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ANTIPATHOGENIC TEXTILES COATED WITH SILVER@COPPER CORE SHELL NANOPARTICLES

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Abstract

The growing concern over microbial contamination, especially in healthcare, hygiene, and personal protective equipment (PPE), has driven significant interest in the development of advanced antimicrobial textiles. This study explores the fabrication, characterization, and performance of textiles coated with silver@copper (Ag@Cu) core–shell nanoparticles as a novel and efficient antipathogenic solution. The Ag@Cu core–shell structure leverages the high antimicrobial efficacy of silver and the cost-effectiveness and redox activity of copper, offering a synergistic approach that enhances performance while maintaining economic feasibility. Ag@Cu nanoparticles were synthesized using a controlled chemical reduction process that ensures the formation of a stable copper core enveloped by a thin silver shell. These nanoparticles were subsequently deposited onto textile substrates via dip-coating followed by thermal curing, resulting in uniform distribution and strong adhesion to the fabric fibers. Characterization using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) confirmed the presence and integrity of the core–shell structure on the textile surface. The antimicrobial properties of the coated fabrics were evaluated against common and clinically relevant pathogens including *Escherichia coli*, and *Staphylococcus aureus*. Results demonstrated over 99% microbial reduction, confirming the potent and broad-spectrum antimicrobial activity of the Ag@Cu-coated textiles. Furthermore, wash durability tests showed minimal loss of effectiveness even after multiple laundering cycles, highlighting the strong binding of the nanoparticles and the long-term usability of the fabric. This work demonstrates the promising potential of Ag@Cu core–shell nanoparticle coatings in the development of next-generation antimicrobial textiles. Such materials can play a critical role in preventing infections in healthcare settings, improving hygiene in everyday wear, and enhancing the protective capabilities of PPE. Future studies should further explore scalability, environmental safety, and cytocompatibility for practical deployment.

INTRODUCTION

Antimicrobial fabrics have attracted a lot of attention in recent decades because of their potential uses in a range of industries, including consumer goods and healthcare. The increased incidence of hospital-acquired infections (HAIs), antibiotic-resistant bacteria, and infectious disorders are the main causes of the growing demand for textiles that provide protection against microbial threats. Despite being a necessary component of daily living, textiles frequently harbor bacteria, viruses, and fungi, which can pose serious health hazards. Therefore, creating fabrics with antipathogenic qualities is essential to reducing these dangers (Casey AL, 2010) . The World Health Organization (WHO) also stated that antimicrobial resistance is considered one of the most significant global health threats, causing a death rate that was estimated at 700,000 people every year and is predicted to lead to hundreds of thousands of deaths every year unless new antimicrobial solutions are established (WHO, 2020). This has led to the production of new type of antimicrobial textiles which are able to mitigate the spread of pernicious pathogens (Ali, Baheti, Militky, & Khan, 2018).

People now strongly need textiles with active antimicrobial properties because of their growing significance. The need for improved infectious disease management has significantly increased because of multiple disruptive elements affecting the healthcare environment. Public health systems remain vulnerable because of newly discovered infectious diseases which include SARS-CoV-1 and MERS-CoV along with H1N1 influenza and Ebola and the most recent threat SARS-CoV-2 from COVID-19. EIDs need immediate environmental mitigation protocols due to their fast global transmission pattern (Anand & Remers, 2010)

Textiles serve as ideal surfaces for microbial colonization due to their fibrous structure, which provides both a physical and chemical environment conducive to microbial growth. Pathogens can be transferred to and from textiles through direct contact or through airborne transmission (Xu, Zhang, & Tao, 2008) . In healthcare settings, contaminated textiles such as hospital linens, gowns, and bandages can serve as vectors for pathogens, contributing to the spread of infections among patients and healthcare workers. For this reason, the development of textiles with integrated antimicrobial properties is of paramount importance in reducing the transmission of harmful microorganisms (Shahid et al., 2021).

Conventional efforts to render antimicrobial to cloths have incorporated the use of the following chemical preparations, quinones ammonium compounds, chitosan, and tricosans. These treatment methods however have many limits such as low durability, environmental care and the possibility of the pathogen resistance. More recently, the major antimicrobial effect, versatility, and capacity to be incorporated in textile fibers between metal (Lim, J.; Vachet, 2003) based nanoparticles especially silver and copper have made them rise to popularity.

Copper and silver also possess documented antibacterial properties, but in addition to their widespread bacterial effect, each has broad-spectrum activity against viruses and fungus. They however differ in the mode of action of their antibacterial effort (Mukherjee et al., 2001) . The ant-bacterial properties of silver have been understood millennia ago. Silver nanoparticles (AgNPs) are quite popular in applications today due to their unique surface-to-volume ratio that causes them to be more reactive and more capable of interacting efficiently with microbial cells than their bulk counterparts. Silver nanoparticles primarily act against bacteria in the following manners. AgNPs could generate ROS such as hydroxyl and hydrogen peroxide that damage microorganisms including DNA, proteins, and cell membranes. The point of this oxidative stress is death of the microbes (Keeney, Yurist-Doutsch, Arrieta, & Finlay, 2014). Rai et al. (2009) suggested that AgNPs are so minute, and have widespread surface areas that allow them to interact with the bacterial cell membrane, breaking its integrity and resulting in the leakage and death of a cell (Pal, Rai, & Pandey, 2018). AgNPs can bind themselves to the proteins and enzymes in the bacteria hindering their functioning and inhibiting microorganisms growth. (Escárcega-González et al., 2018) Silver is practical against a wide range of microbes, such as antibiotic-resistant forms of bacteria, e.g. Escherichia coli and Methicillin-resistant Staphylococcus aureus (MRSA), due to its broad-spectrum antibacterial properties. Silver nanoparticle application, however, brings questions regarding their potential use toxicity towards the environment and the human cells, particularly when exposed to a long duration, and in situations where there is the likelihood of silver leaking into water bodies. Its form (Bharathala & Sharma, 2019) . (Lara, Ayala-Núñez, del Turrent, & Padilla, 2010)..The antimicrobial qualities of copper nanoparticles show wide effectiveness by killing both Gram-positive and Gram-negative bacteria together with different types of fungi and some viral strains. The ability of copper nanoparticles to combat antibiotic-resistant strains makes them increasingly desired for applications which goal to limit the transmission of persistent infections (Nayak, Bhasin, & Nayak, 2019). The use of silver and copper combination with core-shell structure is a new idea regarding the desire to increase the surface of textile materials with antimicrobial characteristics. A core-shell nanoparticle is a particle whose core is made of a material (here, copper) and its shell of another material (silver). It is the structure that enables synergistic advantages of the both metals and mitigates some of the disadvantages of each of them. Core-shell nanoparticles as textile coatings have a number of benefits as compared to methods of separately adding silver or copper nanoparticles. The main advantages of this. (Abdel-Mohsen et al., 2012) . The next key challenge to ways in which these nanoparticles can be used on a regular basis is attaching them in a secure manner to the fibers of the fabric. They must be able to bond well with each other by repeated wears and laundering cycles in order to continue being effective. In addition, their safety should be thoroughly evaluated. Whereas the outer silver layer can provide certain shielding effect to the copper core, the cumulative safety hazard (both to humans and the environment) caused by the liberated silver and copper particles, or ions, should be considered. This is very significant because the interactions that would be involved in the electrochemical facets of the two metals could actually accelerate this release auctionra (Leventis, 2007)

The shell in the core-shell structure gives the potential to combine antimicrobial effects of silver with copper. The copper core has the property to offer structural stability and increased antimicrobial activity, whereas the silver shell has added antimicrobial efficacy.

