

Development of copper-zinc oxide nanocomposite based antimicrobial fabric

Supriya S. More¹, Sagar More², Pankaj S. Ghatage^{*3} and Santosh More⁴

¹Department of Robotics and Automation, Rajarambapu Institute of Technology, Rajaramnagar, Affiliated to Shivaji University, Kolhapur, Maharashtra-415414, India

²Utopia Automation and Control, Satara, India

³Department of Automobile Engineering, Rajarambapu Institute of Technology, Rajaramnagar, Affiliated to Shivaji University, Kolhapur, Maharashtra-415414, India

⁴Aker Powergas Pvt. Ltd., Pune, India

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Abstract. The use of antimicrobial fabric is one of the ways to control pandemic diseases. This research work reports development and characterization of copper-zinc oxide nanocomposite based antimicrobial fabric. In this research work copper-zinc oxide nanocomposite material is synthesized in innovative Turbo Galvano Chemical Reactor and is characterized by Scanning Electron Microscope (SEM) and XRD. The copper-zinc oxide nanocomposite is coated on cotton fabric by using spray coating process. The characterization of coated fabric is carried out using SEM and EDXA. The antimicrobial fabric specimens with different loading of copper-zinc nanocomposites from 1GSM to 4 GSM are tested for its efficacy to deactivate bacteria strains like *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Escherichia coli*. The microbe's deactivation test is conducted using AATCC 100 protocol. The fabric with 4 GSM copper-zinc nanocomposite loading shown 99.9 % deactivation of colony forming units of gram positive and gram-negative bacteria. The fabric is tested for its reuse after washing cycles. It also shown less than 4% loss of nanomaterial particles after 60 standard washing cycles. The reusability of the treated fabric enhances its sustainability, reducing waste and supporting environmentally conscious textile applications. The characterization also proved the fabric is safe to use on skin. The demonstrated antimicrobial efficacy and durable integration of the nanocomposite onto fabric surfaces suggest strong potential for commercial applications in medical textiles, protective clothing, and hygiene products. This research will help to explore infinite possibilities of applications of this material in development antimicrobial surfaces.

Keywords: antimicrobial fabric; CuO/ZnO nanocomposite; nanomaterial

1. Introduction

The microbe's contamination on surface is common and unavoidable. This can be minimized by frequently cleaning the surface by effective disinfectant. But frequent cleaning is tedious and its effectiveness depends on many parameters like microbes killing ability of disinfectant, frequency of use and cleaning, method and protocol of cleaning, the skill of person etc. The contamination leads to diseases and further health, financial and psychological issues. Fabric is most common surface human beings are coming in contact with. The wearing, bedsheets, curtain, sofa covers, doormats, towels, handkerchiefs, masks etc. are some forms through which fabric comes in contact with human being. Microbes take advantage of high surface area and moisture retaining property of fabric to stay and increase its colony in quick time (Sanders *et al.* 2021, Gulati *et al.* 2022, Morais *et al.* 2016).

According to the World Health Organization (WHO), healthcare-associated infections (HAIs) affect approximately 7 out of every 100 hospitalized patients in high-income countries, and 15 out of every 100 in low- and middle-

income countries. This statistic underscores the significant burden of HAIs globally (Data from WHO website). Contaminated textiles, including bed linens, gowns, and other hospital fabrics, are recognized as potential vectors for the transmission of pathogens within healthcare settings. Proper handling, laundering, and disinfection of these textiles are crucial components of infection prevention and control strategies. Fabric-associated microbial contamination is a growing concern across multiple sectors, including healthcare, sports, hospitality, and public transportation. Textiles can serve as reservoirs for pathogenic microorganisms, contributing to the spread of infections through direct skin contact or cross-contamination. Studies have shown that contaminated fabrics can retain and transmit bacteria for prolonged periods, with up to 30% of surface-associated infections potentially linked to textile exposure (Sanders *et al.* 2021). These risks underscore the urgent need for antimicrobial fabrics that can effectively inhibit microbial growth and reduce the burden of fabric-mediated transmission in diverse real-world environments. Previous studies have demonstrated that frequently used fabrics, such as cotton and polyester, can harbour pathogenic bacteria such as *Staphylococcus aureus* and *Escherichia coli* for extended periods, posing risks in both healthcare and domestic environments (Neely & Maley, 2000). This gives rise to need of making fabric microbes resistant. The efforts

*Corresponding author, Assistant Professor,
E-mail: pankaj.ghatage@ritindia.edu

have been made to make antimicrobial fabric using cellulose (Nemes *et al.* 2022, Sharma *et al.* 2022) with quaternary ammonium salt by Zhao and Sun (2006), derivatives of cellulose (Khattak *et al.* 2019), bio composites (Bustamante-Torres *et al.* 2022), polysaccharides (Coma *et al.* 2015). The use of nano-materials has also witnessed a good antimicrobial property (Paszkievicz *et al.* 2016, Palanivel *et al.* 2023). Sometimes these nano materials like gold, silver, copper, copper alloys are introduced cellulose stage or at finishing state (El-Naggar *et al.* 2018, Falletta *et al.* 2008). Antimicrobial bio-materials for textiles like metal salts, Quaternary ammonium compounds (Cheng *et al.* 2020), Triclosan, Chitosan, N-halamine, Peroxyacids has been tested for its antimicrobial activities on textile fibres using suitable method of application (during finishing or during extrusion) (Nemes *et al.* 2022). Development of antimicrobial fabric involves chemical deposition of nano-particle (Osório *et al.* 2012), application of natural extracts (plant extracts, chitosan), incorporation of microbial agents (probiotics, certain enzymes) (Kalaiyarasi *et al.* 2023), physical treatment (UV treatment, electrospinning) (Coradi *et al.* 2018, Noorian *et al.* 2015), polymer modification (use of Quaternary Ammonium compounds) (Rodríguez-Tobías *et al.* 2019), biotechnology (genetic modification).

Nanomaterials like copper, copper oxide, silver, silver oxide, zinc oxide used to target antimicrobial property of fabric and has shown excellent bactericidal efficacy (Mao *et al.* 2010, Sataev *et al.* 2014, Onar *et al.* 2011, Bengalli *et al.* 2021, Osório *et al.* 2012, Karunakaran *et al.* 2023, Mahmud *et al.* 2020, Khosroyar and Arastehnodeh, 2018). These materials are applied either in solid form or in the form of colloidal solution either by spraying or by deep coating to achieve antimicrobial characteristic to the fabric. These fabrics are tested by using standard test method and shown great efficacy of microbe's deactivation for all range of microbes including several types of bacteria's, fungi and viruses. The deactivation time of these microbes varies as per the efficacy of antimicrobial material.

Thus, the literature above shows that many attempts were made to develop antimicrobial fabric using biomaterial or metallic nano material. To the best of knowledge of author there is no evidences in literature which speaks about simple and scalable synthesis of Copper Oxide -Zinc Oxide nanocomposite material, the modest method for coating this nanocomposite on cotton fabric.

This research work focuses on synthesis of copper-zinc oxide nanocomposite (hence forth will be referred as Cuo/Zno nanocomposite) with unique and scalable process, impingements of these nanoparticles on cotton fabric by using spray coating techniques, testing of the fabric for antimicrobial property, retention of antimicrobial characteristic and safety of use for human being, result, discussion and conclusion of the study. This material is commercialized as antimicrobial material named 'Weefab antimicrobial fabric' by research team.

