

Article

Development and Evaluation of Antimicrobial Hospital Apparel Incorporating Copper Nanoparticles: Upscaling, Durability, and Hospital Assessment

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Abstract

Healthcare-associated infections (HAIs) remain a major challenge in clinical environments, where textiles frequently act as reservoirs for pathogenic bacteria. This study reports the development, upscaling, and hospital validation of antimicrobial hospital apparel incorporating copper nanoparticles (CuNPs) embedded within polyamide-6 core–sheath bi-component filaments. A CuNP–polyamide masterbatch was produced through ultrasound-assisted melt extrusion and processed into continuous filament yarns under varying draw conditions. Filaments drawn at 1500 m/min exhibited uniform nanoparticle distribution, improved sheath exposure, and suitable mechanical properties for weaving. The optimized yarns were incorporated into woven narrow fabrics and integrated into prototype medical coats. Antimicrobial assays demonstrated >90% inhibition of *S. aureus* and 70% inhibition of *P. aeruginosa*. Durability testing showed minimal activity loss after 10 laundering cycles and no significant decline after up to 200 abrasion cycles. Cytotoxicity evaluation confirmed high fibroblast viability (97%), supporting the biocompatibility of the materials. In a hospital field trial, antimicrobial uniforms achieved substantial reductions in microbial burden, particularly at sleeve cuffs (30% total bacteria, 55% Gram-positive, 70% Gram-negative). It was demonstrated that intrinsically antimicrobial CuNP-embedded textiles offer a durable and safe strategy for reducing bacterial contamination in healthcare apparel and improving infection-control practices.

Keywords: copper nanoparticles; antimicrobial textiles; core–sheath bicomponent filaments; ultrasound-assisted extrusion; medical coats



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1. Introduction

Healthcare-associated infections (HAIs) are among the most significant challenges in current healthcare systems. They are responsible for extended hospital stays, increased healthcare costs, long-term disability, preventable deaths, and massive costs for the health systems of various countries. The World Health Organization (WHO) estimates that 10% of hospitalized patients of high-income countries suffer from at least one HAI; the percentage increases to 20% in low- and middle-income countries [1,2]. HAIs are caused by pathogens present in healthcare units that can survive for extended periods on medical devices, textiles [3], and any surfaces. Among the most frequent are *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa* [4,5]. In particular, the uniforms of healthcare workers have been identified as reservoirs for pathogen transmission [6], where microbial loads increase during a shift [7,8].

To mitigate this risk, antimicrobial textile treatments using both organic and inorganic agents have gained considerable attention [9–13]. In the first case, quaternary ammonium compounds, triclosan, and chitosan have been proposed [14]. In the latter, metal-based nanomaterials have demonstrated superior durability and a broader antimicrobial spectrum, particularly under the repeated laundering and abrasive conditions typical of hospital use [15,16].

Metallic NPs have become effective tools for combating bacteria resistant to conventional antibiotics [17]. In addition, bacteria find it difficult to develop resistance to NPs because they can simultaneously target multiple cellular pathways, including disruption of cell membranes, generation of reactive oxygen species, and binding to microbial proteins and nucleic acids [18,19]. Among the most studied metal-based nanoparticles for their antimicrobial performance are silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnO), titanium dioxide nanoparticles (TiO₂), and copper nanoparticles (CuNPs). AgNPs exhibit strong antimicrobial properties; however, their high cost, potential toxicity, and bacterial resistance have hindered their long-term application [20–22]. ZnO and TiO₂ nanoparticles also exhibit antimicrobial effects; however, their antimicrobial activity depends on their photocatalytic activity, and hospital lighting can limit their effectiveness in hospital environments [23,24]. On the other hand, CuNPs represent a cost-effective alternative that combines strong antimicrobial activity with very low toxicity, ensuring safe use in consumer and medical applications [25–27].

Copper nanoparticles have been integrated into textile filaments via surface coating, inkjet printing, sol–gel treatments, and direct incorporation into polymer matrices during filament spinning [28–33]. Direct incorporation of CuNPs during melt extrusion is expected to offer superior durability, since the nanoparticles are embedded within the textile filament structure and can reduce leaching during laundering. Nonetheless, challenges such as nanoparticle dispersion, industrial-scale filament processability, long-term mechanical properties, and validation of antimicrobial activity under real-use conditions remain.

The ACTIn (Antimicrobial Textiles for the Healthcare Sector) project was established through a UK–México collaboration to address these challenges. Within this framework, CuNPs were incorporated into Polyamide-6 filaments using a core/sheath bicomponent extrusion process, optimized under different drawing conditions to enhance nanoparticle localization in the sheath and maximize antimicrobial activity. The filaments were then textured, used for woven narrow fabrics, and incorporated into prototype hospital apparel. Finally, the apparel underwent standardized durability tests (washing and abrasion) and was evaluated in a clinical setting at the Hospital Regional de Alta Especialidad del Bajío in León, México.

This work presents the development of antimicrobial apparel from nanoparticle dispersion to hospital validation. The objectives were to: (i) optimize filament yarn extrusion

and textile fabrication processes, (ii) evaluate the durability of the antimicrobial effect under laundering and abrasion, and (iii) validate the antimicrobial effectiveness of hospital apparel during routine use.

2. Materials and Methods

2.1. Materials

Copper nanoparticles (CuNPs) (57 wt% metallic copper in isopropanol) were provided by Promethean Particles Ltd. (Nottingham, UK), with a particle size < 100 nm and semi-spherical morphology. Polyamide-6 (Zytel 7301, DuPont, Wilmington, DE, USA) was used as the filament-forming polymer, characterized by an intrinsic viscosity of 150 g/dL, a melting point of 225 °C, and a melt flow index of 5 g/10 min at 260 °C (2.16 kg). Polyester yarns (AKRA Polyester, Monterrey, México; 180 dtex, 48 filaments, semi-dull luster) were used as warp in woven narrow fabrics.

