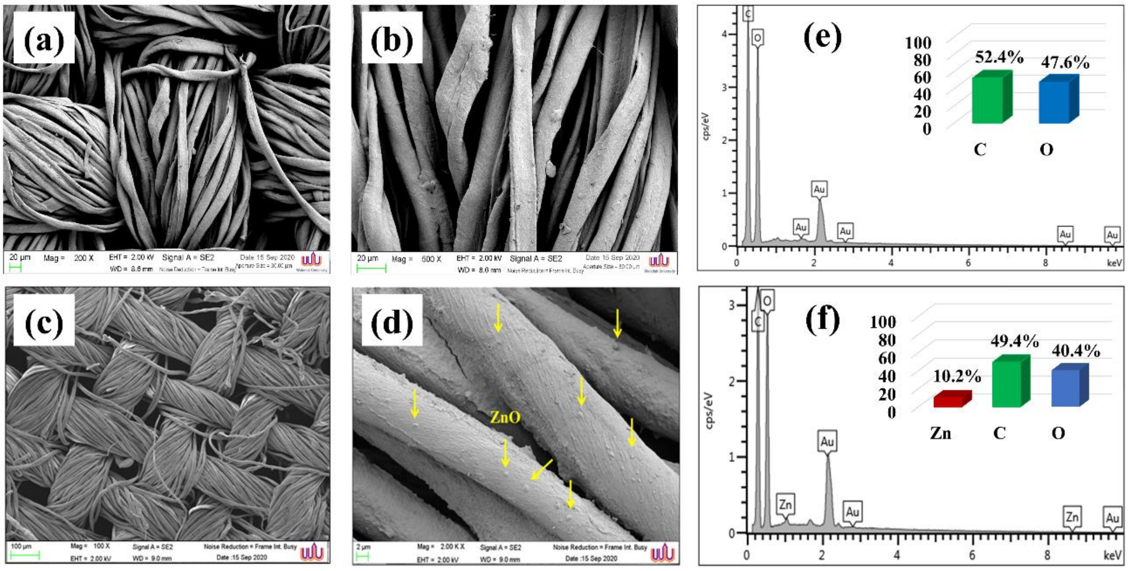

Figure 5 SEM image of (a) uncoated cotton fabric at 100×, (b) uncoated cotton fabric at 2K×, (c) coated cotton fabric at 100×, (d) coated cotton fabric at 2K× (e), EDX patterns of uncoated cotton fabric, and (f) EDX patterns of uncoated cotton fabric.

FTIR analysis

The biosynthesis of ZnO NPs and the interaction between the cellulose fiber of cotton fabric with ZnO NPs were characterized using the FTIR technique. **Figure 6** presents the FTIR spectrum of banana peel extract, bio-synthesized ZnO NPs, uncoated cotton fabric, and cotton fabric-coated ZnO NPs, which were acquired in the range of 4,000 to 400 cm^{-1}. The spectrum of zinc oxide nanoparticles displayed bands for the functional groups at 3,385, 1,631, 1,384, 1,440, 817, and 487 cm^{-1} [53]. The strong broad peaks in the higher region at 3,385 cm^{-1} are attributed to the stretching vibration of hydroxyl (OH) groups, while the vibration peaks around 1,631 are associated with the C=O functional group of banana peel extract capping. Moreover, the ZnO presents a band peak at 485 cm^{-1} that corresponds to the Zn-O vibration. Additionally, the possible biomolecules responsible for the bioreduction of zinc oxide nanoparticles were identified through FTIR analysis. The FTIR spectral analysis reveals that the significant broadband (3,100 - 3,700 cm^{-1}) centered around 3,410 cm^{-1} is attributed to the vibration stretching -OH in cotton fiber cellulose, which is characteristic of the -OH functional group. Notably, the weak bands in the 900 - 1,300 cm^{-1} and 1,300 - 1,500 cm^{-1} ranges correspond to C-O and C-H vibrations of cellulose. Moreover, the spectrum of ZnO NPs is visible at a wavenumber of approximately 487 cm^{-1}. A change in intensity is observed in the -OH group and C-O group of coated cross-linker-coated textiles and ZnO NPs. A significant increase in intensity was noted in textiles coated with bio-synthesized ZnO NPs due to the interaction between the hydroxyl groups and ZnO nanoparticles after the coating, thereby confirming the coating of nanoparticles on cotton fabric fibers.

