Multifunctionality of Layered Fabric Systems Based on Electrospun Polyurethane/Zinc Oxide Nanocomposite Fibers

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ABSTRACT: To examine the feasibility of developing multifunctional textiles, layered fabric systems with electrospun polyurethane/zinc oxide nanocomposite fiber webs layered on cotton substrates were developed to impart UV-protection and antibacterial functions. The morphology of polyurethane/zinc oxide nanocomposite fibers was examined using a field-emission scanning electron microscope and a transmission electron microscope. UV transmission properties were assessed for layered fabric systems with various levels of electrospun web area density. Antimicrobial properties of zinc oxide nanocomposite fibers and layered fabric systems were evaluated qualitatively using the Parallel Streak method, and quantitatively by measuring the bacterial reductions of a Gram-positive bacterium (*Staphylococcus aureus*) and a Gram-negative bacterium (*Klebsiella pneumoniae*). A thin layer of electrospun zinc oxide nanocomposite fiber web significantly reduced the transmission of UV radiation and exhibited an ultraviolet protection factor of greater than 50, indicating excellent UV protection. Layered fabric systems with zinc oxide nanocomposite fiber webs containing 5 wt % zinc oxide exhibited over 98% reduction in both *Staphylococcus aureus* and *Klebsiella pneumoniae*. The results show that the successful imparting of multifunctionalities such as UV-protection and antibacterial functions to cotton fabrics is achievable through simultaneous electrospinning of the polymer material with zinc oxide nanoparticles. J Appl Polym Sci 114: 3652–3658, 2009

Key words: nanotechnology; nanocomposite; nanoparticle; multifunctionality; electrospinning

INTRODUCTION

Electrospinning is a fiber forming technique that uses electrostatic force to produce polymer fibers with diameters in the nanometer to micron range. The major advantage of the electrospinning process is that it can produce polymer fibers with diameters on the nanometer-scale through a simple process compared with traditional fiber forming methods. Nonwoven mats of electrospun nanofibers provide exceptionally high ratios of surface area to volume with very small pores, which makes them attractive for a wide range of potential applications, ranging from filter media to biomaterials, reinforced composites, sensors, and protective clothing.[1,2]

Another advantage of electrospinning is that additional functionalities can be imparted to polymer nanofibers by simultaneous spinning of the polymer material with a functional material.[3] Functionalized polymer nanofiber composite materials can be directly fabricated by electrospinning. Electrospun nanofibers can provide large surface areas to be functionalized; thus, it may be possible to achieve functionalities that are superior to those of conventional fibers with typical diameters of several microns.

Several studies[4,5] have incorporated nanoparticles into electrospun fibers to impart a functionality. Xu et al.[4] incorporated nanosilver particles into poly(L-lactide) (PLA) ultrafine fibers via electrospinning to impart antibacterial properties. Kim and Ahn[5] fabricated electrospun polystyrene/gold nanoparticle composite fibers. Electrospun nanofibers not only provide a large surface area for functionalization but also they are lightweight, ultrathin, and mechanically flexible.[6] Thus, nanostructures with desired properties could be achieved without significant increases in weight or thickness by incorporating functional materials into electrospun nanofibers.

Growing awareness of health and hygiene has increased the demand for functional clothing materials.[7] Cotton is a widely used textile material for outdoor sport and leisure in summer. However, lightweight cotton fabrics commonly worn in hot weather do not provide sufficient protection against UV radiation.[8] Textiles made of natural fibers such as cotton, which is highly moisture absorbent, is an excellent medium for the growth of microorganisms

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when perspiration, soil, and appropriate temperature are present.[9] Thus, imparting UV-protection and antimicrobial functions to cotton fabrics would be very useful for potential applications such as outdoor sport clothing and work clothing.