2.2. Methods

2.2.1. Masterbatch Fabrication

Previous studies in the literature suggest using copper concentrations of 0.6–5 wt% [34]. Furthermore, in a previous study by our group [35], different concentrations of CuNPs (0.5–5 wt%) were used in PP/Cu monofilaments against bacteria similar to those used in the current study. Based on these studies, a masterbatch with 3 wt% CuNPs was obtained by dispersing the nanoparticle suspensions into Polyamide-6 pellets, followed by variable frequency ultrasound-assisted melt extrusion [29] using a twin-screw extruder model Prism TSE 24-MC from Thermo Fisher Scientific (Karlsruhe, Germany) at 235 °C (screw speed 100 rpm, feed rate 3.5 kg/h). The extrudates were dried overnight at 115 °C to remove moisture, and then diluted with neat Polyamide-6 in the twin-screw extruder to achieve a final concentration of 2 wt% CuNPs for spinning filament yarns.

2.2.2. Filament Yarns Extrusion and Texturizing

Bi-component filaments with a core/sheath structure were produced using an FET-100 system (Fibre Extrusion Technology, Leeds, UK). The core was composed of pure Polyamide-6 while the sheath contained Polyamide-6 with 2 wt% CuNPs. Continuous filament yarns were extruded through an 18-hole spinneret (0.6 mm diameter, L/D = 0.4) at 240–260 °C and 60 bar.

The as-spun filaments were drawn at roller speeds of 300, 900, and 1500 m/min to investigate the influence of drawing on morphology and performance. It is expected that higher drawings will reduce filament diameter and increase the confinement of CuNPs within the sheath, thereby improving their exposure at the filament surface. Filament yarns obtained at 1500 m/min were selected as the optimal candidate for further processing. Texturizing was performed using a Barmag AFK machine, Pfäffikon, Switzerland (216 positions, heater length: 1.10 m, temperature: 160 °C, speed: 400 m/min, ceramic discs), resulting in yarns with enhanced resilience and improved weaving performance.

2.2.3. Narrow Fabric Weaving and Apparel Fabrication

The texturized filament yarns were woven into narrow fabrics using a shuttle Jacquard loom manufactured by Etiquetas R. Chavez (Estado de México, México). The warp consisted of twisted filament PET yarns, while the weft incorporated either Polyamide-6/CuNP filament yarn or neat Polyamide-6 (controls). A plain weave (taffeta 1/1) was selected. Woven narrow fabrics were prepared with different Polyamide-6/CuNP:PET ratios (40:60, 57:43, 67:33). The 57:43 ratio was identified as optimal and used for apparel fabrication.

Apparel prototypes were manufactured by Industrializadora Sharyl (Saltillo, Mexico). A total of 40 apparel items were produced: 20 incorporating antimicrobial narrow fabrics (in sleeve cuffs, pocket edges, and standard plackets) and 20 control items with narrow fabrics without an antimicrobial agent. The apparel, designed as hospital medical coats, were used in durability and hospital validation tests.

2.3. Characterization

2.3.1. Optical and Scanning Electron Microscopy

Optical microscopy images of control and antimicrobial filaments were obtained with transmitted light on a Carl Zeiss model PrimoStar microscope, Oberkochen, Germany. A FE-SEM (Field Emission Scanning Electron Microscope) JEOL model JSM-7401F, (Tokyo, Japan) was used to observe the CuNPs in the filaments with different magnifications coupled to an energy-dispersive X-ray spectroscopy (EDS) system. Samples were spun-coated with Au/Pt for 60 s, to ensure a good contrast.

2.3.2. Durability Testing Methods

The durability of the textile samples was evaluated using standardized laundering and abrasion tests to simulate real conditions and assess long-term performance:

Laundering durability was assessed according to the AATCC TM61-2013 [36] (Test Method 2A), established by the American Association of Textile Chemists and Colorists. Samples were laundered at 49 °C for 45 min, up to 20 cycles, to evaluate fastness and structural integrity under accelerated washing conditions.

Copper content in the woven fabrics before and after washing and in the residual water was determined using an ICP Thermo Jarrel Model 7400 Duo from Thermo Scientific (Beijing, China). For the woven fabrics, the samples were digested in 5 mL of H₂SO₄ on a hot plate at high temperature, then in 5 mL of HNO₃ at medium temperature. The resulting medium was filtered through Whatman No. 42 paper and brought to a final volume of 50 mL with deionized water. Residual water was only filtered. Additionally, the presence of copper ions was determined by UV-Vis spectroscopy using an UV-Vis Cary 60 equipment from Agilent (Santa Clara, CA, USA) in the range of 200–800 nm.

Abrasion durability was tested using a Taber Abraser, (Taber Industries, North Tonawanda, NY, USA) following the ASTM D4060-19 Standard Test Method [37] for Abrasion Resistance of Organic Coatings by the Taber Abraser, established by the American Society for Testing and Materials (ASTM International). The test was conducted using CS-10 abrasive wheels (Taber Industries, North Tonawanda, NY, USA) at 100, 150, and 200 cycles. This method quantifies surface wear by subjecting the fabric to controlled mechanical abrasion. After each treatment, the antimicrobial performance of the narrow fabrics was reassessed.

2.3.3. Antimicrobial Assays

Antibacterial activity of CuNPs, filaments, and fabrics was measured against *Staphylococcus aureus* (a Gram-positive bacterium, ATCC 6538) and *Pseudomonas aeruginosa* (a Gram-negative bacterium, ATCC 13388), which were all purchased from American Type Culture Collection (ATCC, Manassas, VA, USA). All samples were sterilized by ultraviolet germicidal irradiation at 254 nm for 30 min. Antibacterial activity of CuNPs was determined using CuNPs suspensions (100, 200, 400, and 800 µg/mL) prepared in PBS/Tween 80 buffer and sonicated for 2 min at 70% amplitude, and 1×10^5 bacteria/mL in LB broth. NPs and bacteria were mixed in equal volumes and incubated for 30 min at 37 °C. The bacteria were diluted, plated, incubated for 16 h, and counted. To determine the antibacterial activity of the filaments, 25 cm lengths of different types of filaments were placed on a microscope slide, and 1×10^5 bacteria were placed on the filaments and covered with a coverslip