2. Material and method

There is ancient history for use of nanoparticles in

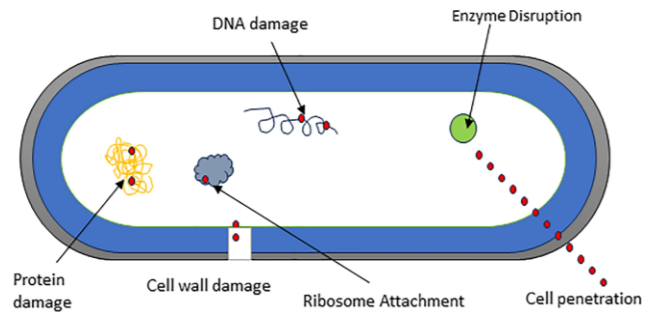


Fig. 1 Microbes' deactivation mechanisms

medical field includes drug delivery, chronic wound healing and antimicrobial activities. The field of antimicrobial surfaces is vast includes the development of antimicrobial coatings, paints, fabrics even on internal surface of water carrying PVC pipes (Supraja *et al.* 2017).

Microbes are primarily bacteria, fungus and virus. Bacteria are of two types gram positive bacteria and gram-negative bacteria. This research work is focusing on deactivation of bacteria, two representative bacteria i.e., Staphylococcus which is commonly called as S. aureus (gram positive bacteria) and Escherichia coli commonly called as E. coli (negative gram bacteria) are used for determination of efficacy of antimicrobial fabric.

The bacteria can be deactivated by antimicrobial material using cell wall damage, protein damage, DNA damage, inhibition of enzyme action, ribosome attachment, inhibition of nuclei acid synthesis etc. (Mendes *et al.* 2022) as shown in Fig. 1.

Thus, to activate this antimicrobial mechanism on fabric, the scalable manufacturing of antimicrobial nanoparticles and its proper attachment on fabric is crucial task. These two processes are explained step by step in next sessions.

2.1 Materials

The cotton fabric substrate used in this research work is woven, 45 GSM (from Rashtra Shakti Textile, Ichalkaranji, Maharashtra). Reagents used for synthesis of Cuo/Zno nanocomposite are copper sulphate pentahydrate LR, (Supplied by Sigma Aldrich). Sodium hydroxide LR detergent commercial; grade is used for pre-treatment of fabric. Acrylic binder IDRRYL ABR 407 and fixer commercial grade (Supplied by VIJET Products PVT. LTD. Ichalkaranji) are used for binding nanoparticles with fabric.

2.1.1 Substrate

The woven cotton fabric has good tensile strength, as it has orderly arrangement of fibres. The cotton fabric has flexibility to be used for daily wearing, athletic wear, footwear, medical aprons, hospital bedsheets, hospital curtains, houseware applications like towels, carpets, doormats, dusting towels, baby carpets, baby wears etc. This substrate is easily available, user friendly, easy to clean and maintained in good condition for good number of use cycles. It has good porosity so can be used comfortably on skin as well as in applications like face mask.

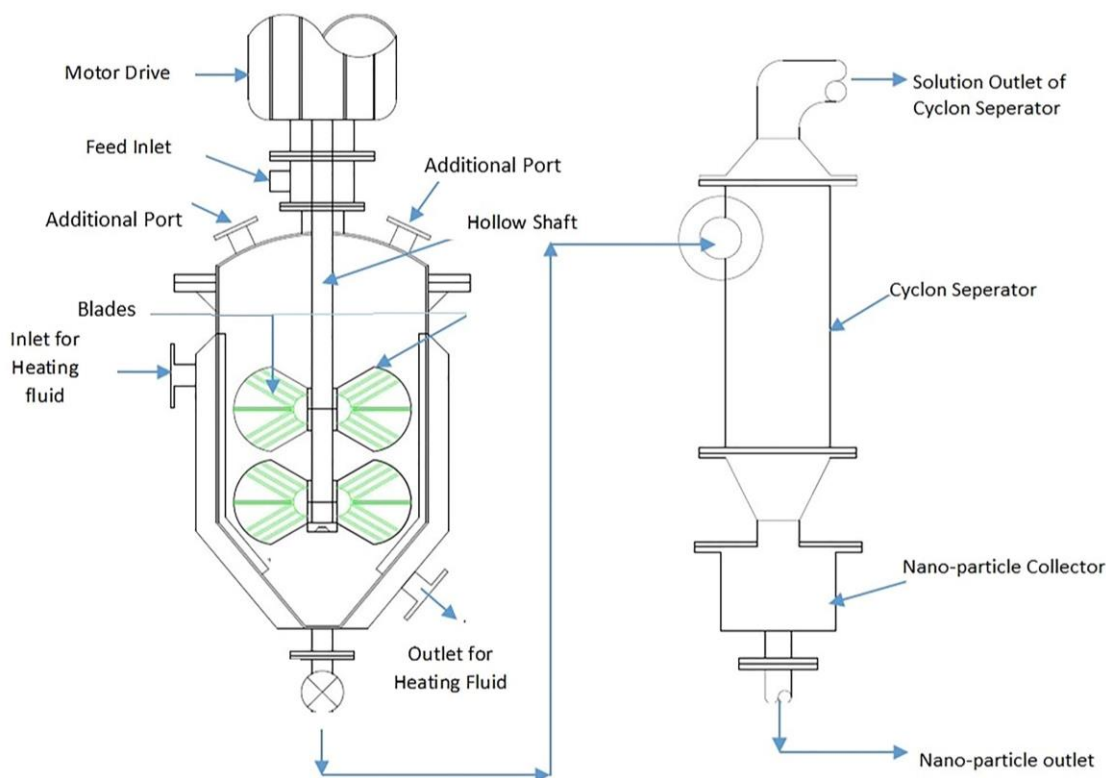


Fig. 2 Process block diagram of the continuous Turbo Galvano Chemical Reactor (TGCR reactor)

2.2 Synthesis of copper-zinc oxide nanocomposite

This research work focuses on antimicrobial effect of metallic nano-particles. Many researchers have studied antimicrobial property of fabric developed by embedding copper nano-particles (Chang *et al.* 2021), copper oxide (Emam *et al.* 2014), silver nano-particles (Sagadevan *et al.* 2019), gold nano-particles by Russell and Hugo (1994), titanium oxide nano-particles (Kalachyova *et al.* 2017), zinc oxide nano-particles (Alvarez-Amparán *et al.* 2022, Chang *et al.* 2021). The synthesis and characterization of copper oxide and zinc oxide nanoparticles is carried out by Rai and Bajpai (2021), however they have not developed antimicrobial fabric using developed particles. In the present research work Copper-Zinc oxide nanocomposites are developed by using unique and simplest scalable method. The details of the same are discussed in this section.