The combination makes it more active against a wide range of pathogens (Wang et al., 2015). The core shell structure will also eliminate hasty loss of silver ions, a feature that would be an issue in silver nanoparticle production. Incorporation of silver@copper core-shell nanoparticle into textile is of great potential in a broad market.

The antimicrobial action is synergistic since the silver in the core ion-release is reinforced by the independent actions of the copper shell that has its own antimicrobial properties (Rai et al., 2009; Chatterjee et al., 2014). Other than essential fields like the medical field, the performance sportswear would be another important field that will make an impact. Bacteria in sweaty clothing often leads to odor-related problems; Ag@Cu nanoparticle infusion into the material of sports clothes suppresses the growth of the odor-causing bacteria and therefore can improve personal hygiene and comfort during and after exercise (Sugimoto et al., 2021). Moreover, the direction of the uses of these high-tech textiles touches upon other promising lines.

Antimicrobial products have been introduced into everyday life; this is because of the increasing demand of consumers who use the products in textiles, e.g. clothing, beddings and other household materials. Core shell nanoparticles to prevent pathogenic attack Silver coating on copper silver@copper nanoparticle-coated textiles provide consumers pathogen protection that is non-washable, enhancing the durability of a consumers textiles and increasing the hygiene performance of these textiles. Antipathogenic textiles covered with a layer of silver@copper core-shell nanoparticles will have great importance to the field of materials science and textile engineering. These fabrics provide superior antibacterial performance such as broad-spectrum antibacterial capability against bacteria, fungi, and viruses; thus, they are extremely helpful when applied in healthcare, consumer life, and sportswear. The synergistic effect of silver and copper, together with low-cost controlled release and robustness of the core-shell design offer a great prospective of handling the issues of microbial contamination and antimicrobial resistance. With the further development of research in this direction, silver@copper core-shell nanoparticle-coated fabrics will soon become a basis in the battle against infectious diseases and encouraging wellbeing in the masses. Certainly, people are much more concerned with the issues of hygiene and the spread of germs nowadays, and the trend has become especially apparent recently (as of April 12, 2025). Owing to this fact, there is a high demand on antimicrobial products among consumers, which promotes the preferences in more advanced treatments within daily products, clothing, sheets and bed linens, towels, and others. This consumer interest is addressed directly through fabrics with engineered nanoparticles of a silver core and a copper shell (Ag@Cu). They have both practical benefits like long-term germs protection, in part due to how the core-shell structure can regulate the delivery of active compounds (Liu et al., 2010; Siddiqi et al., 2018). This has the benefit to the users in terms of cleaner homes, perhaps less microbe-related skin irritation or allergies, effective prevention of odor in clothing and antimicrobial qualities of a product that lasts throughout use and washing, a value-added aspect to the product.

1.1 Aims and Objectives:

To identify the key challenges currently facing the antimicrobial textile industry, such as environmental regulations, health concerns, and the cost and availability of raw materials.

To outline the future trends and opportunities in the field of antimicrobial textiles, including the development of sustainable alternatives, enhanced durability, and the integration of multifunctional properties.

- Ultimately, to provide valuable insights and guidelines for the further development and application of antimicrobial textiles to enhance hygiene, prevent infections, and improve public health across various industries and consumer markets.

2. Experimental

2.1 Materials

The present research involved a range of chemicals, solvents, reagents, and textile substrates necessary for the synthesis of silver-coated copper (Ag@Cu) core-shell nanoparticles and their application onto fabrics. Copper nitrate trihydrate (Cu(NO$_3$). 3H$_2$O) and silver nitrate (AgNO$_3$) were precursors of main metals. The reducing agent in copper nanoparticle formation was sodium borohydride (NaBH$_4$) and ascorbic acid was utilized in the mild and controlled reduction of silver ions in the shell formation. Non-ionic polymeric stabilizers used were polyvinylpyrrolidone (PVP) to inhibit nanoparticle agglomeration and to manipulate particle size during the synthesis. All chemicals were purchased from sigma Aldrich. Plain woven fabrics of cotton were used as the textile substrates. The cotton was chosen on the basis of industries and because they are highly used in the production of clothing materials and in the medical textiles. Choice of cotton fabric based on its softness, moisture absorbency and biocompatibility. The fabrics were purchased from Arif Textile Mills, Sargodha road, Faisalabad, Pakistan. Pathogenic strains of microorganisms were utilized in order to assess the antimicrobial activity, and these include Gram-negative *Escherichia coli (E. coli)*, Gram-positive *Staphylococcus aureus (S. aureus)* and *fungal one Candida albicans* were obtained from Ayyub research institute.

2.2 Methodology

2.2.1 Pretreatment of cotton fabric

Before applying nanoparticles, all the fabric samples were cleaned and pretreated with 40g/L NaOH in deionized water in order to do away with any drying surface contaminant or finishes that might hinder attachment to the coatings. The fabric was boiled at 40 °C for 30 minutes. The pretreatment was done to swell the fibers structure.

2.2.2 Synthesis of Silver-Coated Copper (Ag@Cu) Core-Shell Nanoparticles

The Ag@Cu core-shell nanoparticles were synthesized through a chemical reduction process, executed in two stages: (1) the formation of copper nanoparticles, and (2) the deposition of a silver shell. In the first step, a solution of 0.1 M copper nitrate was prepared and kept stirring at room temperature. A drop-wise vigorously stirred a cooled solution of sodium borohydride (NaBH$_4$). The reaction was conducted in the presence of PVP, which acted as a capping agent, providing stability and preventing particle aggregation. A brownish-red color change indicated the formation of copper nanoparticles. In the second stage, these freshly prepared CuNPs were used as templates for silver shell formation. A measured amount of silver nitrate (AgNO$_3$) was slowly introduced into the copper nanoparticle suspension. Ascorbic acid was then added as a mild reducing agent to reduce silver ions (Ag^+) to metallic silver (Ag^0), allowing uniform deposition over the copper core. The solution was kept under continuous stirring for several hours to ensure uniform shell formation. The resultant Ag@Cu nanoparticles were collected via centrifugation at 10,000 rpm for 20 minutes and washed repeatedly with ethanol and deionized water to remove residual reactants. Finally, the nanoparticles were stored at 4 °C until further use.