in a humidified chamber. All samples were incubated for 1, 6, and 12 h at 37 °C. After incubation, 5 mL of sterile PBS solution was added to each sample and shaken. Bacteria were diluted, plated, incubated for 16 h, and counted. The fabric assays were assessed according to the AATCC 100 protocol. Briefly, circular swatches of both the woven narrow fabrics with Polyamide-6/CuNP:PET (test) and Polyamide-6/PET without CuNP (control) were placed in a Petri dish, inoculated with 4×10^4 bacteria, and incubated at 37 °C for 6, 12, and 24 h. After incubation, 5 mL of sterile PBS solution was added to the samples and shaken. Bacteria were diluted, plated, incubated for 16 h, and counted. For all the above assays, serial dilutions and LB agar platings were performed using the EasySpiralDilute (Interscience, Puycapel, Cantal, France). After 16 h of incubation, the colony-forming units (CFUs) were quantified using the Scan500 counter (Interscience, Puycapel, Cantal, France). The antimicrobial activity was determined by comparing the reduction in viable bacterial count in the test sample with that in the control sample and expressed as a percentage of antibacterial activity. The assays were performed in duplicate in three independent experiments (3 replicates).

2.3.4. Cytotoxicity Assays

Interaction of narrow fabrics with Polyamide-6 filaments and Polyamide-6/CuNP filaments with foreskin human fibroblast cells (HF BJ ATCC CRL-2522), purchased from American Type Culture Collection (ATCC, Manassas, VA, USA), was performed in 24-well plates containing ca. 5×10^6 cells per well. Glass beads were used to immobilize the narrow fabrics at the bottom of the well during the interaction with HF cells. Interaction assays were performed for 24 h in DMEM media at 37 °C with 5% (*v/v*) CO₂. After interaction, cells were detached with trypsin (Thermo Scientific, Waltham, MA, USA) and recovered in phosphate-buffered saline (PBS). Recovered HF cells were stained with Live/Dead fixable violet cell stain kit (Molecular Probes L34963, Thermo Scientific, Waltham, MA, USA) and processed under the supplier specifications. HF cell viability was determined by flow cytometry using a MoFlo XDP system (Beckman Coulter Life Science, Brea, CA, USA), collecting 50,000 singlet events, gating for total HF cells, and calculating the viability percentage of live cells after interaction with the narrow fabrics. As a mechanical damage control, fibroblast cells were placed under a circular piece of control fabric without CuNPs. With tweezers, the fabric was gently moved side-to-side 5 times and then incubated for 24 h. Cells were then analyzed by flow cytometry for viability as described for the engineered fabrics.

2.3.5. Hospital Validation Trial

Hospital validation was carried out at the Hospital Regional de Alta Especialidad del Bajío (León, México). Ethics approval was granted by the institutional review board of the Universidad de Guanajuato (CIBIUG-P38-2019) and the hospital's Research Ethics Committee (CI/HRAEB/2019/037).

A total of 40 physicians and residents participated. Twenty antimicrobial uniforms and twenty control uniforms were distributed and worn during six-hour morning shifts. Fabric samples were collected from cuffs, pockets, and standard plackets. Swatches were incubated in LB medium, and aliquots were plated on TSA (total bacteria), *Staphylococcus* agar (Gram+), and MacConkey agar (Gram−). After incubation for 24–48 h at 37 °C, CFUs were quantified using an EasySpiralDilute and Scan500 counter (Interscience, Saint Nom la Bretèche, France). Comparative bacterial loads were calculated between antimicrobial and control apparels.

2.3.6. Statistical Analysis

The data generated were analyzed using an analysis of variance (ANOVA). The means were compared using the Tukey–Kramer test to identify statistically significant differences.

The statistical analysis was performed with the aid of R (<http://r-project.org/> (accessed on 20 January 2023) Version 4.0.2) and JMT Pro13 jmp.com (accessed on 20 January 2023) statistical software.

3. Results

3.1. Antimicrobial Characterization of Copper Nanoparticles

The antibacterial activity of CuNPs was evaluated against *Staphylococcus aureus* and *Pseudomonas aeruginosa*. After 30 min in the presence of CuNPs, the bacteria were plated, incubated for 16 h at 37 °C, and the bacterial colonies were counted. The percentage of antibacterial activity was calculated. The CuNPs were more active against *P. aeruginosa* than *S. aureus* (Figure 1). To view the CFU count and plates, see the Supplementary Material (Table S1, Figure S1). These results confirm the strong antimicrobial activity of the CuNPs, in line with previously reported copper-based nanomaterials [38–40].

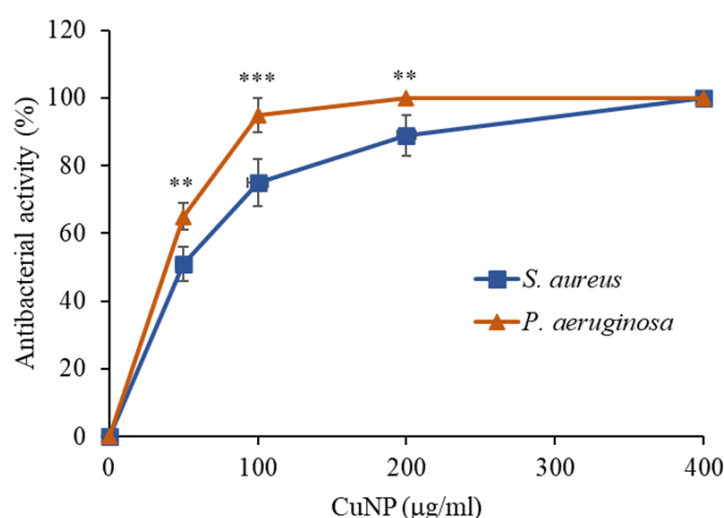


Figure 1. Antimicrobial activity of CuNPs against *S. aureus* and *P. aeruginosa*. Statistically significant differences at $p \leq 0.01$ (**) and $p \leq 0.001$ (***).

3.2. Bi-Component Filaments Characterization

Bi-component filaments with a 50:50 core/sheath configuration were produced using Polyamide-6 in the core and Polyamide-6 with 2 wt% CuNPs in the sheath. The extrusion process was stable for batch sizes of 1–2 kg; however, higher throughputs were occasionally limited by the partial accumulation of metallic particles in the spinneret.