Synthesis of CuO/ZnO nanocomposite is critical task. There are several methods reported for synthesis of CuO/ZnO nanocomposite like thermal decomposition method (Saravanan *et al.* 2013), chemical precipitation method (Kuriakose *et al.* 2015), carbothermal evaporation method, modified perfume spray pyrolysis method (Saravannakumar *et al.* 2018). In the present work, a novel method is developed i.e. Turbo-Galvano Chemical Synthesis (TGCS) process for synthesis of CuO/ZnO nanocomposite (patent no 474766/ Indian Patent Office). The schematic diagram of TGCR is depicted in Fig. 2. CuO/ZnO nanocomposites were synthesized in the TGCR reactor. It involves galvanic reaction of the metal salt precursor and a low redox metal element at turbulence to generate nanoparticle. Distilled water, Copper salt (Copper sulphate pentahydrate) and pure

metal precursor of zinc used for preparation of nano-particles. A 10% by weight copper salt solution was prepared by dissolving analytical grade copper sulfate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) in deionized (DI) water by continuous magnetic stirring. To eliminate any traces of dissolved oxygen that could interfere with the galvanic reaction, the solution was saturated with argon gas using a Venturi injector, ensuring an inert reaction environment. The Turbo Galvano-Chemical Reactor (TGCR), has a high-speed blade-type stirring mechanism, it was preheated to 50 °C and maintained at this temperature for 30 minutes while stirring at a speed of 2400 rpm using a motor-driven hollow shaft under an argon atmosphere.

Once thermal equilibrium was attained, the deoxygenated copper salt solution was introduced into the reactor through the blade-integrated feed mechanism to ensure uniform dispersion. Then, elemental zinc powder was added slowly and controllably to achieve a 2.4% zinc concentration relative to the total solution volume. This precise addition initiated a spontaneous galvanochemical reaction between zinc and copper ions, which was driven by the electrochemical potential difference of the Cu–Zn galvanic couple. The reaction led to the simultaneous reduction of Cu^{2+} to Cu/CuO nanoparticles and partial galvanic displacement forming a Cu–CuO/Zn nanocomposite.

The formed nanocomposite was continuously separated from the liquid phase in a cyclone separator, where centrifugal action efficiently isolated the solid product. The separated Cu–CuO/Zn nanocomposite was then subjected to drying in a vacuum oven at 80 °C and 760 mm Hg for 2 hours to remove residual moisture. To enhance crystallinity and phase purity, calcination was performed at 450 °C for 3

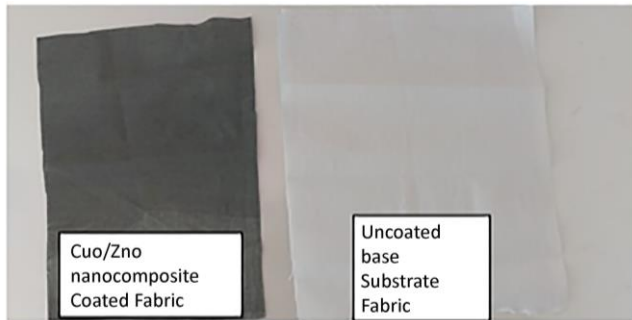
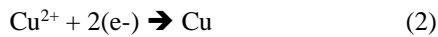
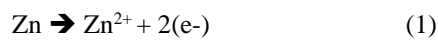


Fig. 3 CuO/ZnO nanocomposite coated fabric

hours in a muffle furnace, resulting in the formation of a well-defined CuO/ZnO nanocomposite.

The chemical reaction is given below in Eqs. (1)-(3).



The size of CuO/ZnO nanocomposite depends on various parameters like speed of motor, concentration of copper sulphate, reaction temperature and pressure. All these parameters are studied and reported in thesis More S.S. (2020) and patent [patent no 474766/ Indian Patent Office].

Manufacturing CuO/ZnO nanocomposites with defined characteristics and high consistency is achievable through careful optimization of key parameters such as temperature, pressure, reaction time, shaft speed, and reactant concentrations. At industrial scale, minor by-products may form, but these can be effectively separated through appropriate downstream processing. Additionally, wastewater generated during synthesis must be managed responsibly, with treatment designed to remove residual nanoparticles, partially reacted species, and trace elemental contaminants.

2.3 Deposition of nano-particles on fabric

There are different methods for embedding nano-material particles on fabric Viz. dip coating, spray coating, sol gel method, chemical vapor deposition, electrospinning, layer by layer assembly, printing technique, physical vapor deposition, roll to roll coating, cross linking agent (You *et al.* 2018, Pakdel *et al.* 2011)

The spraying method has some advantages like uniform coating, feature of controlling layer thickness, less wastage of nanomaterial, requires simple and low-cost equipment, less time involvement, harmless to substrate fabric, scalable and adoptable for any nano-material (Meda *et al.* 2023). These all advantages encouraged to adopt this spray coating method for applying CuO/ZnO nanocomposite on the selected substrate in this research work. In fact, in this research work two methods like crosslinking and spray coating are combined to increase durability and enhance effectiveness of the process (Tania and Ali 2021, Pinho *et al.* 2011). The 1 m² fabric was weighted first. Soaked substrate fabric with 5 gm detergent in 80 °C water for 30

minutes. Washed fabric substrate 4 times in Normal Water. After it was Soaked with 40 gm NaOH in 80 °C water for 30 minutes. Again, the fabric substrate washed 4 times in Normal Water and soaked in shadow. The 4 gm of CuO/ZnO nanocomposite was mixed with 0.8 gm binder and 0.08 gm of crosslinking agent. Sprayed binder on substrate fabric with spray nozzle. After binder the CuO/ZnO nanocomposite solution was sprayed on fabric uniformly. The coated fabric was heated to 80 °C for 1 hour. Then it was washed and ironed. Fig. 3 shows the photograph of fabric before and after coating with CuO/ZnO nanocomposite. The picture shows the uniform distribution of CuO/ZnO nanocomposite on substrate.

2.4 Material characterization

The treated fabric samples were characterized using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analysis (EDXA). SEM provided high-resolution images of the surface morphology, allowing for the visualization of nanocomposite deposition on the cotton fibres. This was critical for evaluating the uniformity, particle size distribution, and physical integration of the Cu-ZnO nanocomposite onto the textile substrate. EDXA, coupled with SEM, was employed for elemental analysis to confirm the successful incorporation of copper and zinc.

The CuO/ZnO nanocomposite material's crystalline structure was examined using X-ray diffraction method (XRD) using Panalytic Xpert Powder Diffractometer (Laxmi Analytics Laboratory, Mumbai, Maharashtra, India). The XRD is done using Copper anode with K alpha1=1.54060 Å, K alpha2=1.5443 Å, K-Beta= 1.39225 Å, current 45 mA and Voltage 45 kV, in 2θ starting at 4.02 ° to 79.98 °.

The external morphology like grain structure and size of particles was observed using Scanning Electron Microscopy (SEM) in Laxmi Analytics Laboratory, Mumbai, Maharashtra, India.

After coating fabric with CuO/ZnO nanocomposite material again the morphology of the antimicrobial fabric was examined using SEM and elemental analysis was confirmed using Energy dispersive X ray Spectroscopy (EDXA) at Yashwantrao Chavan Institute of Science, Satara, Maharashtra, India. The Signal SED with landing voltage of 10 kV, 500X magnification at high vacuum mode with, 500X magnification at high vacuum mode with 54.00 CPS count rate was used.

