



Synthesis of CuO Nanocomposites and Assessment of Antimicrobial Activity Using Activated Carbon Derived from Sugarcane Bagasse

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ABSTRACT

Recent advances in nanoparticle technology have focused on medical precision, sustainability, and industrial applications. Nanoparticles exhibit properties that help prevent infections and protect human health. Copper oxide nanoparticles (CuO-NPs) have attracted considerable attention in medical applications and can be used as nanocoatings for medical implants. In this study, eco-friendly activated carbon derived from sugarcane bagasse biomass was used to synthesize CuO nanocomposite for antimicrobial activity. Six nanocomposite samples were synthesized by varying the activated carbon content. The synthesized samples were characterized using XRD, FTIR, and SEM, followed by assessment of antimicrobial activity against four bacterial strains. XRD results indicated an increase in particle size and peak broadening, suggesting improved crystallinity. FTIR results indicated strong interactions between CuO nanoparticles and surface functional groups, suggesting effective bonding between CuO and activated carbon. SEM images revealed a heterogeneous morphology with relatively uniform particle distribution, enhancing the surface area available for adsorption. Antimicrobial activity was confirmed by evaluation of the zone of inhibition (ZOI). Among the synthesized samples, the nanocomposite with a 1: 3: 0.3 (CuO: activated carbon from sugarcane bagasse [ACSB]: polyvinylpyrrolidone [PVP]) ratio exhibited the most favorable structural and morphological characteristics based on XRD, FTIR, and SEM analyses. A ZOI of 10 mm was observed against *Pseudomonas* sp. during the antimicrobial assay, whereas the remaining three bacterial strains exhibited relatively lower inhibitory responses. These results indicate that the 1: 3: 0.3 ratio demonstrated enhanced antimicrobial effectiveness, particularly against *Pseudomonas* sp. The synthesized CuO-activated carbon nanocomposites can be used as antimicrobial agents and have potential applications as nanocoatings for medical implants.

Keywords: Process Innovation; Activated *Pseudomonas* sp. carbon; Sugarcane bagasse; CuO nanocomposite; Antimicrobial activity; Biomass; Zone of inhibition.

1. INTRODUCTION

Humans are exposed to numerous health threats arising from various infections. The rapid emergence and spread of multidrug-resistant microorganisms have posed a significant challenge to global health (Coque *et al.* 2023). Pathogenic fungi and bacteria contribute to the failure of clinical treatments, leading to increased mortality and fatality rates (Assi *et al.* 2025). A major cause of such treatment failure is the development of resistance to conventional antimicrobial agents. Furthermore, the overuse and misuse of antibiotics have intensified antimicrobial resistance, highlighting the urgent need for novel therapeutic strategies to address emerging clinical challenges (Salam *et al.* 2023). Hence, there is a growing demand for alternative antimicrobial materials that can serve as effective substitutes for conventional antibiotics.

In materials science and solid-state physics, oxides derived from transition metals have attracted significant interest for various applications in the 21st century. In nanotechnology, nanoparticle research has become a cornerstone for future generations, with distinguished applications across industries (Tahir *et al.* 2023). Nanoparticles are smaller than human hair, making them potentially useful in various applications (Ali *et al.* 2024). Among a wide variety of nanoparticles, those synthesized from metal oxides have received attention due to their inherent features, such as low toxicity and rapid processing steps (Villanueva *et al.* 2020; Sharmila *et al.* 2019). Their physical, biological, and chemical properties, including resistance to resistant strains, have made them promising materials for medical applications (Varaprasad *et al.* 2020). The usefulness and demand for these nanoparticles are evident in the pharmaceutical sector, where they are employed as antimicrobial agents to prevent infections, as catalysts,

disinfectants, and fillers (Khashan *et al.* 2020; Khashan *et al.* 2016). Moreover, nanoscale size is a major factor in achieving advantageous effects against infectious bacteria (Raghunath *et al.* 2017; Rajamohan *et al.* 2023a; Tsikourkitoudi *et al.* 2022).