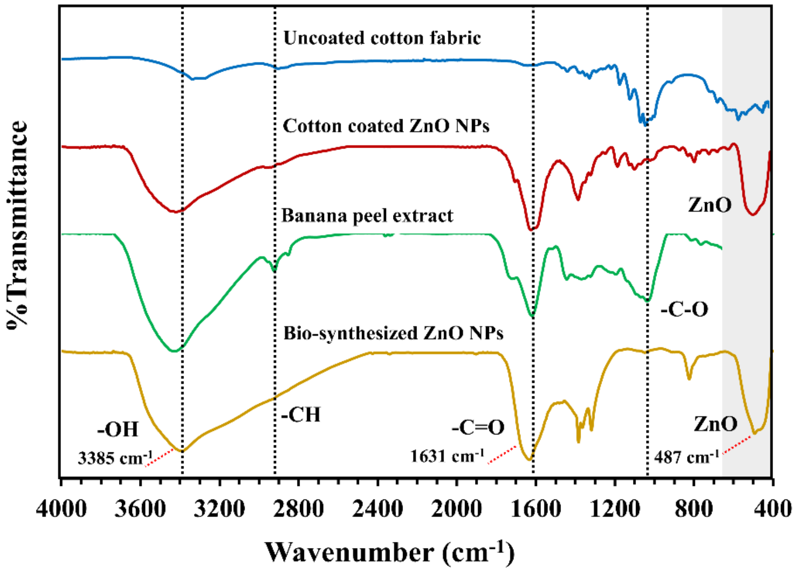

Figure 6 FTIR spectrum of banana peel extract, bio-synthesized ZnO NPs, uncoated cotton fabric, and cotton fabric coated with bio-ZnO NPs, which were surveyed in the range of 4,000 to 400 cm^{-1}.

Figure 7 illustrates the schematic diagram of the format used for coating ZnO NPs on the cotton fabric surface and the proposed mechanism. Ammonium hydroxide was used to maintain the solution in an alkaline state while coating cotton fabrics. Moreover, the experiments were conducted at a pH of 8. Here, NH_4OH is assumed to break down into NH_4^+ and OH^- ions, and the NH_4^+ ions that have the propensity to form a monolayer are subsequently adsorbed on ZnO NPs [54]. The ZnO NPs are deposited into the cotton fabric using either hydrogen bonding or high impact [55]. Wang, Muhammed, Sherif, and Via observed similar NH_4^+ adsorption phenomena [56,57]. As shown in the schematic illustration of the mechanism, it is expected that the nanoparticles scattered ultrasonically across the medium will form high-speed microjets in the form of bubbles, which will collapse on the cellulose fibers and bond uniformly. The coating can be attributed to hydrogen bonding or severe impact. The coating may result from hydrogen bonding or strong impact [58]. If the nanoparticles collapse later, they can be pushed toward the fiber, thereby strengthening the coated layer.

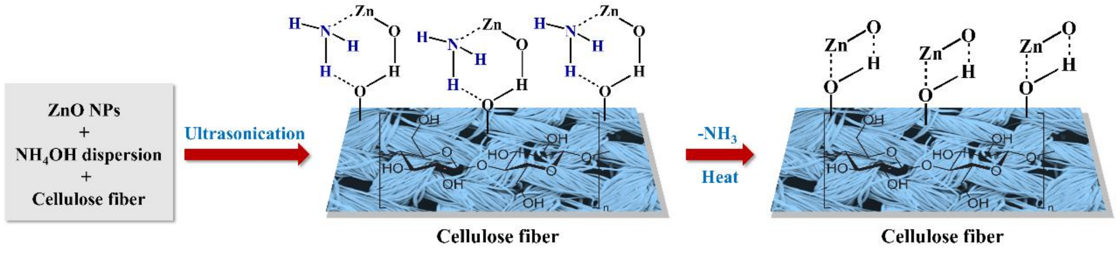

Figure 7 Schematic diagram of the format used for coating ZnO NPs on the cotton fabric surface and the proposed mechanism.

Antibacterial activity analysis

The antibacterial activity of bio-synthesized ZnO NPs and coated cotton fabric against *S. aureus* and *E. coli* bacteria was evaluated by the agar well diffusion method. The findings are displayed in **Figure 8**, which shows the inhibition zone (mm) of ZnO NPs at 1,000 and 2,000 ppm versus commercial ZnO. Moreover, the banana peel extract exhibited inhibition zones against both *S. aureus* and *E. coli*, with diameters of 39.24 ± 2.18 and 27.46 ± 2.26 mm, respectively. The antibacterial activity of ZnO NPs at 2000 ppm presented a clear zone against *S. aureus* bacteria with diameters of 27.48 ± 1.46 mm. However, no inhibition zone was observed against *E. coli* bacteria. Furthermore, the smaller size of the bio-synthesized ZnO NPs results in no bacterial inhibition zone when compared to the antibacterial activity of commercial ZnO NPs [59]. The antibacterial activity of ZnO NPs mechanisms was described as below.