2.5 Antimicrobial efficacy test

There are different methods to check efficacy of antimicrobial fabric VIZ. Agar diffusion Test, Zone of inhibition test, minimum inhibitory concentration test, Minimum bactericide concentration test, Time- kill Assay, Agar Shake flask test, AATCC 100 test, ISO20743:2013, fungicidal activity test (Nakashima *et al.* 2001, Rajendra *et al.* 2010). Out of these all AATCC 100 (Microchem laboratory, 2016) method is used for testing efficacy of bacterial deactivation of antimicrobial fabric developed in this research work. This method is standardized and specifically designed for textile, and provides flexibility to choose gram-positive and gram-negative bacteria, provides quantitative data of bacterial

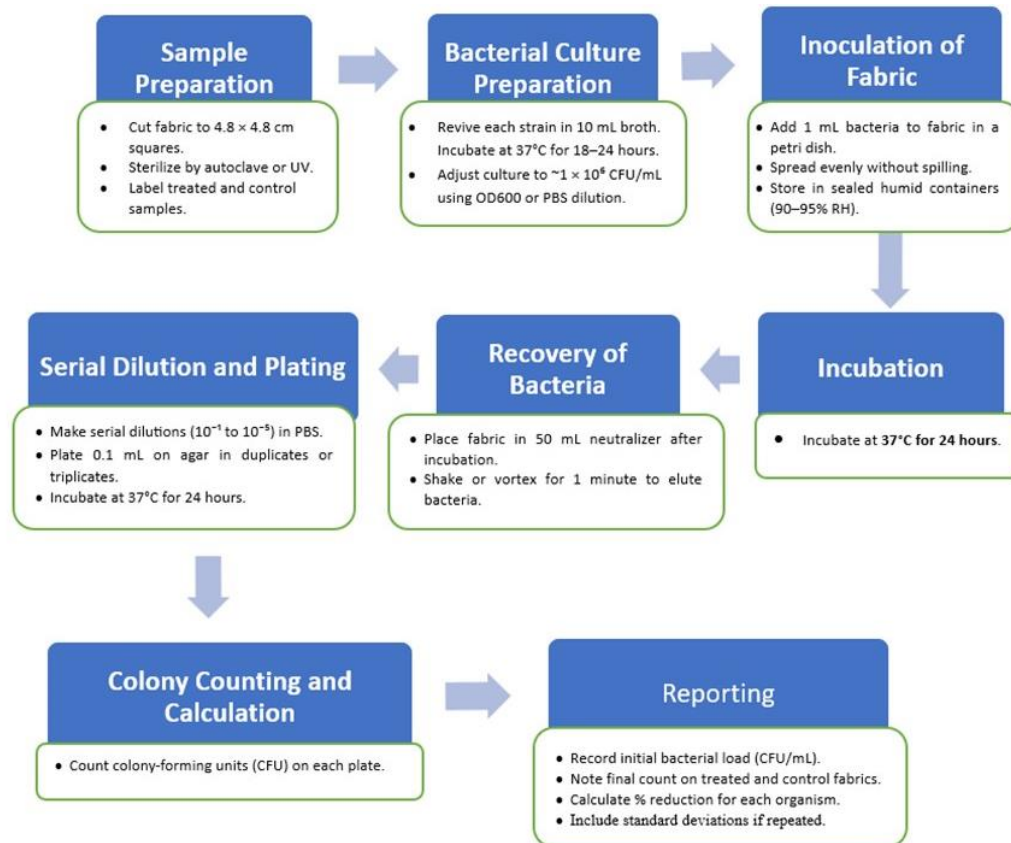


Fig. 4 General process of testing fabric for antimicrobial efficacy using AATCC 100 protocol

deactivation, Variable contact time ensures durability of antimicrobial treatment, the test is useful for bacteriostatic and bactericidal effect.

Including of above characteristic AATCC 100 processes has one more strength that, the process of this test is clearly defined starting from bacterial solution preparation, incubation environment, and measurement of bacterial count which ensures accuracy of results.

The Cuo/Zno nanocomposite based antimicrobial fabric developed in this research work was tested at ‘The Bombay Textile Research Association’ (The laboratory recognized by Ministry of Science and Technology, India) The test method is AATCC100. The sample is of 4.8 ± 0.1 cm. *Staphylococcus aureus* ATCC 6538, *Klebsiella pneumoniae* ATCC 4352 and *Escherichia coli* ATCC 25922 these bacterial stains were used for checking microbe’s deactivation efficacy. Media used was Nutrient Agar, DE Broth, the sample was tested at 37°C and for a period of 24 hours. Steam flow sterilization method was used to sterilize surface. Fig. 4 shows steps followed for AATCC 100 test for testing efficacy of bacterial deactivation of each of bacterial strains.

To check effect of Cuo/Zno nanocomposite loading on antimicrobial activity, 4 different samples were prepared. Fig. 5 shows samples with different Cuo/Zno nanocomposite, starting from 1 gram per square meter (GSM) to 4 GSM loading of Cuo/Zno nanocomposite by incremental difference of 1 GSM. While preparing the sample all procedure followed was same. The Samples were named as Fabric 1, Fabric 2, Fabric 3, Fabric 4 as shown in Fig. 4.

2.6 Nano-particle retention test

As anti-microbial material developed can be used for many applications from daily wearing to dusting towel, it will go through number of washing cycles (Ghosh *et al.* 2010). It becomes necessary to check Cuo/Zno nanocomposite retention on antimicrobial fabric so that the microbe’s deactivation can be effectively done on antimicrobial fabric after wash. The washing test was conducted using DI water at 25 °C. The non-ionic detergent was used for washing with 1% concentration for the test. The standard washing procedure was followed with hand wash.

2.7 Safety test

There are different tests for determining safety profile of antimicrobial fabric like, acute and subacute dermal, primary skin sensitization and irritation, skin patch test etc. (White *et al.* 2003)

Skin irritation study of the antimicrobial fabric developed in this research work was conducted by patch test. This test is a blind fold test. 50 number of people with different age, sex and belonging to different geographical area were selected for test. 25 bands of Cuo/Zno nanocomposite based antimicrobial fabric and 25 bands of non-coated cotton base substrate fabric of size that was comfortable to fold on wrist were blindfold randomly on wrist of 50 people. After 8 hrs of their normal working, observations were recorded were recorded of their experience about skin irritation/skin itching.



Fig. 5 Sample of fabric with different Cu/ZnO nano-composite loading on fabric

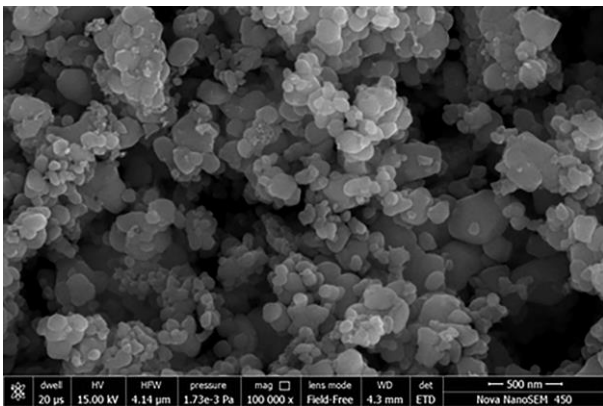


Fig. 6 Scanning Electron Microscope (SEM) image of Cu/ZnO nanocomposite

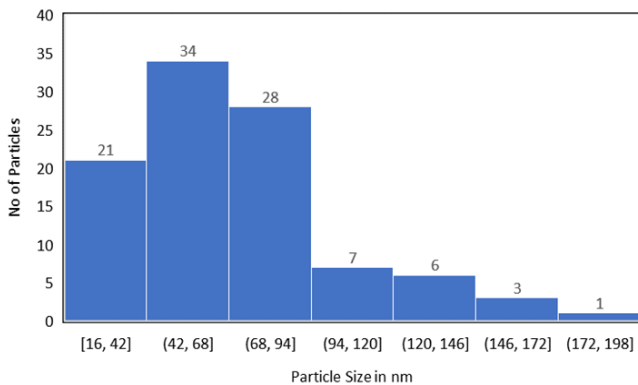


Fig. 7 Particle size distribution of Cu/ZnO nanocomposite

3. Result and discussion

3.1 Morphological analysis of copper-zinc oxide nanocomposite

Fig. 6 shows SEM of Cu/ZnO nanocomposite. The Cu/ZnO nanocomposite particles can be observed in SEM image. The SEM of Cu/ZnO nanocomposite shows that the particles are approximately 110 ± 10 nm.