Zinc oxide has long been used as a UV-blocking agent for fabrics and personal care products such as sunscreens because of its nontoxicity.[10] Moreover, zinc oxide is an interesting multifunctional material that offers UV-shielding, antimicrobial, and antistatic properties, among others.[11–13]

The objective of this study is to examine the feasibility of imparting multifunctionalities, such as UV-protection and antimicrobial functions, to a textile material by applying zinc oxide nanoparticles using electrospinning. Zinc oxide nanoparticles are incorporated into polyurethane fibers to impart antimicrobial and UV-protection functions. Layered fabric systems with a very thin layer of functional nanocomposite fiber web layered on cotton substrates are developed, and the UV-protection and antimicrobial properties are assessed. Various concentrations of zinc oxide and web area densities are examined to optimize UV-protection and antimicrobial functions.

EXPERIMENTAL

Materials

Commercial-grade polyurethane pellets (Pellethane™, 2103-80AE, Dow Chemical Company) [Midland, MI] were used. *N,N*-dimethylformamide (DMF) (Junsei Chemical, Japan) was used as a solvent. Nanophase Technologies (Romeoville, IL) supplied zinc oxide particles with diameters between 24 and 71 nm. Electrospinning solutions were prepared by dissolving the polymer in DMF. Polymer solution concentration ranged from 10 to 15 wt % polymer in DMF. After complete dissolution, zinc oxide (ZnO) nanoparticles were added to the polymer solution under constant stirring. The resulting solution was then kept under constant agitation on a magnetic stirrer for 12 h.

To form a layered fabric system, a 100% cotton, lightweight, plain-weave fabric was used as a substrate. The cotton fabric has a thickness of 0.40 mm, a weight of 81.6 g/m^2, and a fabric count of 43×33 $(W \times F)$/in.

Electrospinning process

Electrospinning was performed in a horizontal electrospinning setup, which consists of a syringe with its needle, a precisely-controlled syringe pump (model 781100, KD Scientific), a high voltage power supply capable of 0–30 kV (NNC-30kV-2mA, NanoNC, Korea), and a grounded collector.

The ZnO/polyurethane solution was loaded into the syringe, and an electrode was clipped onto the needle. The syringe pump controlled a constant volumetric feed rate, which ranged from 0.2 to 0.6 mL/h. A high voltage of 10–20 kV was applied to the needle. The needle gauges used were 23 and 26 (0.34 and 0.26 mm i.d., respectively). As the applied voltage increased, a droplet at the needle tip deformed into a conical shape. When the voltage was sufficiently high, an electrically-charged jet was ejected from the tip. Fibers were laid down on the grounded collection plate, which was placed 10–15 cm from the tip, and formed a nonwoven web. Zinc oxide nanocomposite fibers were electrospun from DMF and deposited directly onto a cotton substrate to form a layered fabric system.

Fiber morphology

The morphology of electrospun polyurethane fibers and zinc oxide nanocomposite fibers was examined using a field-emission scanning electron microscope (FE-SEM) (Hitachi Model S-4200, Nissei Sangyo, Japan) after sputter-coating with Pt/Pd. The SEM micrographs were taken at magnifications of $\times$10,000.

A transmission electron microscope (TEM) (HR TEM 2100F, JEOL, Japan) equipped with an energy dispersive x-ray analysis system (EDX) was used to further characterize the morphology of ZnO nanocomposite fibers and examine the chemical composition of the fibers. For the preparation of TEM samples, the nanocomposite fibers were collected on a carbon coated copper specimen grid.

UV transmission properties

The transmission of UV rays through layered fabric systems and control fabrics was measured in accordance with the American Association of Textile Chemists and Colorists (AATCC) Test Method 183-2004, Transmittance or Blocking of Erythemally Weighted Ultraviolet Radiation through Fabrics. Measurements were carried out in the wavelength range from 280 to 400 nm in 2 nm steps using a UV/VIS/NIR spectrophotometer (Perkin-Elmer Lambda 950, PerkinElmer) equipped with an integrating sphere. Transmission was measured four times for each sample. The results are the mean value of these measurements.