Optical microscopy and scanning electron microscopy analysis revealed that filaments textured at low draw ratios (300 m/min) exhibited larger diameters (~120 µm) and heterogeneous nanoparticle distribution. In contrast, drawn filaments at 900 and, especially, 1500 m/min had smaller diameters (~70 µm), with a homogeneous sheath thickness and CuNPs uniformly dispersed, thereby increasing their surface exposure (Figure 2). Table 1 presents the diameter and the core-to-sheath ratio as a function of the roller speed. Non-drawn Polyamide-6 shows a diameter of ~435 µm, while the bi-component filaments show a diameter of ~380 µm. Moreover, it can be observed that the higher the drawing ratio (higher roller speed), the smaller the filament diameter for both samples, reaching ~30 and 70 µm, respectively, at 1500 m/min. Finally, the proportions of core and sheath are very close to the theoretical 50:50, suggesting that the conditions used to fabricate these filaments are optimal.

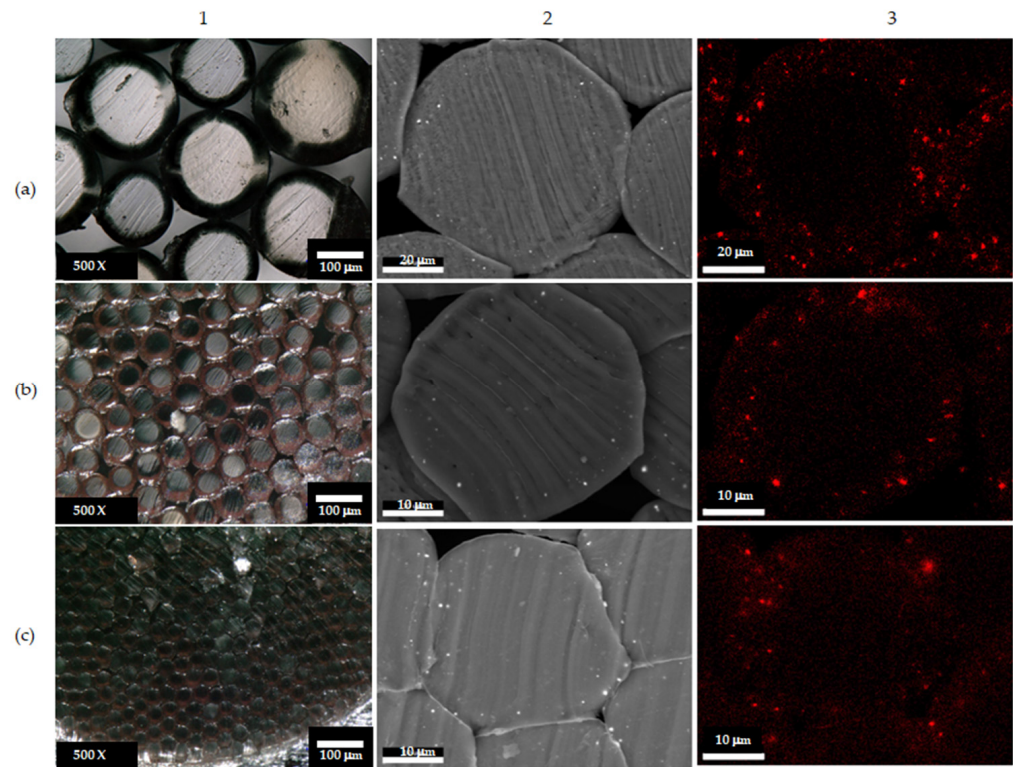


Figure 2. Optical microscopy (column 1), scanning electron microscopy (column 2), and its CuNPs distribution (red) (column 3) of bi-component core/sheath filaments drawn at different speeds (a) 300 m/min, (b) 900 m/min, and (c) 1500 m/min.

Table 1. Effect of the roller speed on the diameter size (μm) and core/sheath proportion (%) of Polyamide-6 and bi-component filaments.

Roller Speed, m/min	0		300		900		1500	
Diameter of Polyamide-6 filaments, μm	434.75		65.00		37.50		30.50	
Bi-component filament diameter, μm	382.47		124.92		71.53		68.65	
Configuration	Core	Sheath	Core	Sheath	Core	Sheath	Core	Sheath
Proportion, %	41	59	41	59	45	55	47	53

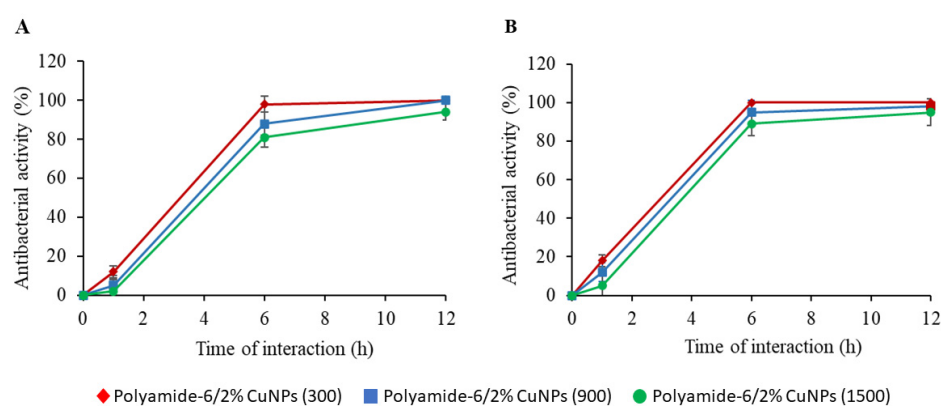
Decitex (dTex) is a unit of measurement used to determine the linear density of yarns, fibers, or filaments in textile production. Fabrics with yarns of high dTex/filament tend to be thick, sturdy, and durable, while fabrics with yarns of low dTex/filament tend to be sheer, soft, and silky. Table 2 presents the Total dTex and dTex/filament of the control yarns of Polyamide-6 drawn at 300, 900, and 1500 m/min roller speed, as well as the bi-component filaments drawn under the same conditions. It is expected that the higher the draw ratio, the lower Total dTex and dTex/filament. Comparing the Total dTex and dTex per filament of every couple of yarns drawn at the same roller speed, a significant change is observed for those filaments drawn at 1500 m/min, i.e., 138.5/7.70 versus 85.5/4.75 for Polyamide-6 and Polyamide-6/Cu 2 wt%, respectively. In the case of the Polyamide-6 filaments, very coarse filament thicknesses are obtained at low roller speeds, while coarse filaments are obtained at higher speeds. In the case of bi-component filaments, coarse filaments are obtained for 300 and 900 m/min, and medium-thickness filaments for 1500 m/min.