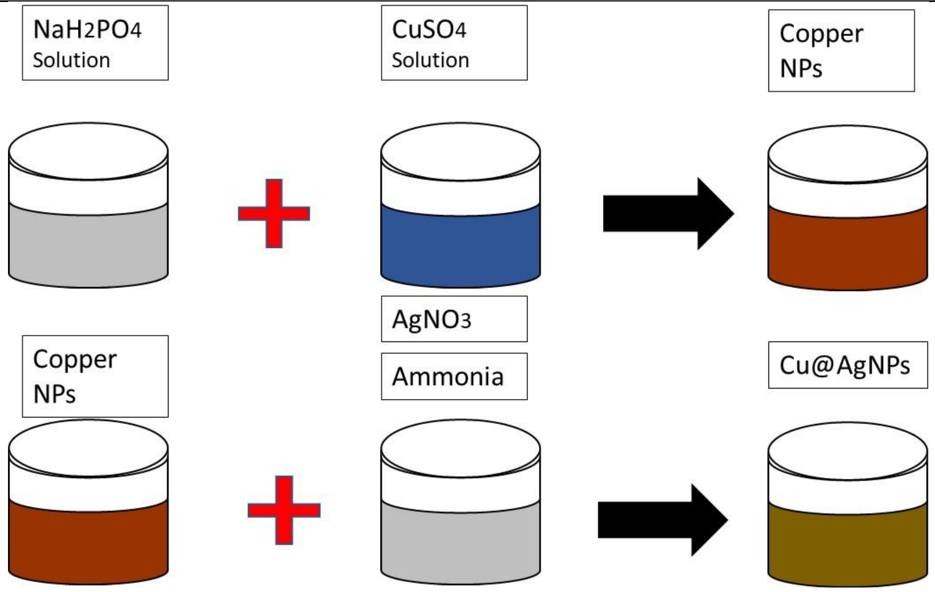

Figure 2.1: Synthesis pathway for Cu@Ag core-shell nanoparticles showing copper core formation (upper) and silver shell coating (lower) with corresponding SEM images of the final nanoparticles.

2.2.3 Coating of Textiles with Ag@Cu Nanoparticles

The application of nanoparticles to textiles was achieved through the dip-coating method, a simple, scalable, and cost-effective technique suitable for industrial applications. Clean, dry pieces of cotton and polyester fabrics were immersed in the Ag@Cu nanoparticle dispersion for a predefined period (typically 10–15 minutes). The fabrics were gently agitated to ensure uniform contact and penetration of nanoparticles into the fabric matrix. After immersion, the fabrics were withdrawn at a controlled speed to ensure an even coating and were allowed to dry at ambient temperature. The coated samples were then cured in a hot air oven at 120 °C for 10 minutes. This thermal treatment facilitated the fixation of nanoparticles onto the textile fibers by promoting better adhesion and reducing nanoparticle leaching during use or washing.

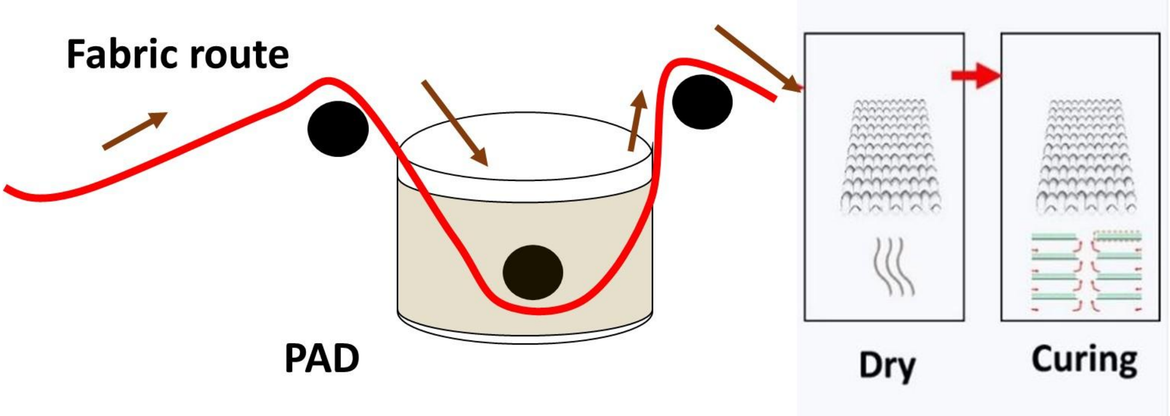

Figure 2.2: Coating of Textiles with Ag@Cu Nanoparticles

3. Testing and characterization

3.1 Surface characteristics

Dynamic light scattering (DLS) was used to evaluate the physical parameters of the manufactured particles. To make diluted dispersion, the pieces were placed into a glass container with distilled water. To ensure sterility, the final solution was sonicated before analysis in a probe sonicator at the power setting of 20 min. Scanning electron microscope (SEM) was used to study shape and structure of the metal-coated samples of the textile. Accelerated voltages were done by TESCAN VEGA III SEM. To determine the weight percentages of the various components, energy-dispersive X-ray analysis (EDX) was used, which is a method allowing potential to be identified and the measurement of the elemental composition of the materials. Moreover, X-ray diffraction (XRD) studies were done by competently utilizing a diffractometer coupled with a standard X-ray tube. It operated at 40 kV, 30 mA of current with Cu K alpha 1 radiation at 1.5406 A wavelength. X-ray diffraction patterns were systematically recorded in the range of 10-80 degrees with measurements of every 0.02 degrees. The rigorous approach was able to provide significant information on the structural aspects of the materials being studied. (Rupp, Liang, Geis-Gerstorfer, Scheideler, & Hüttig, 2018).

3.2 Antibacterial activity

The antibacterial effectiveness was assessed using the disk diffusion technique.