Antimicrobial properties

The antimicrobial activities of ZnO nanocomposite fibers and the layered fabric systems were evaluated both qualitatively and quantitatively. The qualitative assessment was carried out according to AATCC Test Method 147-2004, Antibacterial Activity

Assessment of Textile Materials: Parallel Streak Method. In the Parallel Streak test, antimicrobial activity of a test material is determined by observing interruptions of growth along the streaks of inoculum underneath the test material and a clear zone of inhibition around the material. The quantitative assessment was performed in accordance with ASTM E 2149-01, Standard Test Method for Determining the Antimicrobial Activity of Immobilized Antimicrobial Agents Under Dynamic Contact Conditions. This test method is designed to evaluate the resistance of nonleaching antibacterial-treated specimens to the growth of microbes under dynamic contact conditions. The percent reduction of test organisms after a specified contact time with the specimen is measured using the following formula:

$$R\ (\%) = \frac{B - A}{B} \times 100 \qquad (1)$$

where R is the reduction rates in the number of colonies; A is the number of bacterial colonies for the flask containing treated fabrics after a specified contact time; and B is the number of bacterial colonies for the flask before the addition of treated fabrics.

For the qualitative and quantitative assessments of antimicrobial efficacy, *Staphylococcus aureus* (ATCC 6538, Gram-positive bacterium) and *Klebsiella pneumoniae* (ATCC 4352, Gram-negative bacterium) were used as representative microorganisms to challenge the antimicrobial functions of the electrospun zinc oxide nanocomposite fiber web.

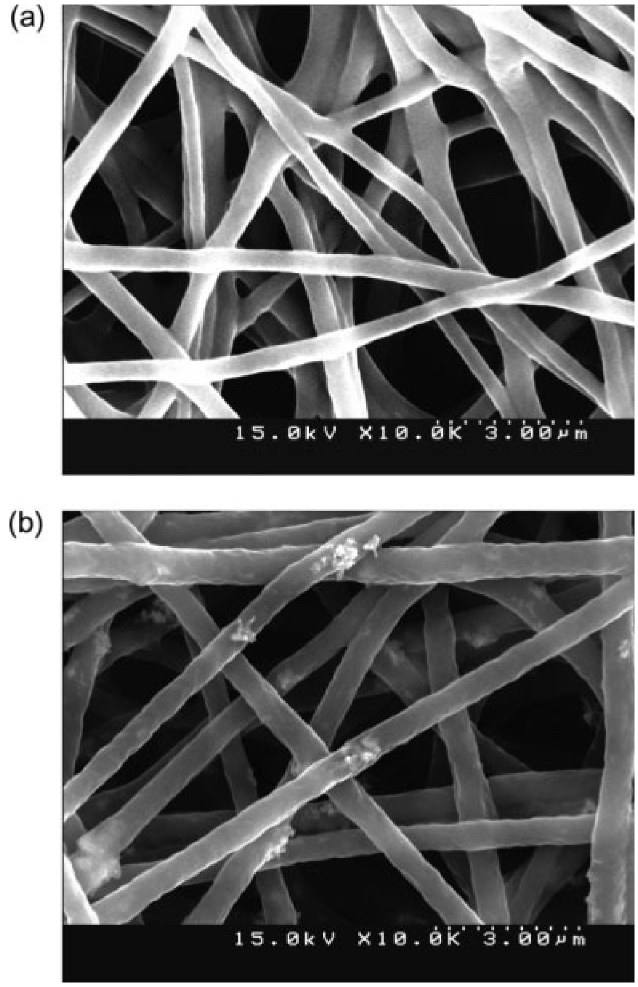

Figure 1 SEM micrographs of (a) electrospun polyurethane nanofiber web, (b) electrospun polyurethane/zinc oxide nanocomposite fiber web.

RESULTS AND DISCUSSION

Fiber morphology

On the basis of previous research,[14,15] polyurethane fibers were electrospun under various conditions to find optimum spinning conditions for our electrospinning setup. The conditions include different polyurethane solution concentrations, electric voltages, feed rates, collecting distances, and capillary diameters. Figure 1(a) shows electrospun polyurethane fibers obtained from a 13 wt % polyurethane solution with a 26-gauge needle at a feed rate of 0.2 mL/h, a voltage of 15 kV, and a collecting distance of 15 cm. These conditions yielded cylindrical fibers with diameters ranging from 300 to 600 nm.