Fig. 7 shows particle size distribution of Cu/ZnO nanocomposite obtained using image J software, which depicts that D 90 of nanoparticles are of size 110 ± 10 nm.

Fig. 8 shows energy dispersive X-ray analysis of Cu/

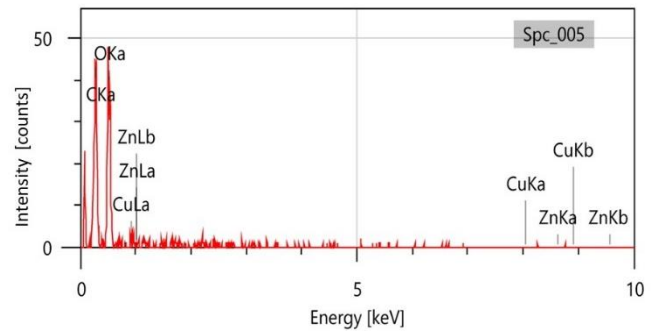


Fig. 8 Energy dispersive X-Ray analysis of Cu/ZnO nano-composite based antimicrobial fabric

Table 1 Elemental analysis result

Element	Line	Mass%	Atom%
C	K	44.54 ± 1.47	54.45 ± 1.79
O	K	47.69 ± 2.93	43.77 ± 2.69
Cu	L	6.09 ± 0.5	1.41 ± 0.39
Zn	L	1.68 ± 0.112	0.38 ± 0.025
Total		100	100

ZnO nanocomposite based antimicrobial fabric. In XRD 2θ peaks at 25.47° , 35.57° , 38.76° resembles the copper oxide and the 2θ peaks at 36.46° , 48.87° , 61.51° resembles with reference pattern of the zinc oxide. The sharp peaks of both CuO and ZnO depicts that the material is crystalline. This confirmed that material is composite of copper oxide and zinc oxide. The correlation and interpretation of XRD of CuO/ZnO nanocomposite disclosed that, it contains 87 % copper oxide and 13% zinc oxide.

3.2 Morphological analysis of copper-zinc oxide nanocomposite based antimicrobial fabric

Fig. 8 and Table 1 shows the result of EDX analysis. It shows that the antimicrobial fabric contains copper, zinc, oxygen and carbon. The percentage distribution shows that it contains 6.09 % copper and 1.68 % zinc. As the ratio molecular weight of copper and copper oxide is 1.25. It means that, the material contains 7.612 gm of copper oxide, similarly it contains 2.08 gm of zinc oxide as recorded in Table 2. Thus, in total the total weight of CuO/ZnO nanocomposite is 9.69 gm. The weight analysis of 1 m^2 antimicrobial fabric is shown in Table 2 where comparison of experimental and EDXA result is given. The percentage weight of CuO/ZnO nanocomposite actually loaded on fabric and percentage weight that is depicted from EDXA analysis is almost same with less than 1% variation in result.

Fig. 9 gives SEM analysis of CuO/ZnO nanocomposite based antimicrobial fabric. Fig. 9a represents oven structure of cotton fabric. This 100-micrometre scale image shows long, cylindrical, twisted oven fabric. Fig 9b shows 50-micrometre scale image in which the CuO/ZnO nanocomposite material distribution over fabric structure can be observed clearly. Fig. 9c with 10 micrometre scale shows the irregular shaped nanocomposites on fabric. This figures also shows that, the CuO/ZnO nanocomposite are partially

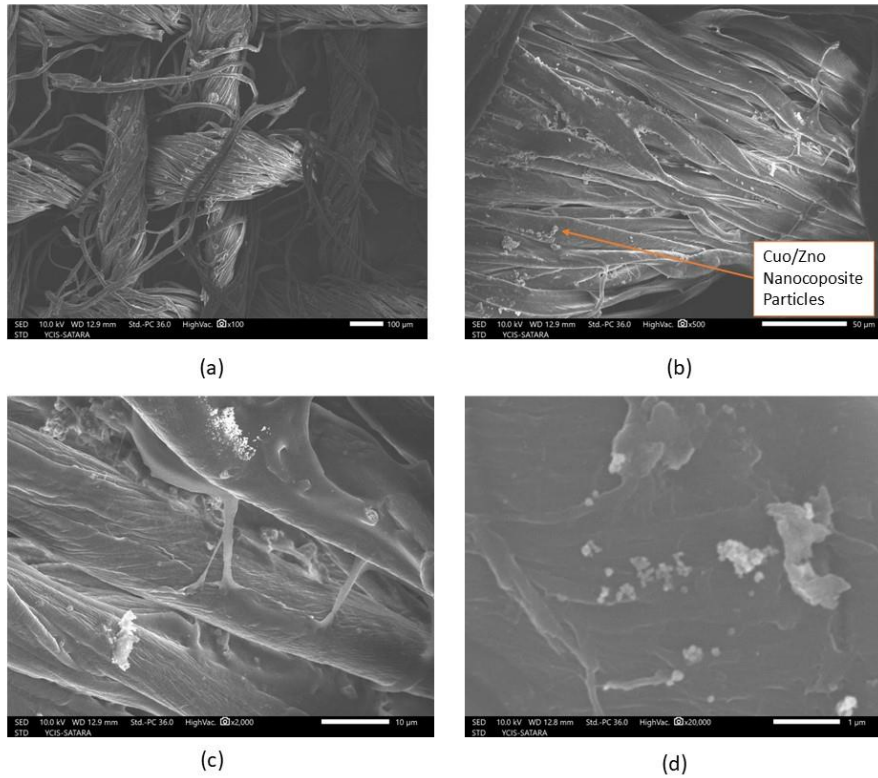


Fig. 9 Scanning Electron Microscope (SEM) image of CuO/ZnO nanocomposite based antimicrobial fabric

Table 2 Comparison of elemental analysis with experimental observations

Particulars	GSM	Mass % (Experimental)	Mass % (EDXA)
Weight of Fabric Before Pretreatment	42.13183	-	-
Weight of Fabric After Pretreatment	37.49531	88.57142857±1	88.38±1
Weight of CuO/ZnO nanocomposite	4.031754	9.523809524±0.3	9.7145±0.25
Weight of Binder	0.806351	1.904761905±0.02	1.9±0.018
Total Weight of Fabric	42.33342	100	100