3.2.1 Determination Zone of Inhabitation

The antibacterial effectiveness of the nanoparticles was assessed using the conventional AATC147 inhibition assay. Both qualitative and quantitative techniques were used to examine the antibacterial qualities of cotton textiles treated with the produced particles (Chen, Hwang, Gleaton, Titus, & Hamlin, 2019) . Cotton cloth coated in copper and silver and featuring a unique pattern of 6 × 6 mm squares was put straight onto agar plates that had already been infected with bacteria. A control sample made of cleaned cotton cloth was used for comparison. All samples were then incubated for 24 hours at 37°C, including the contaminated agar plates. The total diameter (in millimeters) of the fabric particles in relation to the region where bacterial proliferation was inhibited was used to measure how well the copper@silver-coated fabric inhibited bacterial growth. To guarantee dependability, each experimental trial was carried out three times, and the Gram-positive and gram-negative bacterial strains were the two groups into which they were divided. Nutrient agar served as the culture medium. The two bacterial species, which were examined in the qualitative investigation, were Gram-positive *Staphylococcus aureus* (CCM-3953) and *Gram-negative Escherichia coli* (CCM-3954). A single colony of each strain was inoculated into nutrient broth and incubated overnight (37 °C) with shaking to make fresh bacterial culture. Then new agar plates were prepared to have subsequent antimicrobial test. It was necessary to ensure that the cell concentration was same by adjusting the bacterial suspensions to an optimal optical density of 0.1 at 600 nm (OD600). The suspension was dispensed into sterile cotton swab that was used to uniformly inoculate the agar plates surface after all right disinfection mechanisms have been observed. The plates were then tested with antibiotics so as to ascertain the inhibitory zone.

average outcomes were computed to offer a thorough study..(Bist & Saud, 2022).

3.2.2 Quantitative test (The reduction)

The AATCC standard, Method 100-2004, was used for the measurements. The reduction factor in this numerical study indicates the percentage drop in bacterial concentration brought on by the sample effect. After counting the number of surviving bacterial colonies (colony-forming units), the percentage neutralization was computed. This implies that samples from the various treatments must be evaluated under the same circumstances. In accordance with AATCC Standard Test Method 100-2004, measurements were conducted. The reduction factor is used in this numerical study to show the percentage drop in bacterial concentration brought on by the antibacterial action of the sample. The percentage neutralization was computed following the quantification of the surviving bacterial colonies, expressed as colony-forming units (CFU). All samples from the treatments were assessed under the same experimental circumstances in order to guarantee accurate and comparable results. .(Bist & Saud, 2022).

4. Results and Discussion

4.1 Characterization of Nanoparticles and Coated Textiles

Comprehensive characterization of the synthesized Ag@Cu core-shell nanoparticles and their deposition on textile substrates is essential to validate their morphology, elemental composition, structural integrity, and surface functionalities. A series of advanced analytical techniques were employed to ensure the successful synthesis, stability, and effective application of the nanoparticles. These techniques also confirmed the homogeneity of coating on textile fibers and the nanoparticles' potential for antimicrobial performance.

4.2 UV-Visible Spectroscopy (UV-Vis)

UV-Vis spectroscopy was used to monitor the formation and stability of Ag@Cu nanoparticles by recording the absorbance spectra in the range of 200–800 nm. Copper nanoparticles typically show a plasmon resonance peak around 570 nm, whereas silver nanoparticles show an absorption peak around 395–420 nm. The presence of a distinct peak or shoulder near these wavelengths, or a redshift, indicated successful coating of silver over copper and formation of core-shell structures. A stable absorption profile over time confirmed nanoparticle stability in dispersion. The combination of organic and metallic materials is fundamental to antipathogenic textiles, as the core-shell Ag/Cu nanoparticles are the antimicrobial components and the organic matrix is needed to guarantee flexibility and durability. In case this was a UV-Visible spectrum, which would indicate that the nanoparticles have formed and that there is core-shell interaction.

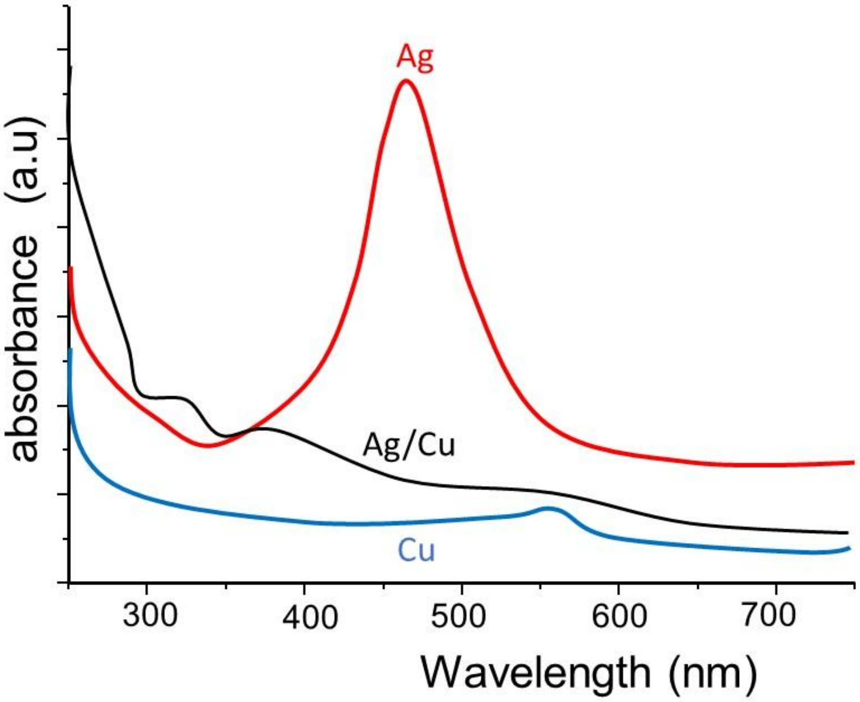

Figure 3.1: UV-Vis absorption of Ag/Cu core-shell nanoparticles on textile, revealing plasmonic peaks for antimicrobial activity.

4.3

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy was employed to investigate the functional groups present on the surface of nanoparticles and to analyze potential interactions with the textile fibers. The presence of characteristic peaks corresponding to hydroxyl (-OH), carbonyl (C=O), and amine (-NH) groups provided evidence of PVP and ascorbic acid capping or interaction with fabric cellulose. Shifts in peak positions after coating the fabric also indicated binding or adsorption of nanoparticles onto the textile matrix. FTIR spectrum reveals important information about the structural and functional characteristics of antipathogenic textiles coated with silver (Ag) on copper (Cu) core-shell particles. The spectrum displays distinct transmittance bands corresponding to various functional groups and interactions. The occurrence of C-H stretching bands at ~3000 cm^{-1} imply acknowledge the organic nature of and coatings textile fibers, whereas bands at ~1600-1700 cm-^{1} could represent carbonyl (C = O) or amide (C-N) groups likely due to the coating material or trimmers. The low wavenumber area (< 1500 cm^{-1}) indicates multiple vibrations that may be pertinent to the backbone of the polymer stabilizing the textile or interactions of the coating with the fabric. It is important to note that the spectrum also shows incorporation of Ag and Cu, whereby the exciting possibility of Ag-O or Cu-O vibrations is observed to be at 500 cm^{-1} that proves the presence of metal oxides or coordination complexes. The combination of organic and metallic materials is fundamental to antipathogenic textiles, as the core-shell Ag/Cu nanoparticles are the antimicrobial components and the organic matrix is needed to guarantee flexibility and durability. In general, the results obtained concerning FTIR indicate the prime coverage of the textile with Ag/Cu particles that is ever-important to carry out its pathogen-preventing feature.