Zinc oxide was incorporated into polyurethane fibers by the inclusion of zinc oxide nanoparticles in the electrospinning dope. Zinc oxide nanocomposite fibers were electrospun under a variety of spinning conditions to optimize spinning conditions. Figure 1(b) shows electrospun polyurethane/zinc oxide nanocomposite fibers obtained from a 13 wt % polyurethane solution containing 1 wt % ZnO nanoparticles. The fibers were fabricated with a 23-gauge needle at a feed rate of 0.6 mL/h, a voltage of 10 kV, and a collecting distance of 15 cm. Zinc oxide nanoparticles are clearly visible in the nanocomposite fibers in Figure 1(b). The diameter of the nanocomposite fibers ranged from 300 to 700 nm.

Figure 2 shows the TEM image and EDX spectrum of the electrospun polyurethane/zinc oxide nanocomposite fibers. Nanoscale zinc oxide particles are observed inside the nanocomposite fiber as well as on the surface of the fiber [Fig. 2(a)]. The EDX analysis of the nanocomposite fibers confirms the presence of zinc oxide in these fibers [Fig. 2(b)].

UV blocking of layered fabric systems

Layered fabric systems with electrospun ZnO nanocomposite fiber webs layered on cotton substrates were fabricated for the development of multifunctional material via electrospinning. Zinc oxide nanoparticles of 1 wt % were added to a 13 wt % polyurethane solution to impart multifunctionality.

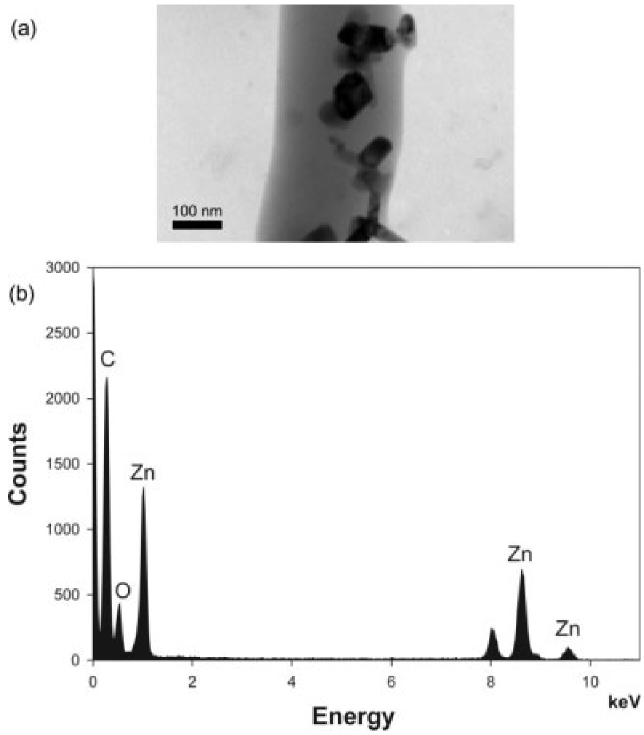

Figure 2 (a) TEM micrograph of electrospun polyurethane/zinc oxide nanocomposite fiber (b) EDX spectrum of electrospun polyurethane/zinc oxide nanocomposite fiber.

At the optimal spinning condition, polyurethane/ZnO nanocomposite fibers were electrospun directly onto a cotton substrate to form a layered fabric system. To examine the effect of nanocomposite fiber web area density on the UV-protective properties of layered fabric systems, nanocomposite fibers were electrospun onto cotton substrates over a range of web area densities. The UV-protective properties were then examined for the layered fabric systems.

Figure 3 shows the UV transmission spectra of layered fabric systems and control fabric. The UV profiles of the untreated fabric are compared to the spectra collected from those fabrics treated with ZnO nanoparticles. This comparison shows that the UV transmission was reduced considerably by electrospun ZnO nanocomposite fiber webs for both UV-A and UV-B regions.