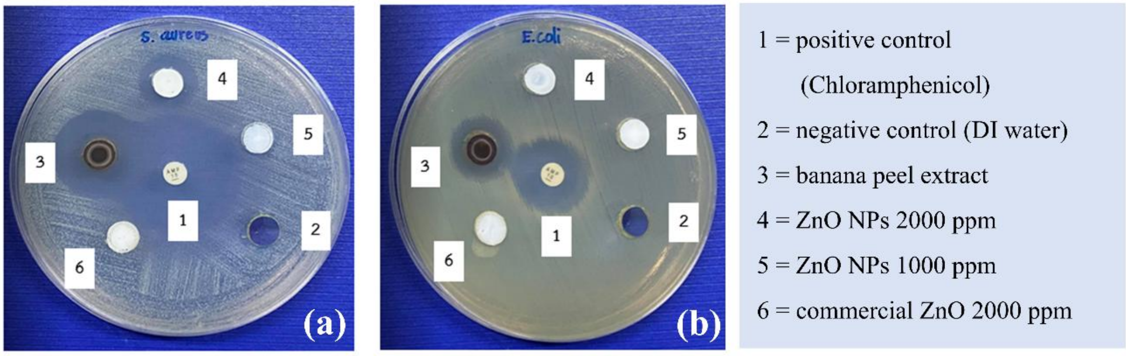

Figure 8 Zone of inhibition of positive control, negative control, pure ZnO NPs 1,000 and 2,000 ppm versus commercial ZnO against (a) *S. aureus* and (b) *E. coli* bacteria.

As depicted in **Figure 9**, uncoated cotton fabric does not exhibit an inhibition zone. However, after coating ZnO nanoparticles on the cotton fabric, a strong zone of inhibition was observed against *S. aureus* bacteria with diameters of 26.17 ± 1.12 mm. This implies that ZnO nanoparticles act as antibacterial agents.

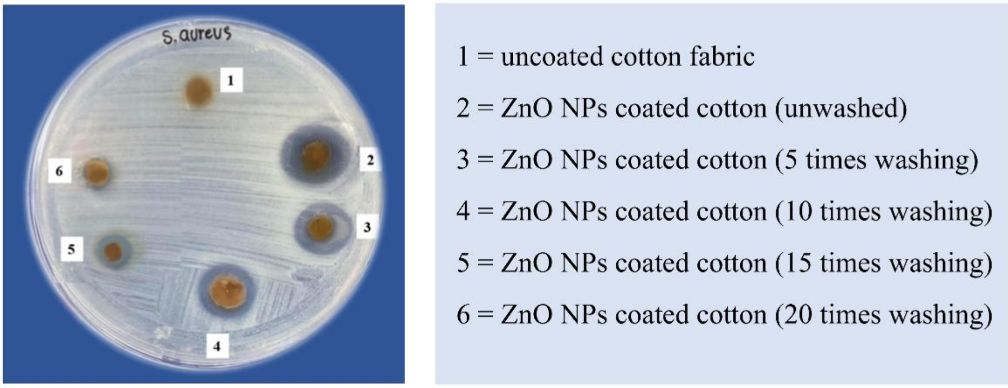

Figure 9 Zone of inhibition of uncoated cotton fabric, ZnO NPs coated cotton before washing and after washing 5 - 20 times.

Additionally, the antibacterial activity of ZnO NPs-coated fabrics was analyzed after 20 wash cycles, which were tested every 5 washes. Notably, the cotton fabrics containing ZnO NPs were effective against *S. aureus* bacteria. Furthermore, it successfully retains its antibacterial properties even after washing. Nevertheless, the antibacterial efficacy drops after 5, 10, 15, and 20 washes as compared to before washing. However, the antibacterial effect remains after twenty washes. The antibacterial mechanism of ZnO NPs can be analyzed by assessing the specific binding of the agent's surface to a microorganism and the subsequent metabolism of the agent within the microorganism [60].

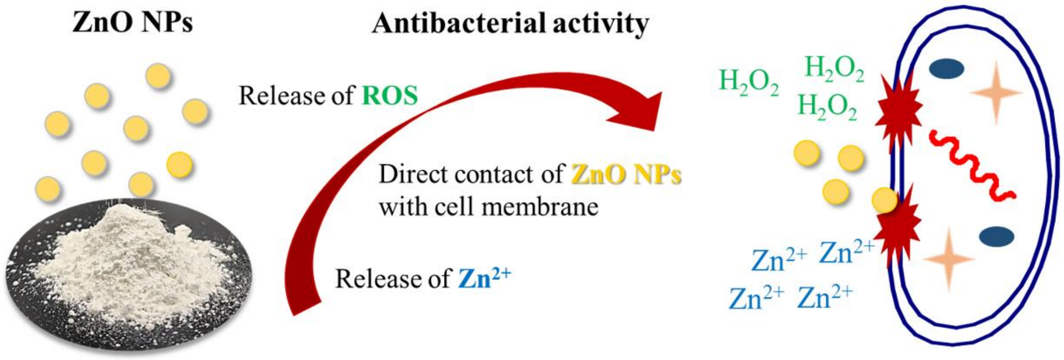

Figure 10 Basic mechanism of antibacterial activity of ZnO nanostructures.