Table 2. Total dTex and dTex per filament of Polyamide-6 and bi-component filaments.

Sample	Polyamide-6 Filaments			Bi-Component Filaments		
Roller Speed, m/min	300	900	1500	300	900	1500
* Average mass of filament, g	0.6300	0.2067	0.1247	0.6337	0.1990	0.0770
Total dTex	700.0 (Very coarse)	229.7 (Coarse)	138.5 (Coarse)	704.1 (Very coarse)	221.1 (Coarse)	85.5 (Medium)
dTex/filament	38.89	12.76	7.70	39.12	12.28	4.75

* 3 filaments of 9 m length were weighed to obtain the average mass (g). Total dTex = mass (g) per 10,000 m of filament. The yarn has 18 filaments.

The antimicrobial activity of the filaments was assessed according to the AATCC 100 with *Staphylococcus aureus* and *Pseudomonas aeruginosa*. Filaments drawn at 300 m/min showed complete inhibition (>95%) (Figure 3). Filaments drawn at 900 m/min achieved nearly complete inhibition (90–95%), while those drawn at 1500 m/min showed significant improvement (85–90%) against both bacterial strains. The performance of bi-component filaments was comparable to or better than that of other antimicrobial filaments reported in the literature, such as AgNP- or ZnO-modified filaments, which typically achieve 80–99% inhibition [41,42]. Thus, all drawn bi-component filaments can be considered antimicrobial. An attempt was made to embroider the filaments; however, due to the demanding mechanical conditions, none of the yarns produced supported this process. Thus, it was decided to texturize the filament yarns and manufacture woven narrow fabrics that can be sewn to hospital medical coats. For this purpose, bi-component filament yarns drawn at a roller speed of 1500 m/min were selected for upscaling. Although they showed the lowest antimicrobial activity, they can still be considered as antimicrobial filaments and are less prone to elongation than the bi-component filaments produced at lower roller speeds.

**Figure 3.** Antimicrobial activity of bi-component filament yarns drawn at different roller speeds against (A) *S. aureus* and (B) *P. aeruginosa*. No statistically significant differences.

7 kg of bi-component filaments were upscaled and drawn at a roller speed of 1500 m/min, which achieved a dTex of 181.3 g/10,000 m (± 1.24), a tenacity of 33.8 cN/tex (± 2.36), and an elongation of 49.0% (± 4.07), and can be classified as a POY (partially oriented yarn). Its relatively moderate strength and higher extensibility, compared with fully oriented yarns, indicate that the filaments remain in an intermediate structural state suitable for subsequent drawing or texturizing processes. These filament yarns can be considered weavable, particularly for fabrics where a balance of strength and extensibility is acceptable.

3.3. Woven Narrow Fabrics Characterization

The optimized filament yarns were texturized and used to weave narrow fabrics using polyester filament yarns in the warp, with different polyamide-6/CuNP:PET ratios 40:60 (Textile 1), 57:43 (Textile 2), and 67:33 (Textile 3). Textiles with filaments without CuNPs did not show antimicrobial activity. The weft-to-warp ratio strongly influenced antimicrobial activity. Narrow fabrics with only 40% antimicrobial filament yarns showed reductions of 50% against *S. aureus* and 50% against *P. aeruginosa*. Increasing the antimicrobial filament yarns content to 57% significantly improved performance, achieving reductions of over 90% against *S. aureus* and 70% against *P. aeruginosa* while maintaining good mechanical properties. Narrow fabrics with 67% antimicrobial filament yarns have slightly higher antimicrobial efficacy but poorer weaving performance due to increased yarn fragility (Figures 4 and 5).

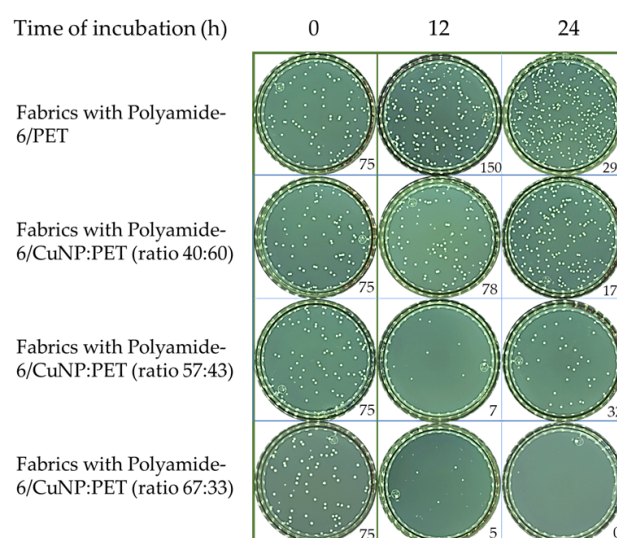


Figure 4. Colony-forming units (CFU) of *S. aureus* after exposition to woven narrow fabrics with different Polyamide-6/CuNP:PET ratios. The fabrics were incubated for 0, 12, and 24 h. The fabrics were washed, diluted 5000-fold, plated, and incubated for 16 h. The images of the plates are representative of three independent experiments, each performed in duplicate. The number in the lower right corner of each plate corresponds to the CFU.