The UV transmission data were used to calculate the blocking percentage of UV and the ultraviolet protection factor (UPF). The blocking percentage of UV was determined for UV-A (315–400 nm) and UV-B (280–315 nm) radiation from the transmission spectra of the samples. The UPF is widely adopted by the textile and clothing industry to denote the protective ability of a textile.[16] The UPF values were calculated according to the AATCC test method using the following equation:

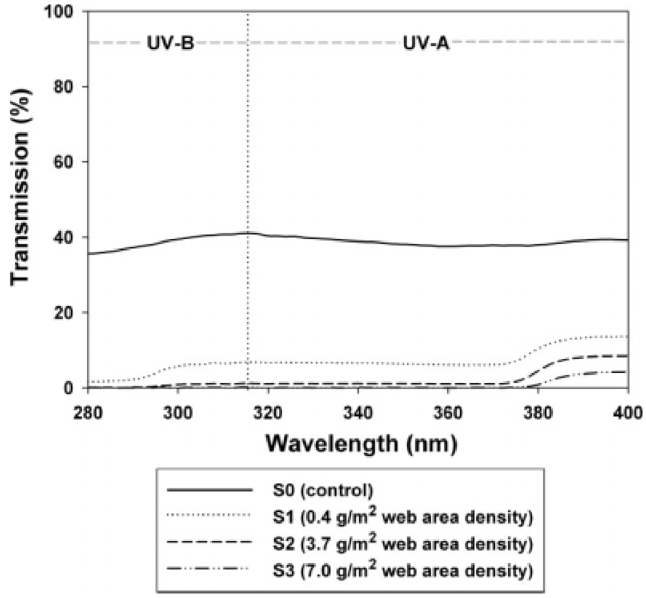

Figure 3 UV transmission spectra of layered fabric systems and control fabric.

$$\mathrm{UPF} = \frac{\sum_{\lambda=280}^{400} E_\lambda S_\lambda \Delta\lambda}{\sum_{\lambda=280}^{400} E_\lambda S_\lambda T_\lambda \Delta\lambda} \tag{2}$$

where E_λ is the relative erythemal spectral effectiveness; S_λ is the solar spectral irradiance (W/cm^2/nm); T_λ is the mean measured transmittance of the specimen (%); and $\Delta\lambda$ is the measured wavelength interval (nm).

Table I presents the blocking percentages for A-range ultraviolet (UV-A) and B-range ultraviolet (UV-B) radiation, and the UPF values of the layered fabric systems and control fabric. The table clearly shows that in both UV-A and UV-B regions, the UV blocking ability of layered fabric systems increased with increasing electrospun web area density of the zinc oxide nanocomposite fiber web.

The UPF value indicates the ability of a fabric to block UVR. The Australian/New Zealand (AS/NZ)

TABLE I
Blocking Percentages for UV-A and UV-B Radiation, and UPF Values of Layered Fabric Systems and Control Fabric

Sample code	ZnO concentration (wt %)	Web area density (g/m^2)	UV-A[a] (%)	UV-B[b] (%)	UPF[c]
S0	0	0	62.6	63.4	3
S1	1	0.4	97.1	95.6	15
S2	1	3.7	97.7	99.6	50+
S3	1	7.0	98.8	100	50+

[a] UV-A (percent blocking for UV-A).
[b] UV-B (percent blocking for UV-B).
[c] UPF (Ultraviolet Protection Factor).

standard establishes a system for classifying fabrics according to their sun-protective properties.[17] Fabrics with UPF values of 40–50 and above block greater than 97.5% of UVR and are classified in the Excellent UV protection category. Fabrics with UPF values greater than 25 but less than 40 block from 96.0 to 97.4% of UVR and are classified in the Very Good UV protection category. Finally, fabrics with UPF values higher than 15 but less than 25 block from 93.3 to 95.9% of UVR and are classified in the Good UV protection category. A textile must have a UPF of at least 15 to be rated as UV-protective.[16]

Table I shows that the initial UPF value of the untreated fabric is 3, indicating that it offers little protection against UV radiation. A very thin layer of ZnO nanocomposite fiber web significantly improved the UV-protective properties of the cotton substrate. According to the UPF rating of the AS/NZ 4399 standard,[17] layered fabric systems with nanofiber webs containing 1 wt % ZnO nanoparticles at 3.7 g/m^2 web area density and at 7.0 g/m^2 web area density provide excellent UV protection with UPFs of greater than 50. In the case of the cotton substrate used for this study, the use of 1 wt % ZnO nanoparticles at 3.7 g/m^2 web area density is sufficient to impart the UV-blocking property to the layered fabric systems.