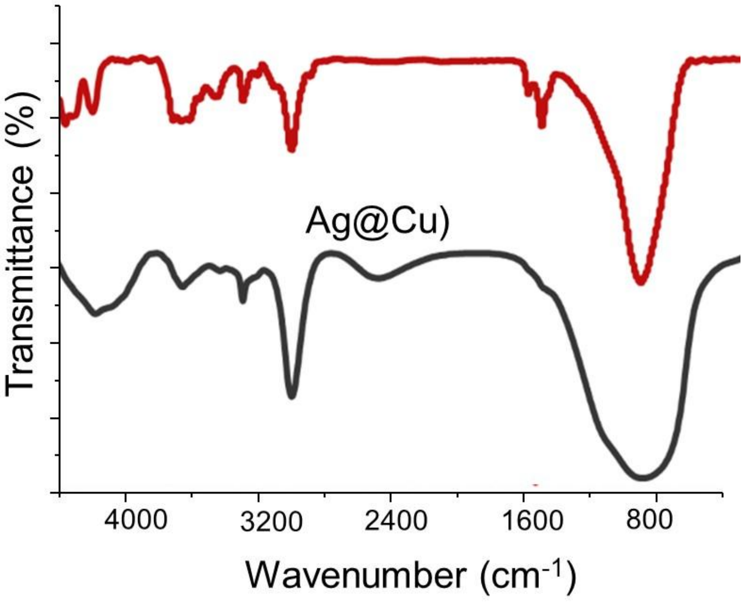

Figure 3.2: FTIR spectral characterization of Ag/Cu core-shell nanoparticle-coated textile, demonstrating preservation of textile matrix (C-H stretch) and successful nanoparticle deposition (metal-oxygen vibrations).

The FTIR spectrum provides valuable insights into the chemical composition and bonding interactions of antipathogenic textiles coated with silver-copper core-shell nanoparticles. The prominent absorption bands in the 2800-3000 cm^{-1} region clearly indicate C-H stretching vibrations, characteristic of the organic polymer matrix that forms the textile substrate. This confirms the structural integrity of the base fabric has been maintained during the coating process. More importantly, the spectrum reveals distinct metal-oxygen interactions through broad absorption features in the 500-600 cm^{-1} range, corresponding to Ag-O and Cu-O vibrational modes. These signatures demonstrate the successful incorporation of silver and copper nanoparticles onto the textile surface. The absence of significant interfering peaks in the 1500-2000 cm^{-1} region suggests a clean coating process with minimal organic contaminants. The coexistence of these organic (textile) and inorganic (nanoparticle) spectral features confirms the hybrid nature of the material, where the textile provides structural support while the metallic coating delivers antimicrobial properties. The spectrum's overall profile indicates strong interfacial interactions between the nanoparticles and textile fibers, which is crucial for ensuring coating stability and long-term functionality. This FTIR analysis thus verifies the successful fabrication of a composite material combining textile flexibility with the antipathogenic benefits of silver-copper nanoparticles. For a more comprehensive understanding of the nanoparticle characteristics, these findings could be complemented with additional spectroscopic and microscopic analyses.

4.4 Scanning Electron Microscopy (SEM)

SEM analysis was performed to examine the surface topography and morphology of uncoated and nanoparticle-coated textile samples. High-resolution micrographs revealed the distribution, size, and agglomeration behavior of nanoparticles on fabric fibers. Coated fabrics showed a rougher surface compared to untreated samples, indicating successful deposition of nanoparticles. Uniform distribution and lack of large agglomerates were desirable features confirming the effectiveness of the dip-coating technique.

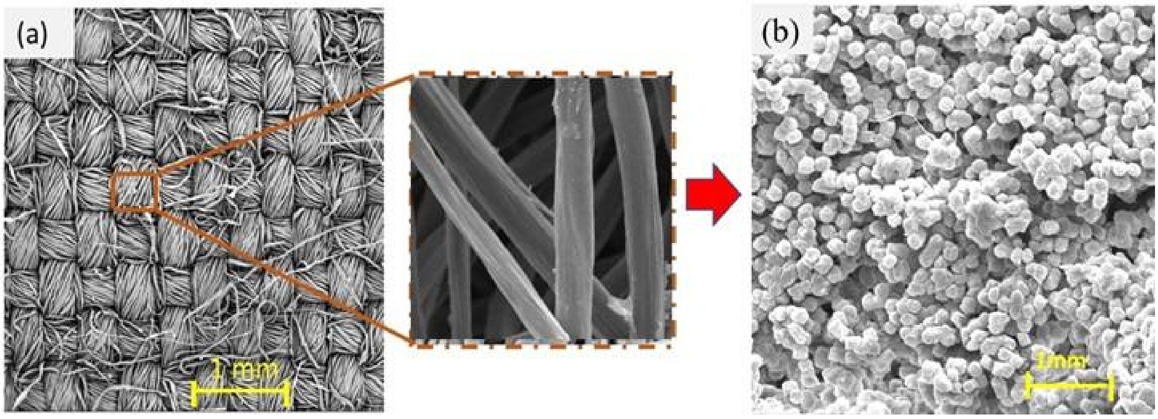

Figure 3.3: SEM images of untreated cotton fabric (a) and fabric treated with Cu@Ag nanoparticles (b).

The SEM images illustrate the morphological changes in textile fibers before and after functionalization with silver-coated copper core–shell nanoparticles (Ag@Cu NPs), aimed at developing antipathogenic textiles. Image (a) displays the untreated textile surface, revealing smooth and clean fibers without any noticeable surface modification, serving as the control. In contrast, image (b) shows the textile fibers after coating with Ag@Cu nanoparticles. A clear difference is observed, as the fiber surfaces appear rougher and are visibly covered with nanoscale deposits, indicating successful nanoparticle loading. The highlighted region in image (b) marks the presence of CuONPs, which may form during oxidation of the copper core, while the silver shell helps stabilize the structure and enhances antimicrobial activity. The rough surface morphology and visible nanoparticle clusters suggest strong adhesion of the core–shell particles to the fiber substrate. This nanoscale coating is crucial for imparting durable antimicrobial functionality to the textile, as both silver and copper are known for their broad-spectrum antibacterial and antiviral properties. The core–shell structure further offers synergistic effects, controlled ion release, and improved stability, making such coated textiles promising candidates for healthcare and hygienic applications. The SEM images provide morphological evidence supporting the development of antipathogenic textiles coated with silver at copper core–shell nanoparticles (Ag@Cu NPs). Image (a) represents the untreated textile fibers, displaying smooth and uniform surfaces with no particulate matter, serving as a reference.