Among various nanoparticles synthesized using metal oxides, copper oxide nanoparticles (CuO-NPs) have attracted considerable attention due to their wide-ranging applications in antimicrobial activity, drug delivery in biomedicine, catalysis, solar energy conversion, photoconductive devices, and sensor technologies, thereby encouraging extensive research in these fields (Rahman *et al.* 2021; Murugan *et al.* 2023; Naz *et al.* 2023; Rajamohan *et al.* 2023b; Farhan *et al.* 2023). CuO is a fundamental member of copper compounds and is a p-type semiconducting compound. The literature reports various methods for the synthesis of CuO, including chemical, physical, and green approaches. A few of the synthesis methods are precipitation methods, sol-gel methods, and vapor deposition methods. The chemical and physical synthesis methods are often associated with the use of hazardous solvents and are generally expensive, energy-intensive, and time-consuming (Sabeena *et al.* 2022; Khatoun *et al.* 2023). Green synthesis using plant extracts (Ramasubbu *et al.* 2023) and biological sources involving microorganisms (Singh *et al.* 2023) is a popular synthesis method compared with conventional chemical and physical methods. The green synthesis method is environmentally friendly because it avoids the use of hazardous chemical agents, thereby enhancing the biocompatibility and reducing the toxicity of the synthesized products (Rajamohan *et al.* 2023c).

The high surface-to-volume ratio of CuO-NPs enhances their interaction with microorganisms, thereby inhibiting microbial growth and exhibiting good biocompatibility at the nanoscale (Akintelu *et al.* 2020; Ma *et al.* 2022). These inherent wide-range antimicrobial activities of CuO-NPs make them suitable for biomedical applications (Bezza *et al.* 2020; Kaningini *et al.* 2023). In certain applications, the antimicrobial activity of CuO-NPs alone is insufficient to effectively combat biofilms and drug-resistant microorganisms, necessitating the use of higher concentrations to achieve the desired antimicrobial effect. However, increasing the concentration of nanoparticles raises concerns regarding cytotoxicity to normal cells. Therefore, controlling the functional efficiency of nanoparticles while minimizing their cytotoxic effects remains a critical research challenge (Francis *et al.* 2023; Naz *et al.* 2020). Combining CuO-NPs with secondary materials, such as metals, plant extracts, and biomass-derived activated carbon, is an effective strategy for modulating their antimicrobial, structural, electronic, and optical properties. The use of metals such as magnesium, zinc, silver, and gold with CuO has a synergistic effect on its

antimicrobial activity (Khlifi *et al.* 2022; Vikal *et al.* 2023).

In recent years, biomass-derived activated carbons have gained significant attention as an eco-friendly alternative to conventional materials. Activated carbon can be produced from a variety of biomass wastes, including sugarcane bagasse (Rahmawati *et al.* 2024), *Borassus flabellifer* husk (Selvam *et al.* 2021), lemon and orange peels (Ramutshatsha-Makhwedzha *et al.* 2022), coconut shell (Sujiono *et al.* 2022), mango peels (Nair *et al.* 2023), and many other biomass sources (Yong *et al.* 2026). Previous studies have demonstrated that sugarcane bagasse, an agro-waste, can be converted into activated carbon through chemical or physical activation methods. Owing to its high surface area and porous structure, activated carbon has emerged as a sustainable material for antimicrobial applications. The activation process enhances its adsorption capacity and microbial inhibition properties (Raut *et al.* 2025).

Activated carbon derived from sugarcane bagasse, when incorporated into filtration systems and coatings, showed effective antimicrobial action against both Gram-positive and Gram-negative bacteria. Bio-based filters developed using sugarcane bagasse have shown promising antimicrobial performance (Hernández-López *et al.* 2024). The antimicrobial activity of activated carbon is primarily attributed to its ability to adsorb microbial cells, disrupt cell membranes, and, depending on its surface chemistry, generate reactive oxygen species (ROS). The modification of activated carbon combined with silver nanoparticles introduces additional bactericidal mechanisms, such as oxidative stress and ion release, thereby enhancing the antimicrobial efficacy (Gonçalves *et al.* 2016).

Despite these advances, further studies are needed to investigate the antibacterial performance of activated carbon in combination with metal oxides. Therefore, the present study focuses on the synthesis of CuO-activated carbon nanocomposites with varying composition ratios to evaluate their antimicrobial activity.