Antimicrobial properties of layered fabric systems

Natural fibers are more susceptible to microbial attack than synthetic fibers.[7] Cotton is very absorbent, which makes cotton more prone to microbial attack since soil and perspiration offer ideal living conditions for microbes. Unlike synthetic fibers into which functional materials can be incorporated during the spinning process to impart desired properties, it is difficult to impart functionalities to the natural cellulose fibers of cotton, as it must be done in conventional finishing processes. In this study, an electrospinning technique was applied as one approach to impart multifunctionalities, including antimicrobial properties, to a textile material.

First, antibacterial activity of electrospun polyurethane fiber webs with ZnO nanoparticles was evaluated qualitatively according to AATCC 147-2004, Parallel Streak Method to verify the antimicrobial activity of ZnO nanocomposite fibers. *Staphylococcus aureus* was used as a representative Gram-positive organism, and *Klebsiella pneumoniae* was used as a representative Gram-negative organism. In the Parallel Streak test, five streaks of a test bacterium are inoculated onto a nutrient agar plate. The specimen is placed in intimate contact with the agar previously streaked with the inoculum of the test bacterium. The plate is then incubated at a temperature of 37°C for 24 h. After the incubation, a clear area of

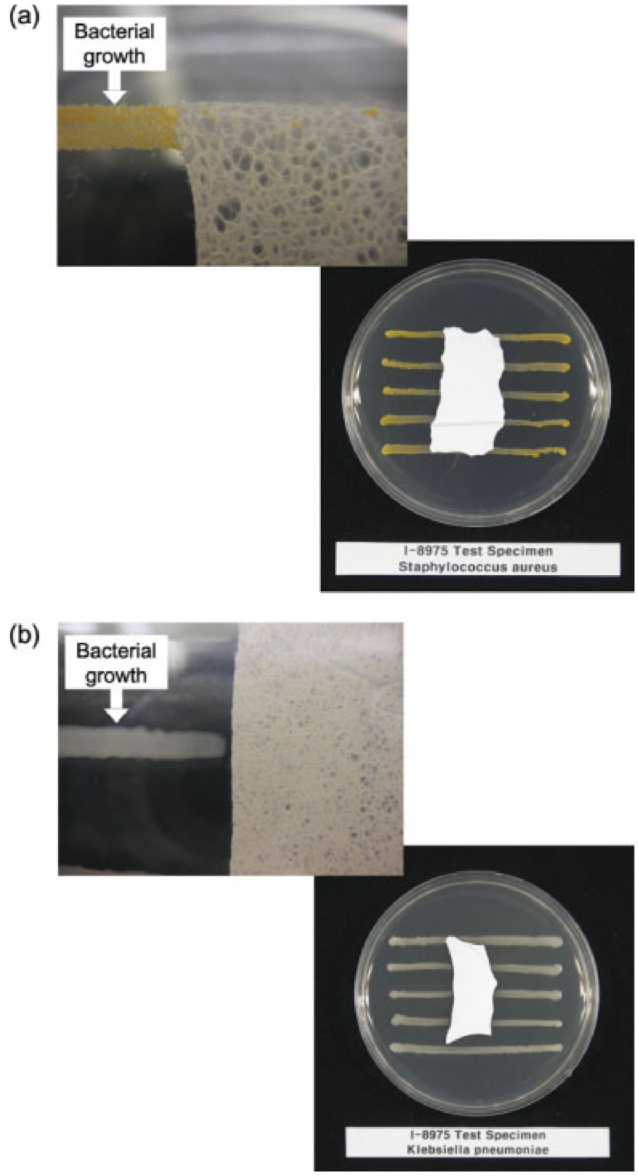

Figure 4 Antimicrobial activity of electrospun polyurethane/zinc oxide nanocomposite fibers: (a) 5 wt % ZnO (5.0 g/m^2 web area density) against Staphylococcus aureus; (b) 5 wt % ZnO (7.0 g/m^2 web area density) against *Klebsiella pneumoniae*. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

interrupted growth underneath the test specimen and along the sides of the specimen (zone of inhibition) indicates the antimicrobial activity of the specimen.