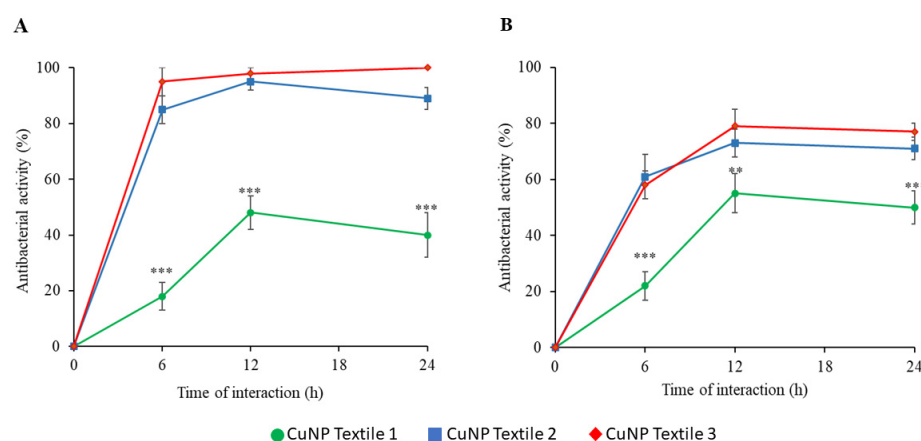


Figure 5. Antimicrobial activity of woven narrow fabrics with different Polyamide-6/CuNP:PET ratios 40:60 (Textile 1), 57:43 (Textile 2), and 67:33 (Textile 3) against (A) *S. aureus* and (B) *P. aeruginosa*. Statistically significant differences at $p \leq 0.01$ (**) and $p \leq 0.001$ (***).

Accelerated laundering tests, conducted according to AATCC TM61-2013 (Test Method 2A), demonstrated that the antimicrobial activity of the treated narrow fabric Polyamide-6/CuNP:PET (57:43) (Textile 2) was retained mainly after 10 washing cycles, with only a minor reduction (<10%) in colony-forming unit (CFU) inhibition (Table 3). However, after 20 cycles, antimicrobial efficacy against *S. aureus* decreased by approximately 40%, suggesting partial leaching or deactivation of surface-bound nanoparticles. This durability performance is comparable to previously reported AgNP-functionalized textiles, where antimicrobial effectiveness typically declines significantly after 5–10 laundering cycles [16,39]. The amount of copper determined by ICP for the narrow fabric Polyamide-6/CuNP:PET (57:43) was 0.5334 wt%, and 0.3373 and 0.3181 wt% after 10 and 20 washing cycle, respectively. The amount of copper lost in the first 10 cycles is considerable and can be related to superficial copper not attached to the polymer matrix. However, over 10–20 washing cycles, copper release is minimal (estimated at 0.0002 ppm), suggesting that most of the copper is well incorporated into the fibers. Although these results do not agree well with the antibacterial activity, the antimicrobial effect persists after 20 washing cycles, with minimal copper release. Thus, the antimicrobial activity can be optimized by increasing the number of copper-containing fibers. On the other hand, we detected no copper in the residual water. For this reason, unfiltered residual water was analyzed using UV-Vis. A peak in the 205–225 nm range was observed (Figure S2), corresponding to aqueous copper ions (Cu^{2+}). However, its amount could not be determined. Therefore, it is possible that the copper ions were trapped in the filter prior to ICP analysis.

Table 3. Effect of laundering and abrasion cycles on antimicrobial activity of woven narrow fabrics of Polyamide-6/CuNP:PET ratio 57:43 (Textile 2).

Treatment of Woven Narrow Fabrics	Antibacterial Activity Against <i>Staphylococcus aureus</i> (%) *
Untreated (control)	95 ± 4
10 laundering cycles	92 ± 6
20 laundering cycles	55 ± 12
130 abrasion cycles	91 ± 6
200 abrasion cycles	94 ± 5

* The antibacterial activity is presented as the percentage decrease in colony-forming units (CFU) compared to the narrow fabrics of Polyamide-6 subjected to the same treatment.

The abrasion resistance of woven narrow fabrics of Polyamide-6/CuNP:PET (57:43) (Textile 2) was evaluated according to ASTM D4060-19 (up to 200 cycles). Results showed no significant loss of antimicrobial activity, indicating that mechanical wear does not dislodge nanoparticles embedded in the filaments' sheath (Table 3). This contrasts with surface-coated fabrics, where nanoparticle detachment under abrasion is a commonly reported issue [27,40].

Cytotoxicity activity of woven narrow fabrics of Polyamide-6/CuNP:PET ratio 57:43 (Textile 2) on foreskin human fibroblast cells was evaluated by flow cytometry using a live–death fluorescent marker. Figure 6 shows the HF cell viability after 24 h of interaction with narrow fabrics. Control cells incubated for 24 h without fabrics showed 99% of viability. Mechanical damage was performed on cells as a positive control, resulting in a 15% reduction in viability. HF incubated for 24 h with narrow fabrics Polyamide-6/CuNP:PET ratio 57:43 (Textile 2) exhibited 97% of cell viability (Figure 6). Supplementary Figure S3 includes one example of a complete set of experiments measuring cell viability.

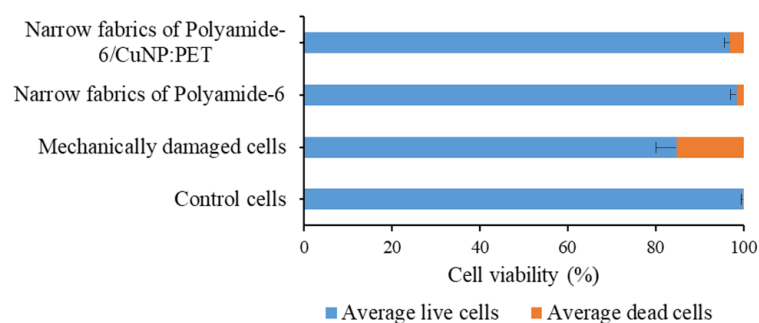


Figure 6. Viability of HF cells interacted with narrow fabrics of Polyamide-6 and Polyamide-6/CuNP:PET ratio 57:43 (Textile 2).

3.4. Hospital Validation Trial

The hospital field trial involved 20 antimicrobial medical coats and 20 control medical coats worn by medical residents during six-hour shifts. Microbial analysis of swatches from cuffs, pockets, and standard plackets demonstrated that antimicrobial uniforms significantly reduced bacterial colonization in specific areas.