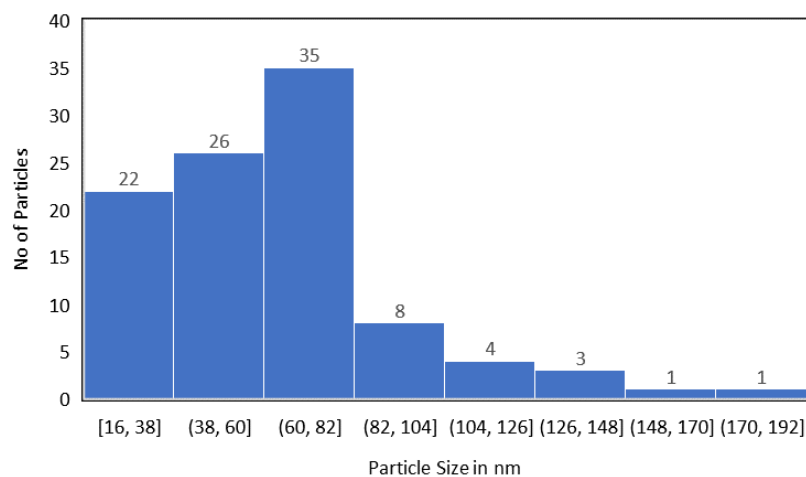


Fig. 10 Particle size distribution on antimicrobial fabric

penetrated into the fabric which might have been resulted into good particle retention by antimicrobial fabric as observed in particle retention test results discussed in section 3.4. Fig. 9d shows SEM with 1 micrometre scale

shows the CuO/ZnO nanocomposite particle size varies from 20 nm to 185 nm and some clusters are also get formed on fabric.

Fig. 10 shows the particle size distribution on antimicrobial

Table 3 Results of AATCC100 test with statistical analysis

Sr. No	Sample Name	CZCNPs Loading in GSM	% Bacterial Deactivation			Observation
			Staphylococcus aureus ATCC 6538 % Reduction	Klebsiella pneumoniae A ATCC 4352% Reduction	Escherichia coli ATCC 25922 % Reduction	
1	Fabric 1	1	0.00	0.00	0.00	No Bacterial Deactivation
2	Fabric 2	2	18.00	20.00	21	Poor Bacterial Deactivation
3	Fabric 3	3	46.00	45.00	48	Better Bacterial Deactivation
3	Fabric 4	4	99.94	99.86	99.99	Excellent Bacterial Deactivation
p-value			<0.01	<0.01	<0.01	
Significance			significant	significant	significant	

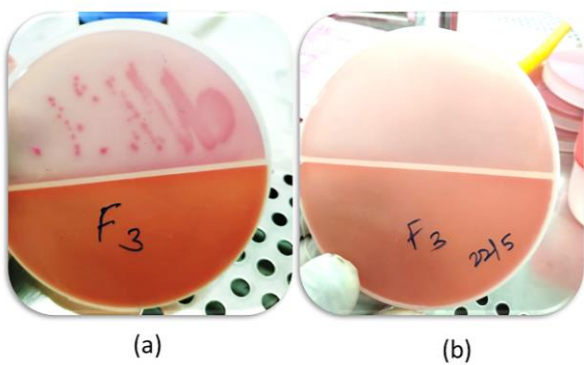


Fig. 11 Test results of antimicrobial fibre using AATCC100 (a) Initial sample (b) Sample after TAT ~ 0 CFU

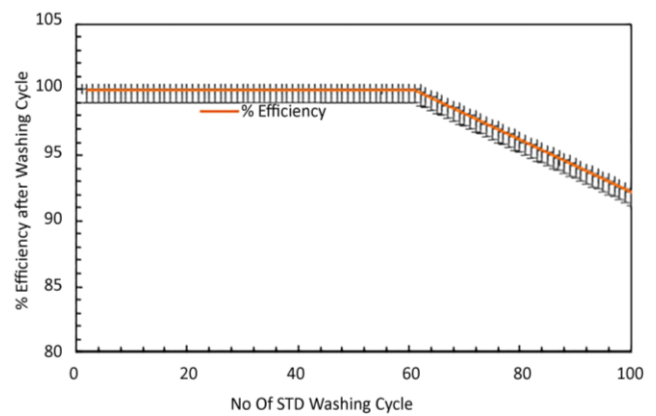


Fig. 13 Effect of washing cycle on bacterial deactivation

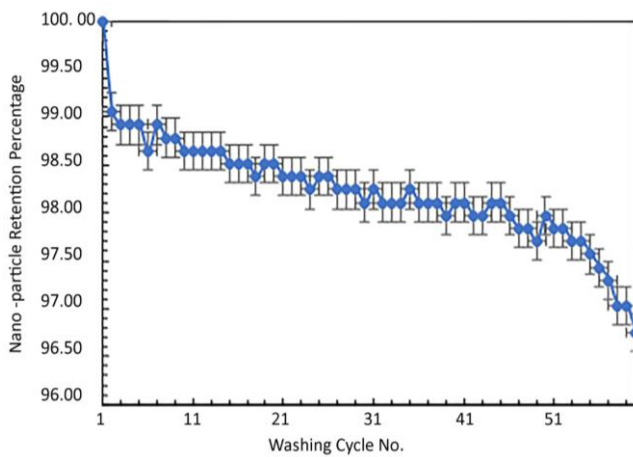


Fig. 12 Washing cycle results of antimicrobial fabric

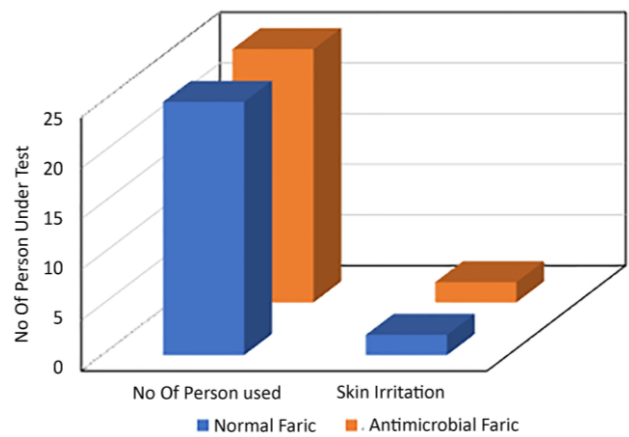


Fig. 14 Safety test results of Cuo/Zno nanocomposite based antimicrobial fabric

fabric. The particle size on fabric resembles with particle size of nanocomposite shown in Fig 7. Thus, it confirmed that there is no formation of agglomerates of large size even after deposition of fabric.

3.3 Microbe’s deactivation efficacy

The four samples described in section 2.5 were tested using AATCC100 test. The test was carried out for standard time of 24 hrs. Table 3 shows the Bacterial Colony Forming Units (CFU) on samples of the fabric after standard time

and percentage reduction in bacterial count. It shows that the specimen fabric with Cuo/Zno nanocomposite loading of 1 GSM, 2 GSM, 3 GSM were unable to deactivate all CFU of selected species of bacteria under standard test condition. The specimen fabric with 4 GSM loading deactivated 100% microbes from its surface under standard test conditions. Fig. 11 shows the sample pictures for initial and final samples with incubation of bacteria on the specimen having 4 GSM loading of Cuo/Zno nanocomposite on its surface. Thus, loading more than 4 GSM