Polyurethane/ZnO nanocomposite fibers containing 1–10 wt % of zinc oxide nanoparticles were fabricated with a range of web area densities and assessed for antibacterial activity. Figure 4(a,b) present the antibacterial activity of electrospun polyurethane webs containing ZnO nanoparticles against *Staphylococcus aureus* and *Klebsiella pneumoniae*,

TABLE II
Antibacterial Activity of Layered Fabric Systems

Sample code	ZnO concentration (wt. %)	Web area density (g/m^2)	Reduction rate of bacteria (%)	
			Staphylococcus aureus	*Klebsiella pneumoniae*
S0	0	0	NR	NR
S3	1	7.0	99.9	60.0[a]
S4	5	7.0	99.9	98.7

[a] NR (no reduction).

respectively. The bottom right pictures in Figure 4(a,b) show five streaks of the test bacterium over which the specimen is laid after incubation at 37°C for 24 h. As shown in the enlarged pictures [see upper left in Fig. 4(a,b)], the growth of both *Staphylococcus aureus* and *Klebsiella pneumoniae* was found surrounding the specimens, but there was no bacterial growth underneath the polyurethane/ZnO nanocomposite specimens for both microorganisms. Although there was no distinct zone of inhibition beyond the sample edge, interruption of bacterial growth in the streaks of inoculum beneath the sample where there was direct contact of microbes with the specimens clearly shows the presence of antibacterial activity of ZnO nanocomposite fibers against both Gram-positive and Gram-negative bacteria.

Following the qualitative assessment of antimicrobial activity of ZnO nanocomposite fibers, antimicrobial activity was assessed quantitatively for layered fabric systems with electrospun polyurethane/ZnO nanocomposite fiber webs layered on cotton substrates in accordance with ASTM E 2149-01. On the basis of qualitative analysis, layered fabric systems with ZnO nanocomposite fibers containing 1 and 5 wt % of zinc oxide were fabricated with a web area density of 7.0 g/m^2. Table II presents the antibacterial activity of layered fabric systems as a percentage of bacterial reduction. Layered fabric systems with electrospun polyurethane webs containing 1 wt % ZnO nanoparticles at 7.0 g/m^2 web area density exhibited a 99.9% reduction in *Staphylococcus aureus*. However, the same system exhibited only a 60.0% reduction in *Klebsiella pneumoniae*. As the ZnO concentration increased to 5 wt %, layered fabric systems with polyurethane/ZnO nanocomposite fibers showed a 99.9% reduction in *Staphylococcus aureus* and a 98.7% reduction in *Klebsiella pneumoniae*. On the basis of the results, the use of 5 wt % ZnO nanoparticles is recommended to impart antimicrobial properties against both *Staphylococcus aureus* and *Klebsiella pneumoniae*.

Antimicrobial substances differ in the mechanisms through which the treated textiles are rendered resistant to biological attack.[18] Antimicrobial agents of a leaching variety function by a controlled release mechanism. A leaching antimicrobial is released at a rate adequate for killing or inhibiting microbial growth on the fabric. The Parallel Streak method determines the antimicrobial activity of diffusible antimicrobial treated textiles by the presence of a clear zone of inhibition around the specimen, which occurs as a result of the diffusion of the antimicrobial agent from the specimen. On the other hand, antimicrobial agents of a nonleaching type are not free to diffuse into their environment. Thus, the antimicrobial activity of these agents is dependent on direct contact with microbes. Such nonleaching antimicrobial agents function by a barrier or blocking mechanism. The ASTM E 2149, a quantitative procedure for the evaluation of the degree of antibacterial activity, determines the antimicrobial activity of treated textiles by shaking the samples of a nonleaching antimicrobial in a bacterial suspension for a specified contact time while ensuring good contact between the bacteria and the treated textiles, and then measuring the reduction of the organisms that results from contact with the specimen.