At sleeve cuffs, bacterial burden was reduced by 30%, 55% for Gram-positive bacteria, and 70% for Gram-negative bacteria compared with controls (Table 4). This is clinically relevant since cuffs are frequently in contact with patients and surfaces. In contrast, pockets and standard plackets showed smaller differences, with significant reductions observed mainly for Gram-negative bacteria. These results highlight the importance of medical coat design in maximizing antimicrobial exposure of narrow woven fabrics at high-contact areas.

Table 4. Bacterial burden on medical coats with woven narrow fabrics exposed in a hospital environment.

Part of the Medical Coat Evaluated	Polyamide-6			Polyamide-6/CuNP:PET Ratio 57:43 (Textile 2)		
	Bacterial Burden *	Gram (+) *	Gram (−) *	Bacterial Burden *	Gram (+) *	Gram (−) *
Cuffs	1317.7 ± 122	72.9 ± 8	304.8 ± 29	949.2 ± 50	33.7 ± 6	93.6 ± 17
Pockets	533 ± 51	22.8 ± 5	246.2 ± 30	606.5 ± 89	32.9 ± 10	61.2 ± 19
Standard plackets	937.1 ± 54	0.3 ± 0.1	152.8 ± 25	888.4 ± 45	0.0	35.2 ± 12

* Colony-forming units (CFU) per 2.4 cm diameter sample cut from different areas of the uniforms.

4. Discussion

4.1. Antimicrobial Efficacy and Mechanism of Action

The near-100% antimicrobial activity of CuNPs against *S. aureus* and *P. aeruginosa*, and their performance once incorporated into the woven narrow fabrics (90% and 70%, respectively), can be related to their multiple-target action mechanisms, including membrane disruption, oxidative stress, and interference with essential cellular processes [17]. This variety of antimicrobial mechanisms is expected to hinder the development of resistance to metallic nanoparticles [17,43]. The greater antimicrobial effect against *S. aureus* (Gram-positive) than against *P. aeruginosa* (Gram-negative) is consistent with the well-known interactions between bacterial cell walls and metallic nanoparticles. Of particular interest is the antimicrobial activity against *S. aureus*, given its presence in hospital environments and its status as a notorious healthcare-associated pathogen with inherent resistance to

antimicrobial agents [44]. Thus, given the performance of CuNPs embedded into core-sheath fibers woven in narrow fabrics (functionalized textiles), it is expected that this type of material can address challenging pathogens such as methicillin-resistant *Staphylococcus aureus* (MRSA) and other multidrug-resistant organisms [45,46].

4.2. Durability and Practical Implementation

Antimicrobial activity of woven narrow fabrics against *S. aureus* after 10 laundering cycles decreased by less than 10% in CFU inhibition, whereas it decreased approximately 40% after 20 cycles. This performance is relevant to the report of Cayrou et al. [6]. These authors showed that domestic laundering poses significant challenges to disinfection efficacy and risks antibiotic resistance, where conventional laundering often fails to eliminate resistant pathogens from healthcare textiles, highlighting the importance of materials with intrinsic antimicrobial properties. However, other studies of functionalized fabrics with metallic nanoparticles have shown high antimicrobial efficacy. For example, Román et al. [47] produced a polyester/cotton fabric impregnated with copper oxides having 99% antimicrobial activity after 10 and 20 wash cycles. Recently, the use of polypropylene and polyester fabrics coated with crystalline phosphate-copper(II) nanoparticles showed that antiviral activity did not decline after 12 months of aging. However, the samples underwent six washing cycles [48]. However, no evidence of cytotoxicity was provided in both cases. Finally, environmental implications arise from the fact that nanoparticles can be released during laundering; i.e., the fate of metallic nanoparticles released from textiles during laundering remains an area that requires further study. Nonetheless, it is expected that the use of stabilizing agents [49,50] during nanoparticle synthesis and the embedding of nanoparticles in polymer matrices, as in the present study, can help address this issue.

On the other hand, the outstanding abrasion resistance of woven narrow fabrics, with no significant loss after 200 cycles, addresses a key limitation of surface-coated antimicrobial textiles. It is suggested that this durability performance is due to the incorporation of copper nanoparticles into the polymer matrix during the extrusion process, thereby preventing mechanical wear does not affect the antimicrobial activity [51,52].

Recent reports have demonstrated the feasibility of industrial-scale production of antimicrobial textiles. For example, González-Sánchez et al. [29] produced bi-component polyester fibers with embedded CuNPs, achieving 99% antimicrobial activity at very low loading (0.5 wt%). In another report, Chen et al. [53] embedded Cu₂O into polymer master-batches for production that is compatible with industrial processes. These developments, along with the results of this study, suggest that durable, intrinsic antimicrobial textiles can be manufactured at an industrial scale for healthcare apparel.

4.3. Hospital Validation and Toxicity

A significant reduction in bacterial colonization was observed during the hospital validation trial, particularly in sleeve cuffs (30% reduction in total bacteria, 55% in Gram-positive bacteria, and 70% in Gram-negative bacteria). These results validate the key role of targeting specific textile components for antimicrobial inhibition, as noted by Owen and Laird [3], who emphasized the critical role of high-contact areas, such as cuffs and pockets, in pathogen transmission in healthcare environments.

It is well documented that textiles serve as microbial reservoirs in healthcare environments. Rozman et al., 2018 identified up to 63 genera/species on hospital textiles, including hospital-relevant organisms such as *Acinetobacter* and *Staphylococcus*, demonstrating that textiles provide conditions favoring microbial growth, dissemination, and long-term survival [54]. Similarly, recent studies have confirmed that hospital environmental surfaces, including textiles, play a significant role in the transmission of healthcare-acquired

multidrug-resistant bacteria [55]. The clinical impact of antimicrobial textiles has been evaluated in several systematic reviews and meta-analyses, with mixed results. Fan et al., 2020 conducted a meta-analysis of six controlled studies and found no overall significant reduction in healthcare-associated infections (HAI) with copper-impregnated hospital linen. However, they noted subgroup signals for a decrease in all-HAI [56]. In another study, Schneider et al. found that textile microbial load can be reduced via impregnation with copper, zinc, and silver, among other antimicrobial agents. However, these authors highlighted that consistent laundering protocols and resistance monitoring still need to be implemented [57].