Table 4 Comparison of current research with literature

Nano-material	Average size in nm	Loading of Nanomaterial in GSM	Antimicrobial Efficacy/ zone of inhibition dia in mm	Durability in terms of washing cycle	Safety (Hodge and Sterner Scale)	Compatibility	Scalability	Reference
Cu	60-100	5	Escherichia coli (97.69%)	NA	4 (Slightly toxic)	100% woven cotton fabric	No	Shatma <i>et al.</i> 2022, Chen <i>et al.</i> 2006
Cuo	45	3	Escherichia coli (97%) Staphylococcus aureus (92%) C. albicans (95%) M.canis (92%)	NA	3 (Moderately toxic)	100% woven cotton fabric	No	Chen <i>et al.</i> 2006, El-Nahhal <i>et al.</i> 2018
Zno	60-75	2.5	Staphylococcus aureus (94%) Escherichia coli (86%)	20	4 (Slightly toxic)	100% woven cotton fabric	No	Rajendra <i>et al.</i> 2010, Chen <i>et al.</i> 2006
Cuo and Zno nanoparticles	24-51	7	pseudomonas aeruginosa (15 mm) Proteus mirabilis (20 mm) E. Coli (18 mm) Staphylococcus aureus (17 mm)	NA	3 (Moderately toxic)	100% woven cotton fabric	No	Saravanakkumar <i>et al.</i> 2018, Chen <i>et al.</i> 2006
Cuo/Zno nanocomposites	200	4	Escherichia coli (97.94%) Klebsiella pneumonia (99.86) Staphylococcus aureus (99.99%)	60	5 (Practically non-toxic)	100% woven cotton fabric	Yes	Current research work

on fabric becomes insignificant and increases production cost.

The test report from laboratory shown that, Staphylococcus aureus deactivation efficacy is 99.94 % and Klebsiella pneumoniae efficacy is 99.86 %. The results also showed 99.99% efficacy for Escherichia coli. Statistical analysis was conducted using one-way ANOVA, revealing that the differences in antibacterial activity between treated and untreated fabrics were statistically significant ($p < 0.01$) as shown in Table 3. The results confirm the strong antimicrobial efficacy of the Cu-ZnO nanocomposite treatment. Copper oxide and zinc oxide nanoparticles have individually demonstrated antimicrobial properties in previous studies. In this research, a novel synthesis approach was employed to create a CuO/ZnO nanocomposite, which was then applied to fabric through a straightforward method. The combined nanocomposite exhibited significantly enhanced antimicrobial activity compared to the individual components. The enhanced antimicrobial activity observed in the CuO/ZnO nanocomposite is attributed to a synergistic interaction between the two metal oxides, each possessing distinct yet complementary mechanisms of action. ZnO nanoparticles are known for generating reactive oxygen species (ROS) and releasing Zn^{2+} ions, which disrupt microbial membranes and interfere with metabolic processes. CuO nanoparticles, on the other hand, release Cu^{2+} ions that bind to cellular proteins and nucleic acids, causing structural and functional damage. When combined, these nanoparticles exhibit enhanced ROS production and simultaneous dual-ion toxicity, creating a multi-targeted antimicrobial effect. This

synergism leads to improved efficacy even at lower concentrations, reduces the likelihood of microbial resistance, and broadens the antimicrobial spectrum, making the composite more effective than either component alone. This synergetic effect makes this nano-composite more effective on bacterial efficacy. The CuO/ Zno nanocomposites are stable in nature in different environmental conditions. The stability makes the nano-composite suitable for long lasting antimicrobial effect. Microorganisms develops resistance to single antimicrobial agent which makes it ineffective over certain time. The combined effect of CuO and Zno effect mitigate this resistance.

3.4 Results of nano-particle retention test

The CuO/Zno nanocomposite retention is important phenomenon in view of sustainable antimicrobial characteristic of antimicrobial fabric. The standard washing cycle results are shown in Fig. 12.

The test was conducted for 60 washing cycle that average fabric goes through. The results showed that, even after 60 standard washing cycle 96.62% of nano-particles retained on the fabric surface. It means there was only 3.38% loss of CuO/Zno nanocomposite after 60 standard washing cycle. This ensured the performance of antimicrobial fabric will be good even after repeated washing and soaking under normal condition.

It becomes important to study the bacterial deactivation efficacy after washing cycle. The study is conducted using

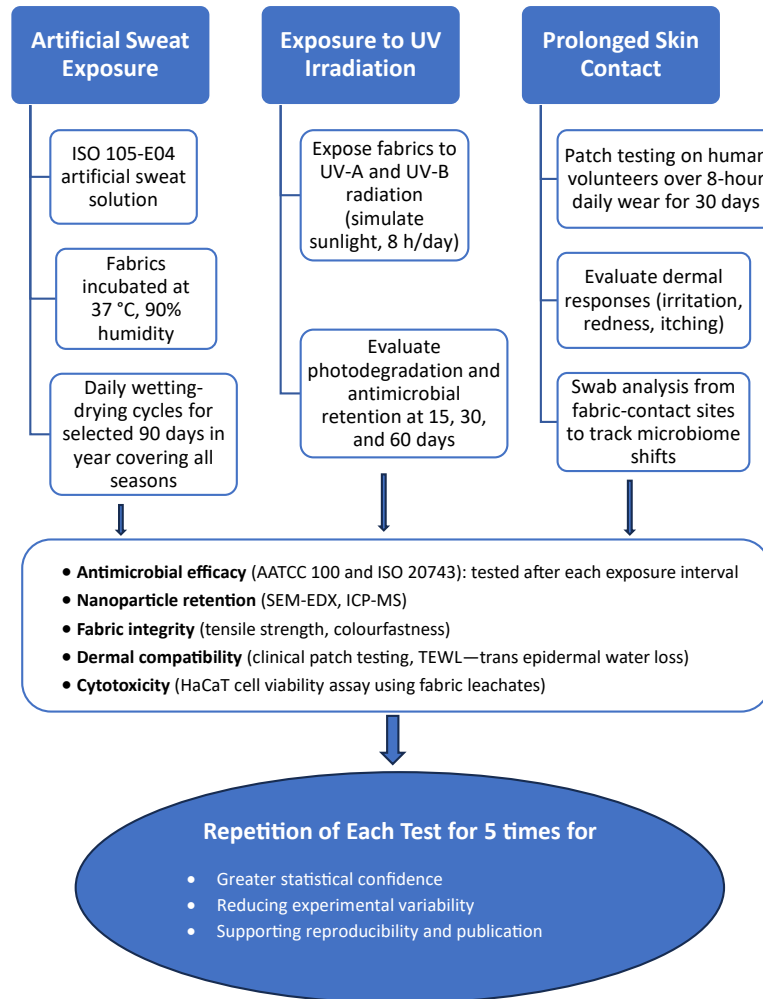


Fig. 15 Follow-up study path to test the real-time efficacy under dynamic conditions

AATCC 100 method after each washing cycle of antimicrobial fabric. The antimicrobial fabric was exposed to 2200 CFU by following standard procedure and CFU of bacteria were counted after 24 Hrs. Fig. 13 shows efficacy of Cuo/Zno nanocomposite based antimicrobial fabric after each standard washing cycle described in section 2.6. Harsh washing processes, including the use of aggressive chemicals and rigorous mechanical action, can significantly impact the durability and efficiency of the washing cycles.

The graph shows that up to 60 standard washing cycle of antimicrobial fabric exhibits almost 100% efficacy of microbe's deactivation. From washing cycle 61 to 100 there is less than 8 % reduction in bacterial deactivation rate. The significant retention of antimicrobial efficacy after multiple washes highlights the fabric's durability and sustained functional performance under regular maintenance conditions. This long-lasting antimicrobial property is particularly important for practical applications where hygiene and infection control are critical, such as in healthcare settings, sportswear, and protective clothing. The fabric's ability to maintain its antimicrobial activity over time reduces the need for frequent replacement and special care, thereby lowering maintenance costs and enhancing its suitability for long-term use.