According to previous reports, ROS provides the main mechanism underlying nano-toxicity [61]. **Figure 10** demonstrates the production of ROS by ZnO nanostructures [62] and the release of Zn^{2+} ions [63], which weaken the cell wall and cause cell death. Notably, the ZnO nanostructures produce electron-hole pairs when exposed to visible or ultraviolet light. These photogenerated holes separate water molecules into OH^- and H^+ ions from zinc oxide suspensions. The reduction of dissolved oxygen species results in superoxide anions ($\bullet O^{-2}$), which subsequently combine with H^+ to form ($HO_2\bullet$). These subsequently produce hydrogen peroxide (H_2O_2) molecules when they collide with hydrogen ions and predominant charge carriers (e^-). The hydrogen peroxide molecules that are produced can penetrate the cytoplasmic membrane and destroy the bacterial cells [64]. The ROS more effective against Gram-positive bacteria (*S. aureus*) because *S. aureus* bacteria have a thick (20 - 80 nm) peptidoglycan layer, which lacks an outer membrane. This means ROS can easily diffuse and penetrate the bacterial membrane. Whereas, gram-negative bacteria (*E. coli*) have a thin peptidoglycan layer (7 - 8 nm) but are protected by an outer lipid membrane, which acts as a barrier to ROS diffusion [65].

Ultraviolet protection factor tests

The effectiveness of ZnO-coated cotton in ultraviolet (UV) blocking was confirmed using UV protection factor (UPF) calculations, achieving a nearly full UV blocking capability. **Table 1** displays UPF classifications and levels of relative transmittance and protection [66]. **Table 2** lists the UPF UV range values for the ZnO-coated samples and control cotton fabric. The transmission spectra of the cotton fabric coated with bio-synthesized ZnO NPs demonstrated excellent protection from UV radiation, providing high UV protection (UPF = 76.82 > 50). Meanwhile, uncoated cotton exhibited insufficient protection with a UPF value of 7.58 ± 0.72. The UV protection performance of coated fabrics maintained remarkable UV protection performance even after 5 to 20 washing cycles.

Table 1 UPF classifications and levels of relative transmittance and protection (Standard AS/NZS 4399:1996).

UPF range	Protection category	Effective UVB Transmission (%)
< 15	Insufficient protection	> 6.7
15 - 24	Good protection	6.7 - 4.2
25 - 39	Very good protection	4.1 - 2.6
40 - 50 and 50+	Excellent protection	≤ 2.5

Table 2 UPF values for untreated and treated fabric.

Samples	UPF* (± SD) value	Protection value
Uncoated cotton fabric	7.33 ± 0.58	Insufficient protection
ZnO NPs coated cotton (unwashed)	82.67 ± 1.53	Excellent protection
ZnO NPs coated cotton (5 times washing)	65.33 ± 1.34	Excellent protection
ZnO NPs coated cotton (10 times washing)	52.29 ± 1.24	Excellent protection
ZnO NPs coated cotton (15 times washing)	35.67 ± 1.23	Very good protection
ZnO NPs coated cotton (20 times washing)	27.78 ± 0.98	Very good protection

Conclusions

In conclusion, this study presents the successful synthesis of zinc oxide (ZnO) nanoparticles using banana peel extract (BPE) as a natural reducing agent, thereby demonstrating a sustainable and eco-friendly approach to nanotechnology. The biosynthesized ZnO nanoparticles were applied to cotton fabrics, considerably improving their UV protection and antibacterial properties. Notably, the coated fabrics achieved excellent UV blocking, retaining effectiveness even after 20 washing cycles, and effectively inhibited bacterial growth, such as *Staphylococcus aureus* and *Escherichia coli*. The findings from this study underscore the potential of utilizing agricultural waste in functional textile development, thus presenting a cost-effective and environmentally conscious solution. Thus, this study contributes to the advancement of green chemistry and sustainable materials, with promising applications in healthcare, protective clothing, and eco-friendly textiles. Future work should focus on exploring scalability and broader material applications.

Acknowledgements

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