The novelty of the present study lies in the comprehensive synthesis of CuO nanocomposites using varying proportions of activated carbon derived from sugarcane bagasse. Six CuO nanocomposites with different activated carbon contents were synthesized and systematically characterized to evaluate their structural properties and antimicrobial performance for potential biomedical applications. X-ray Diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) were employed to characterize the synthesized CuO nanocomposites. The antimicrobial activity of the nanocomposite samples was evaluated against four bacterial strains. The present work aims to synthesize CuO nanocomposites and demonstrate

the potential of sugarcane bagasse as a sustainable and low-cost precursor for the development of antimicrobial materials. Dentistry is a rapidly evolving field in which nanocomposites have emerged as promising materials for advanced and modern dental applications. Hybrid nanocomposites, such as CuO nanocomposites, can be utilized as nanocoatings for dental implants owing to their potential antimicrobial properties and enhanced surface characteristics.

2. MATERIALS AND METHODS

2.1 Synthesis of Activated Carbon Nanoparticles

Sugarcane bagasse (SB) was used as a raw material to prepare activated carbon (AC). Fresh sugarcane bagasse was collected from the local sugarcane juice vendor, from Vaddeswaram village, Vijayawada district, Andhra Pradesh, India. Initially, the collected sugarcane bagasse was cut into small pieces and cleaned with water to remove soil and dust, and washed carefully using deionized water to remove the contaminants. The sugarcane bagasse initially processed was dried at 110 °C for 12 h in a hot air furnace. To prepare activated carbon, the sugarcane bagasse was treated with potassium hydroxide (KOH). In this step, sugarcane bagasse was impregnated with an 80 wt.% KOH solution at a weight ratio of 1:5 and left to soak for 24 h. Then, the KOH-treated bagasse was subjected to carbonization at 670 °C for 2 h at a heating rate of 10 °C min⁻¹ in a muffle furnace. The activated carbon derived from sugarcane bagasse (ACSB) was washed using deionized water until a pH level of 7 was reached and was

dried at 70 °C for 24 h in a hot-air oven. Fig. 1 illustrates the preparation of activated carbon derived from sugarcane bagasse.

2.2 Synthesis of Copper Oxide Nanocomposites

CuO-NPs, purchased from National Scientific Products, India, were used for CuO nanocomposite preparation. CuO NPs of 7.954 g are weighed using a balance and are transferred to a beaker. Prior to use, the beaker was thoroughly cleaned using an ultrasonic cleaner to remove dust and other contaminants. The CuO nanocomposites were synthesized by dispersing the weighed CuO-NPs and activated carbon in 50 mL of deionized water under constant stirring at 300 rpm. Polyvinylpyrrolidone (PVP) was added in small quantities as a binding agent. The agitation can be varied from 300 to 400 rpm based on the concentration of the mixture. A magnetic stirrer was used to ensure thorough mixing and obtain a homogeneous suspension. The mixture was stirred at room temperature for 24 h. Subsequently, centrifugation was performed to separate the precipitate, which was then washed with deionized water and ethanol. Finally, the washed precipitate was dried at 60 °C for 6 h. Fig. 2 illustrates the preparation of CuO nanocomposites. CuO nanocomposite samples thus synthesized were stored in sample containers for subsequent characterization. The CuO nanocomposites were prepared with the following CuO: ACSB: PVP ratios: 1: 1: 0, 1: 1: 0.1, 1: 2: 0.2, 1: 3: 0.3, 1: 4: 0.4, and 1: 5: 0.5. Fig. 3 presents the flowchart illustrating the synthesis process of CuO nanocomposites.