4.5 X-ray Diffraction (XRD)

Crystalline structure and phase purity of the synthesized nanoparticles were checked by XRD. Face-centered cubic (FCC) structures of silver and copper characteristic diffraction peaks, were observed, which confirmed the crystal nanoparticle formation. The smooth edges of the sharp peaks, together with the lack of any oxide-related materials (i.e. CuO, Ag_2O) suggested excellent purity and that reduction occurred in the course of the process. The XRD spectrum is of essential value in assessing the crystalline phases of silver-copper core-shell nanoparticles of antipathogenic applications in the textile coatings. The contents are shown to be a complex mixture of copper phases that have a considerable influence on the antimicrobial performance of said materials. The overlap indicates the presence of a strong metallic copper core in the nanoparticles whose dominant peak is at about 43° the Cu (111)

In contrast, image (b) shows the textile surface after functionalization with Ag@Cu NPs. The fibers exhibit a distinctly rougher texture and are coated with visible nanoparticle deposits, particularly within the highlighted region marked as CuONPs. This confirms the successful immobilization of the core–shell nanoparticles onto the textile surface. The roughness and clustered appearance of the coated fibers enhance the surface area, which is essential for increasing contact with pathogenic microorganisms. The Ag@Cu core–shell structure is strategically designed to combine the broad-spectrum antimicrobial effects of both metals, where the silver shell offers strong bactericidal action and the copper core contributes additional pathogen inhibition while being cost-effective. Further, the core-shell structure gives oxidation stability and durability in release of ions. These surface changes suggest the possibility of the coated textile to serve as a good antipathogenic textile that can be subsidized in medical, protective and health care applications.

crystallographic plane of the metallic copper. Other peaks related to copper are also noticed at approximately 50 and 74 the corresponding to Cu (200) and Cu (220) planes respectively, which verify the face-centered cubic (FCC) crystal structure of the copper core. It is interesting to note that another peak is recorded in the spectrum at 36 the, which is also resulting to Cu_2O (111) indicating that the Cu surface was at least partly oxidized, which is typical during the synthesis of nanoparticle and could actually beneficial to enhance the antimicrobial activity but through the regulated release of cuprous ions. The ability of metallic copper and copper oxide to be found in these core-shell particles is especially advantageous in antipathogenic textiles since it gives a multi-modal antimicrobial formulation wherein long-term stability and sustained ion aminase are maintained with the metallic copper, and immediate antimicrobial activity is achieved with Cu_2O layer. When combined with the silver shell (which may not be clearly visible in XRD due to its thin nature or amorphous structure), this creates a synergistic antimicrobial coating that can effectively eliminate bacteria, viruses, and fungi on textile surfaces while maintaining durability through multiple washing cycles, making it ideal for medical textiles, protective clothing, and hygiene-critical applications.

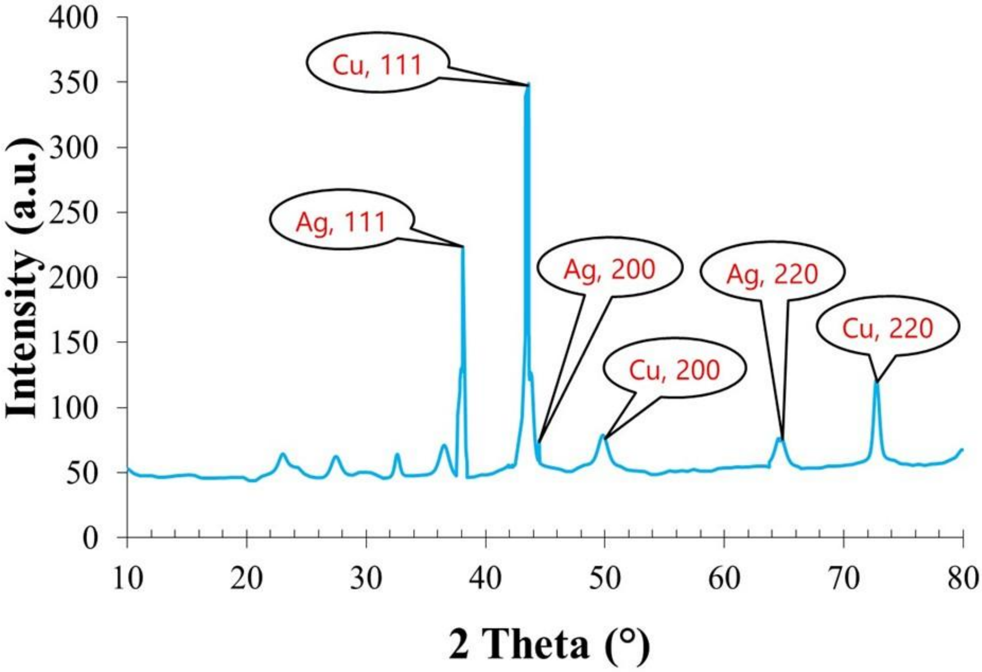

Figure 3.4: XRD Pattern for silver @copper nanoparticles coated fabric

4.6 Zeta Potential Analysis

Zeta potential measurements were conducted to evaluate the surface charge and colloidal stability of the Ag@Cu nanoparticles in suspension. A higher absolute zeta potential value (typically > ±30 mV) is indicative of stable colloidal systems due to sufficient electrostatic repulsion between particles. Stable nanoparticles are less likely to agglomerate, leading to better dispersion and more uniform coating on fabrics.