The quantitative and qualitative assessments of the antimicrobial activity of ZnO nanocomposite fiber webs and the layered structures present the possibility that the antimicrobial mechanism of zinc oxide acts as a barrier. Layered fabric systems with electrospun polyurethane/ZnO nanocomposite webs exhibited high rates of reduction in the number of colonies of both *Staphylococcus aureus* and *Klebsiella pneumoniae* when tested under dynamic contact conditions (Table II). The Parallel Streak procedure also showed no bacterial growth directly underneath the fabric samples (Fig. 4). However, there was no distinct zone of inhibition found surrounding the samples. This implies that the antimicrobial agent functions by direct contact of microbes with the treated textiles, rather than by the diffusion of the agent into its environment. The advantage of nonleaching antimicrobial agents is that the treated textiles show high durability and may not cause any health problems.[19]

Additionally, simultaneous application of zinc oxide and silver nanoparticles onto cotton fabric via electrospinning was attempted to compare the antimicrobial activity. Although silver nanoparticles are more costly than ZnO nanoparticles, silver has been reported as an effective antibacterial agent.[4] Nanomix™ (silver nanoparticles less than 10 nm in diameter; ethanol based) was provided by Nanopoly, Korea. Silver nanoparticles were added to the ZnO/polyurethane solution under constant agitation. Multi-component composite fibers containing ZnO nanoparticles and silver nanoparticles were electrospun and deposited onto a cotton substrate. For antimicrobial activity, layered fabric systems with electrospun polyurethane webs containing 1 wt % ZnO nanoparticles and 0.5 wt % silver nanoparticles at 7.0 g/m^2 web area density showed a 99.9% reduction in *Staphylococcus aureus* and a 98.8% reduction in *Klebsiella pneumoniae*. This implies that the use of 0.5 wt % silver nanoparticles was sufficient to inhibit the growth of *Staphylococcus aureus* and *Klebsiella pneumoniae*. The layered fabric systems exhibited 99.9% of UV blocking for UV-A and 98.8% of UV blocking for UV-B, which might be due to the application of ZnO nanoparticles.

The results indicate that the use of 5 wt % ZnO nanoparticles at a web area density of 7.0 g/m^2 is recommended to impart sufficient antimicrobial and UV-protection functions when developing multifunctional textiles using a single additive, zinc oxide. If multiple additives, i.e., zinc oxide and silver nanoparticles, are used to impart antimicrobial and UV-protection functions, the use of 1 wt % ZnO nanoparticles and 0.5 wt % silver nanoparticles would be sufficient to impart multifunctionalities.

CONCLUSIONS

This study examined the application of zinc oxide nanoparticles to cotton fabrics via electrospinning for the purpose of imparting multifunctionalities, such as UV-protection and antibacterial functions. Layered fabric systems with electrospun polyurethane/ZnO nanocomposite fiber webs were developed by electrospinning a polyurethane solution that contains zinc oxide nanoparticles onto a cotton substrate over a range of web area densities.

A very thin layer of electrospun ZnO nanocomposite fiber web significantly reduced the transmission of UVR and exhibited a UPF rating of greater than 50, which indicates excellent UV protection. In the case of the cotton substrate used for this study, the use of 1 wt % ZnO nanoparticles at a web area density of 3.7 g/m^2 imparted sufficient UV blocking to the layered fabric systems. Layered fabric systems with zinc oxide nanocomposite fiber webs containing 5 wt % zinc oxide exhibited over 98% reduction in both *Staphylococcus aureus* and *Klebsiella pneumoniae*. Antibacterial and UV-protection functions were successfully imparted to cotton fabric by electrospinning of the polymer material with zinc oxide nanoparticles. Simultaneous application of zinc oxide and silver nanoparticles onto cotton fabric via electrospinning was also attempted. Layered fabric systems with electrospun polyurethane webs containing 1 wt % ZnO nanoparticles and 0.5 wt % silver nanoparticles at 7.0 g/m^2 web area density showed over 98% reduction in *Staphylococcus aureus* and *Klebsiella pneumoniae*.

This study demonstrated that functional nanostructures with tailor-made properties can be developed by the electrospinning of mixtures of polymers and functional materials, which is a relatively simple method in comparison to other conventional processes. This result opens the door for diverse possibilities in the preparation of new materials with desired functionalities in various fields and expands the potential applications of electrospun materials.

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