The better antimicrobial performance of cuffs compared to pockets and standard plackets provides valuable insight for future design of healthcare apparel, where differences in contact frequency, contamination levels, and fabric composition ratios play a key role in maximizing infection-control benefits while optimizing material costs [58].

The demonstrated low cytotoxicity (97% cell viability) of our CuNP-incorporated textiles addresses critical safety concerns in healthcare applications. Bearing in mind that textiles impregnated with copper nanoparticles are very stable during laundering and retain their antimicrobial activity [59]. The biocompatibility profile, combined with the intrinsic antimicrobial activity, positions these textiles as viable alternatives to conventional antimicrobial treatments that may pose greater risks to both healthcare workers and patients.

Finally, to ensure the wearer's safety electrical surface resistivity was determined for the woven fabrics (Figure S4).

4.4. Limitations and Future Directions

While our study demonstrates promising results, several areas require further investigation. The 40% reduction in antimicrobial activity after 20 washing cycles indicates the need to optimize nanoparticle retention strategies. Additionally, expanding the antimicrobial spectrum evaluation to include a broader range of healthcare-associated pathogens, including multidrug-resistant organisms, fungi, and viruses, would enhance the clinical relevance of these textiles. Recent studies demonstrating virucidal activity of copper-based textiles against SARS-CoV-2 and other viruses suggest potential for broad-spectrum pathogen control [47,48].

The scale of our hospital trial, while providing valuable proof-of-concept data, would benefit from expansion to include larger cohorts across diverse healthcare settings. Furthermore, long-term studies examining the relationship between antimicrobial textile use and healthcare-associated infection rates would provide crucial evidence for widespread implementation. The systematic review by Fan et al., 2020 highlighted the heterogeneity and quality limitations of existing clinical trials, emphasizing the need for well-designed, adequately powered studies with standardized outcome measures [56].

Future research should also address the environmental lifecycle of antimicrobial nanoparticle textiles, including quantitative assessment of nanoparticle release during laundering, wastewater treatment efficacy, and potential ecological impacts. Development of "smart" antimicrobial textiles that provide visual indicators of antimicrobial activity loss, as demonstrated by Ferrer-Vilanova et al., 2025, could help optimize replacement schedules and ensure consistent infection control performance [60].

5. Conclusions

This study reports the development route—from nanoparticle dispersion to hospital validation—of durable antimicrobial hospital apparel based on copper nanoparticle (CuNP)-incorporated in polyamide-6 core-sheath filaments. The optimized processing con-

ditions (ultrasound-assisted melt extrusion, texturizing, and weaving) and the core–sheath geometry of the filaments ensure uniform nanoparticle dispersion with adequate mechanical properties. Once the core–sheath filaments are incorporated into woven narrow fabrics, a strong antimicrobial effect against both Gram-positive and Gram-negative bacteria is achieved. Antimicrobial effect was largely retained after 10 laundering cycles and remained stable under abrasive wear, highlighting the advantage of embedding CuNPs within the filament sheath. Cytotoxicity analysis confirmed high fibroblast viability (97%), supporting the biocompatibility of the materials and their suitability for direct contact with healthcare workers and patients. The hospital validation trial demonstrated meaningful reductions in microbial load in high-contact areas, particularly sleeve cuffs, where total bacteria decreased by 30%, Gram-positive bacteria by 55%, and Gram-negative bacteria by 70% compared with controls. These results confirm that targeted integration of antimicrobial woven components into healthcare apparel can effectively mitigate bacterial colonization under real-use conditions.

Overall, this work provides strong evidence that intrinsically antimicrobial, CuNP-embedded textiles represent a viable and durable approach to enhance infection-control strategies in healthcare environments. Future work should focus on improving long-term laundering durability, expanding antimicrobial spectrum testing, and conducting larger hospital trials to evaluate their impact on healthcare-associated infection rates.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/textiles6010020/s1>, Figure S1: Colony-forming units (CFU) of *P. aeruginosa* after exposure to different concentrations of CuNPs; Figure S2: UV/Vis spectroscopy of residual water of woven fabrics containing copper after 10 and 20 washing cycles.; Figure S3: Flow cytometry analysis of cell viability of fibroblast cells (NIH 3T3 cell line) exposed to narrow fabrics of polyamide-6/CuNP: PET; Figure S4: a sheet of copper (a) was tested, resulting in $<10^3$ ohms/sq (conductive material), while a polyethylene plate (b) resulted in $>10^{12}$ ohms/sq (insulative material). For the woven fabric with copper (d), a surface resistivity of 10^{12} ohms/sq (insulating material) was measured, whereas it was 10^{11} ohms/sq (static-dissipative material) for the sample without copper (c); Table S1: Colony-forming units (CFU) of *S. aureus* and *P. aeruginosa* exposed to different concentrations of CuNPs.

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Abbreviations

The following abbreviations are used in this manuscript:

AATCC	American Association of Textile Chemists and Colorists
ACTIn	Antimicrobial Textiles for the Healthcare Sector
AgNPs	Silver nanoparticles
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
ATCC	American Type Culture Collection
CFU	Colony-forming units
CuNPs	Copper nanoparticles
dTex	Decitex (unit of linear density)
DMEM	Dulbecco's Modified Eagle's Medium
EDS	Energy-dispersive X-ray spectroscopy
FE-SEM	Field Emission Scanning Electron Microscope
HAI	Healthcare-associated infection
HF	Human fibroblast
ICP	Inductive coupling plasma
IMSS-Bienestar	Instituto Mexicano del Seguro Social para el Bienestar
MRSA	Methicillin-resistant <i>Staphylococcus aureus</i>
NPs	Nanoparticles
PBS	Phosphate-buffered saline
PET	Polyethylene terephthalate (Polyester)
POY	Partially oriented yarn
TiO ₂	Titanium dioxide nanoparticles
UV-Vis	Ultraviolet-Visible
WHO	World Health Organization
ZnO	Zinc oxide nanoparticles

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