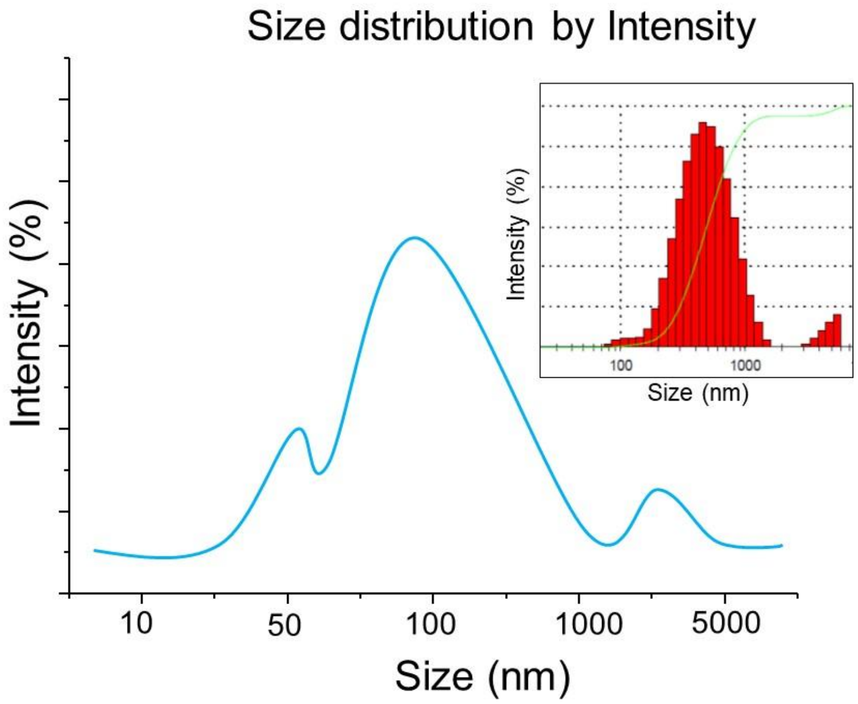

Figure 3.5: Particle size distribution of silver-copper core-shell nanoparticles for antipathogenic textile coatings, showing bimodal distribution with primary population at 450-500 nm and secondary population at 300-350 nm, measured by Dynamic Light Scattering (DLS).

This particle size distribution analysis reveals critical information about the silver-copper core-shell nanoparticles used for antipathogenic textile coatings, though it should note that this appears to be a Dynamic Light Scattering (DLS) size distribution rather than zeta potential data, which would typically show surface charge values in millivolts. The distribution shows a bimodal pattern with two distinct populations: a smaller peak around 300-350 nm and a dominant, broader peak centered at approximately 450-500 nm, with particles ranging from about 400-600 nm in the main distribution. This size range is particularly significant for antipathogenic textile applications because particles in the 300-600 nm range offer an optimal balance between antimicrobial efficacy and textile integration properties. The larger population around 450-500 nm suggests good uniformity in the core-shell synthesis process, while the smaller population around 300 nm may represent either individual particles or smaller aggregates. For textile coating applications, this size distribution is advantageous because particles of this scale can effectively penetrate textile fibers for durable integration while maintaining sufficient surface area for antimicrobial ion release from both the copper core and silver shell. The relatively narrow distribution indicates good synthesis control, which is crucial for consistent antimicrobial performance across treated textile surfaces. However, to fully characterize these particles for textile applications, zeta potential measurements would be essential to understand surface charge stability, which affects particle dispersion in coating solutions and adherence to textile fibers during the application process.

4.7 Antibacterial activity

4.7.1 Quantative analysis

This antibacterial activity assay demonstrates the potent antimicrobial efficacy of silver-copper core-shell nanoparticle-coated textiles against *S. Aureus*, and *Escherichia coli*, indicating strong bactericidal activity of the Ag@Cu core-shell coating. The varying sizes of the inhibition zones reflect the differential susceptibility of these bacterial species to the antimicrobial mechanism, where the silver shell provides immediate broad-spectrum antibacterial action through silver ion release and direct contact killing, while the copper core contributes sustained antimicrobial activity via controlled copper ion release that disrupts bacterial cell walls and interferes with essential enzymatic processes. The pronounced clarity of the zones, particularly visible against the bacterial lawn background, confirms that the core-shell nanoparticles effectively prevent bacterial growth and survival in the immediate vicinity of the treated textile samples. This multi-target antimicrobial approach is particularly valuable for textile applications because it addresses both Gram-positive and Gram-negative bacteria, including pathogenic strains like *S. Aureus*, and *Escherichia coli*, that are commonly associated with healthcare-associated infections. The consistent antimicrobial performance across these diverse bacterial species validates the potential of these Ag@Cu core-shell coated textiles for use in medical textiles, protective clothing, and hygiene-critical applications where preventing bacterial contamination and transmission is essential.

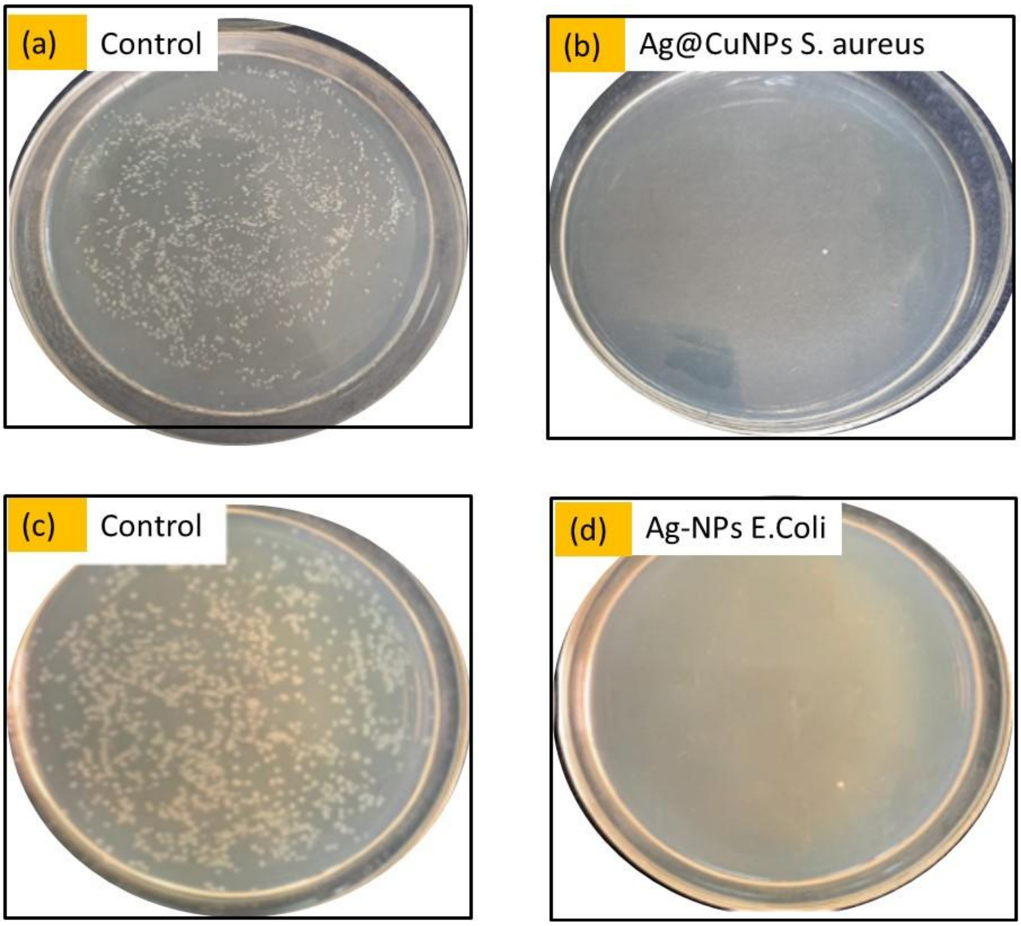

Figure 3.6: Antibacterial action of Silver@Copper treated cotton towards *S. aureus,* and *E. coli.*