3.5 Safety test

The safety performance of Cuo/Zno nanocomposite based antimicrobial fabric was tested using blindfold test. The observations shows that less than 2 % people experienced itching or skin irritation. The fact is that this experience is same for both types of fabric Viz. normal fabric and Cuo/Zno nanocomposite based antimicrobial fabric. Fig. 14 shows that the safety profile of antimicrobial fabric is as good as normal cotton fabric. The retest was conducted for the persons who reported itching/skin irritation by swapping the fabric samples. In retest result there was no any skin irritation/ itching is observed. Although no immediate adverse effects were observed in preliminary assessments, further dermatological testing is necessary to evaluate long-term biocompatibility and the risk of irritation or sensitization under some conditions like low PH value of skin (due to sweat, or any other reason) direct contact with wounds.

Table 4 shows the comparison of this Cuo/Zno nanocomposite based antimicrobial fabric with same category of antimicrobial fabric available in literature. The Table 4 also depicts that, the Cuo Zno nanocomposite developed by Saravanakkumar *et al.* 2018, Chen *et al.* 2006 requires 7

Table 5 Cost comparison of antimicrobial fabric available in market

Sr. No.	Brand name	Nanomaterial used	Cost in INR.
01	Maftsons	Zno	Rs. 250/meter
02	X static	Ag	Rs. 300/meter
03	Green Nano	cu	Rs. 150/meter
04	Weefab (Developed in this research)	Cuo-Zno nanocomposite	Rs. 40/meter

GSM loading and data regarding durability after washing is not available for the same in addition, the research work does not give possibility of scalable manufacturing of nanoparticles. Current research needs less nanoparticle loading 4 GSM, durable up to 60 washing cycle and shows the potential of scalable manufacturing of Cuo/Zno nanoparticles.

The Cuo/Zno nanocomposite based antimicrobial fabric shows great efficacy of deactivation on gram positive and gram-negative bacteria. The durability Cuo/Zno nanocomposite based antimicrobial fabric is best with 60 washing cycle with optimum loading of antimicrobial nanomaterial. The research reports scalable manufacturing of Cuo/Zno nanocomposite based antimicrobial nanomaterial. This research work has been converted into commercial product weefab antimicrobial fabric by research team. The reusable, washable antimicrobial mask is developed by team to serve society during Covid 19 pandemic. The Cuo/Zno nanocomposite based antimicrobial fabric is practically non-toxic and at a scale of 5 when compared to Hodge and Sterner Scale (Rossella Bengalli *et al.* 2021). Thus, Tables 3 and 4 shows that the developed Cuo/Zno nanocomposite based antimicrobial material is superior in efficacy, durability, safety and scalability. Table 5 gives the cost comparison of antimicrobial fabric available in market on this date.

This research represents the next step toward developing an antimicrobial material that is safe, scalable, and cost-effective, harnessing the combined antimicrobial properties of CuO and ZnO.

The antimicrobial fabric, priced at approximately INR 40 per meter, is cost-effective compared to similar functional textiles. However, adoption in low-income or rural areas may be limited by cost sensitivity, awareness gaps, and distribution challenges. Ethical use requires transparency about safety and adherence to regional regulations governing nanomaterial-treated textiles. Pilot programs supported by public or NGO partnerships could help validate performance and improve accessibility in underserved communities.

The antimicrobial fabric developed in this study shows strong potential for application in several high-demand sectors. In the healthcare industry, it can be used in hospital linens, patient gowns, and surgical scrubs to help reduce the risk of hospital-acquired infections. In sportswear and activewear, the fabric offers odor control and hygiene benefits, aligning with the growing consumer preference for performance-enhancing apparel. Additionally, the fabric could serve in the production of reusable face masks and public transportation upholstery, where antimicrobial

properties are increasingly sought after. Market reports indicate a significant rise in demand for antimicrobial textiles, particularly post-COVID-19, with the global market projected to reach USD 20 billion by 2026, underscoring the commercial relevance of the developed material.

4. Conclusions

In this study, Cuo/Zno nanocomposite material is manufactured in a simple and scalable manner and then embedded into fabric to develop antimicrobial fabric. The synthesized nanocomposite material is characterised and the developed fabric is tested for its effectiveness. Based on the study the following conclusions are listed;

- Cuo/Zno nanocomposite particles are manufactured using galvanic pair of copper and zinc in Turbo Galvanic Chemical Reactor. The innovative Turbo Galvanic Chemical Reactor used in this research work ensures scalable manufacturing of Cuo/Zno nanocomposite.

- The Cuo/Zno nanocomposites are characterized for its composition and particle size. The Cuo/Zno nanocomposite size of D 90 of nanoparticles are of size 110 ± 10 nm. The SEM and EDXA of Cuo/Zno nanocomposite based antimicrobial fabric confirms the composition and quantity of material present on fabric substrate.

- The research reports that loading of Cuo/Zno nanocomposite on cotton fabric substrate above 4 GSM of fabric exhibits excellent antimicrobial property. The AATCC100 test of this antimicrobial fabric showed, Staphylococcus aureus deactivation efficacy is 99.94 % and Klebsiella pneumoniae efficacy is 99.86 % and efficacy of Escherichia coli is 99.99%.

- The washing test showed that the antimicrobial characteristics does not hinder even after 60 washing cycle. It is found that even after 60 standard wash 96% Cuo/Zno nanocomposite retain on fabric substrate.

- The skin safety performance of the Cuo/Zno nanocomposite-based antimicrobial is excellent and resembles with normal cotton.

- This research work gives new dimension of development and scalable manufacturing of Cuo/Zno nanocomposite based antimicrobial fabric and many more applications of self-cleaning surfaces.

5. Future Scope

This study demonstrates the development of a durable antimicrobial fabric with high efficacy retention after repeated laundering, indicating strong potential for practical applications. Following are areas which need to be explored in further research.

- Future research should focus on long-term biocompatibility testing, real-world application trials. Additionally, assessing performance under varied environmental conditions will help validate its reliability. Fig. 15 is follow-up path designed for testing of developed fabric for different dynamic conditions like sweat, UV radiation, prolonged skin contact to study real time efficacy.

- The current research showed antimicrobial efficacy for

bacterial strains further systematic study is required to know efficacy of this fabric under fungal, viral, or biofilm-forming pathogens, especially in polymicrobial environments.

- Nanoparticle leaching into wastewater during extended laundering or upon disposal in landfills, as well as the formation of metal-rich residues during incineration. These issues may lead to accumulation in aquatic or soil ecosystems, with possible ecotoxicological impacts. Future work should explore comprehensive life cycle assessments (LCAs), eco-design strategies incorporating biodegradable or recyclable base fabrics, and recovery techniques for embedded nanomaterials to promote a circular and environmentally responsible deployment of antimicrobial textiles.

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Credit authorship contribution statement

Supriya S. More: Investigation, Data curation, Writing – original draft. Sagar More: Methodology, Resources, Validation. Pankaj S. Ghatage: Investigation, Visualization, Writing – review & editing. Santosh More: Visualization, Resources.

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