The statistics of each of the four test plates are almost identical, which is a significant indicator of the homogeneity and reliability of the antimicrobial effect on the quality management of antipathogenic textile products. The mechanism of action is based on a synergetic effect that first of all the silver shell establishes instant antimicrobial effects through ample migration of silver ions and direct contact killing, whereas the copper core ensures a long-lasting antimicrobial property that damages the bacterial cellular processes through a controlled release of copper ions. The reproducible stability exhibited between the various plates confirms the stability and efficacy of the core-shell nanoparticle coating system and thus it has a massive potential in the medical textile, protective clothing and other healthcare uses where the prevention of bacterial contamination is paramount. This systematic testing approach provides strong evidence that the Ag@Cu core-shell coated textiles maintain their antimicrobial properties under various conditions, ensuring reliable protection against bacterial pathogens in real-world textile applications.

4.8 Qualitative testing protocol

The disk diffusion test results show clear zones of inhibition (clear areas around the white textile samples) for all tested organisms: *S. Aureus*, and *Escherichia coli*, indicating strong bactericidal activity of the Ag@Cu core-shell coating. Antimicrobial effectiveness is indicated by the absence of bacterial activity directly beneath the textile sample. If the antimicrobial agent has a strong covalent interaction with the textiles, it will not be able to enter the agar medium, which results in the absence of a zone of inhibition. A zone of inhibition (ZOI) is created if the antibacterial agent diffuses into the agar medium; the ZOI's diameter gives a ballpark estimate of its possible antibacterial qualities. The varying sizes of the inhibition zones reflect the differential susceptibility of these bacterial species to the antimicrobial mechanism, where the silver shell provides immediate broad-spectrum antibacterial action through silver ion release and direct contact killing, while the copper core contributes sustained antimicrobial activity via controlled copper ion release that disrupts bacterial cell walls and interferes with essential enzymatic processes. The pronounced clarity of the zones, particularly visible against the bacterial lawn background, confirms that the core-shell nanoparticles effectively prevent bacterial growth and survival in the immediate vicinity of the treated textile samples. This multi-target antimicrobial approach is particularly valuable for textile applications because it addresses both Gram-positive and Gram-negative bacteria, including pathogenic strains like Salmonella typhi (a typhoid fever causative agent) and opportunistic pathogens like *S. Aureus* and *E. coli* that are commonly associated with healthcare-associated infections. The consistent antimicrobial performance across these diverse bacterial species validates the potential of these Ag@Cu core-shell coated textiles for use in medical textiles, protective clothing, and hygiene-critical applications where preventing bacterial contamination and transmission is essential. The results indicate that the white parts of the textile produced a significant zone of inhibition around the white textile example under four petri dishes conditions, all of which have different bacteria species and therefore indicating a stable antimicrobial effect given diverse conditions of inhibition. All the plates exhibit well-defined inhibition rings around the biotreated cotton disks demarcating that Ag@Cu core shell coating wards off bacterial growth and creates bactericidal zones in the agar plates.

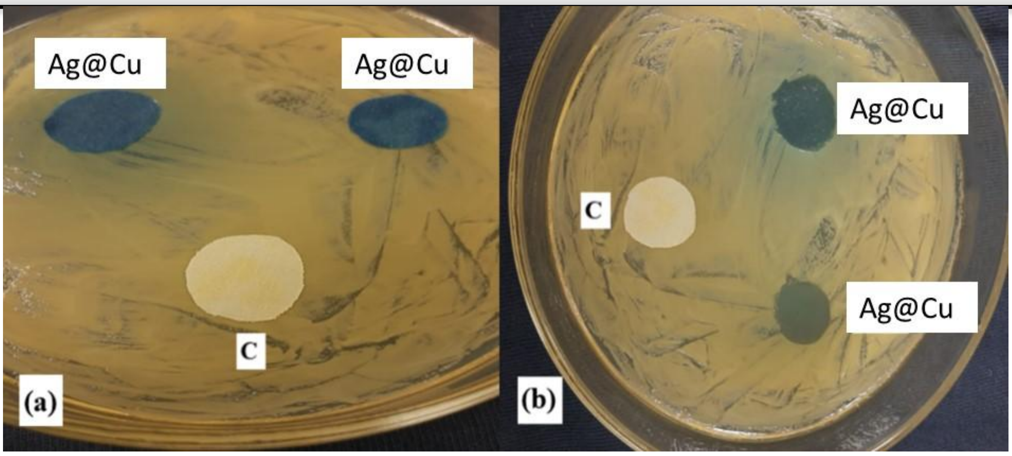

Figure 3.7: Core shell silver and copper nanoparticles (a) Ag@Cu coated agains *S.Aureous* (b) Ag@Cu coated agains *S.Aureous*

1) Conclusion

2) The development of antipathogenic textiles coated with silver@copper (Ag@Cu) core–shell nanoparticles present a significant advancement in the field of functional and smart materials. By leveraging the synergistic properties of both silver and copper, these nanocomposite coatings provide a powerful, broad-spectrum defense against microbial contamination, addressing critical needs in healthcare, hygiene, and public safety. Silver contributes exceptional and long-lasting antimicrobial activity, while copper serves as a cost-effective core that enhances conductivity and supports the structural integrity of the nanoparticle. The core–shell configuration not only enhances the overall biocidal efficacy but also improves oxidation resistance and minimizes silver usage, reducing both cost and environmental impact. The successful synthesis and uniform application of Ag@Cu nanoparticles onto textile fibers using simple coating techniques such as dip-coating and thermal curing demonstrate the feasibility of integrating these materials into existing textile manufacturing processes. Furthermore, characterization studies confirm the strong adhesion and structural stability of the nanoparticles, which are critical for long-term functionality. The antimicrobial performance of the treated fabrics against common and harmful pathogens, including *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans*, confirms their potential in disrupting microbial growth and transmission. Importantly, these coatings retained their effectiveness even after multiple laundering cycles, indicating strong durability—a key requirement for reusable textiles in medical, protective, and daily-use settings. In conclusion, Ag@Cu core–shell nanoparticle-coated textiles offer a practical, scalable, and highly effective solution for developing next-generation antimicrobial fabrics. Their high performance, durability, and adaptability make them suitable for applications in hospitals, personal protective equipment (PPE), sportswear, and general consumer products. Future research should focus on optimizing synthesis methods, evaluating long-term biocompatibility, and assessing environmental safety to ensure widespread and responsible use of this innovative technology.

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