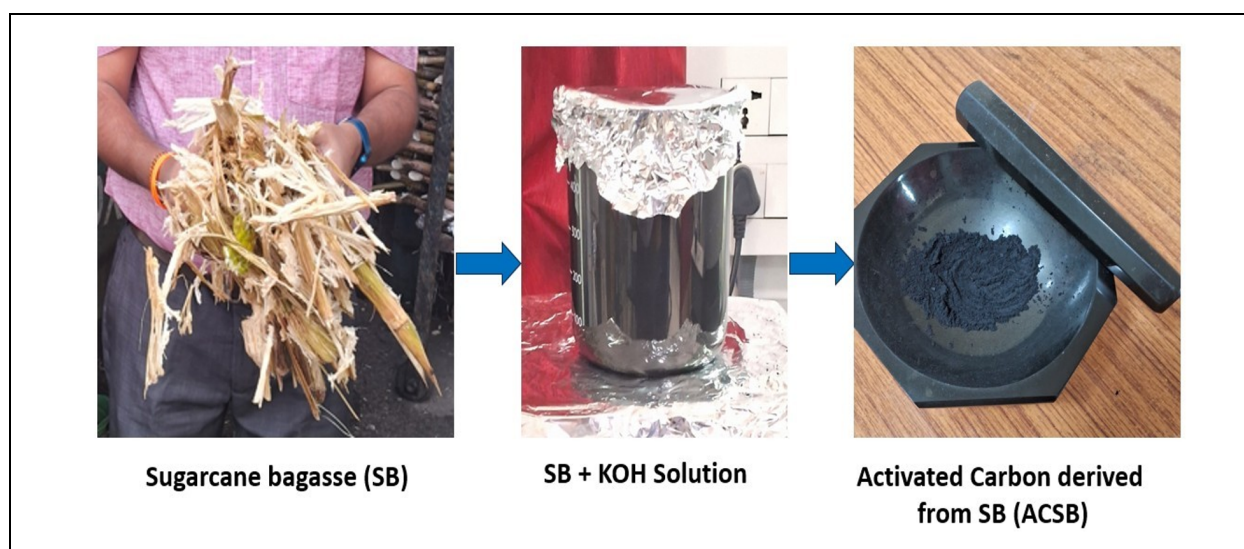


Fig. 1: Steps involved in the preparation of activated carbon from sugarcane bagasse

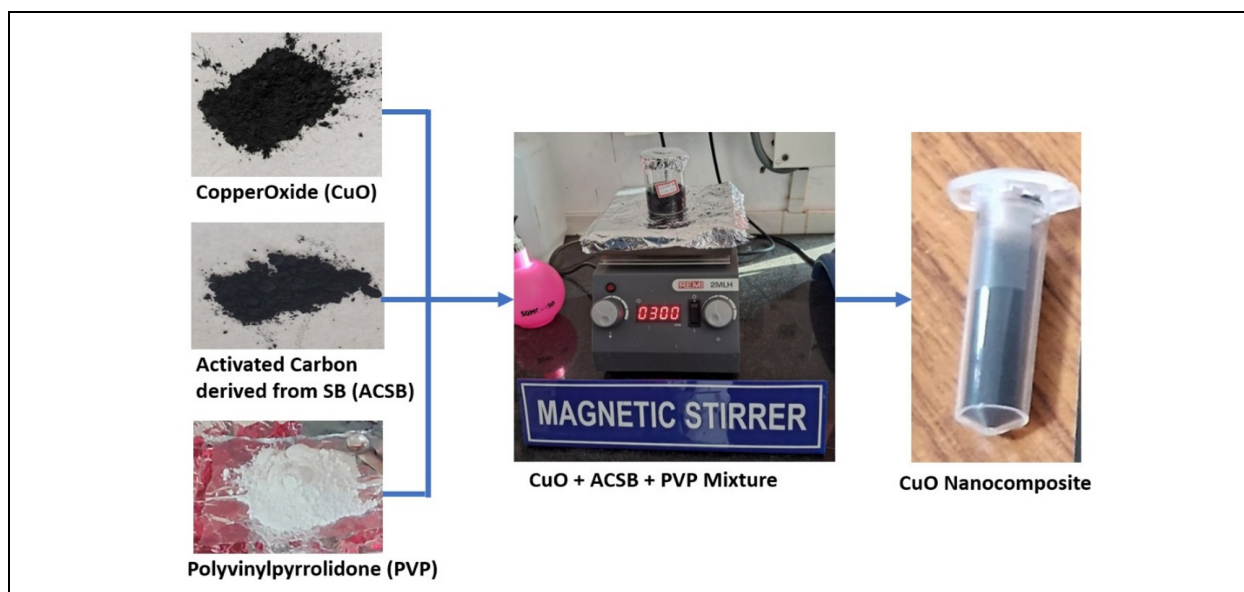


Fig. 2: Steps involved in the preparation of CuO nanocomposite

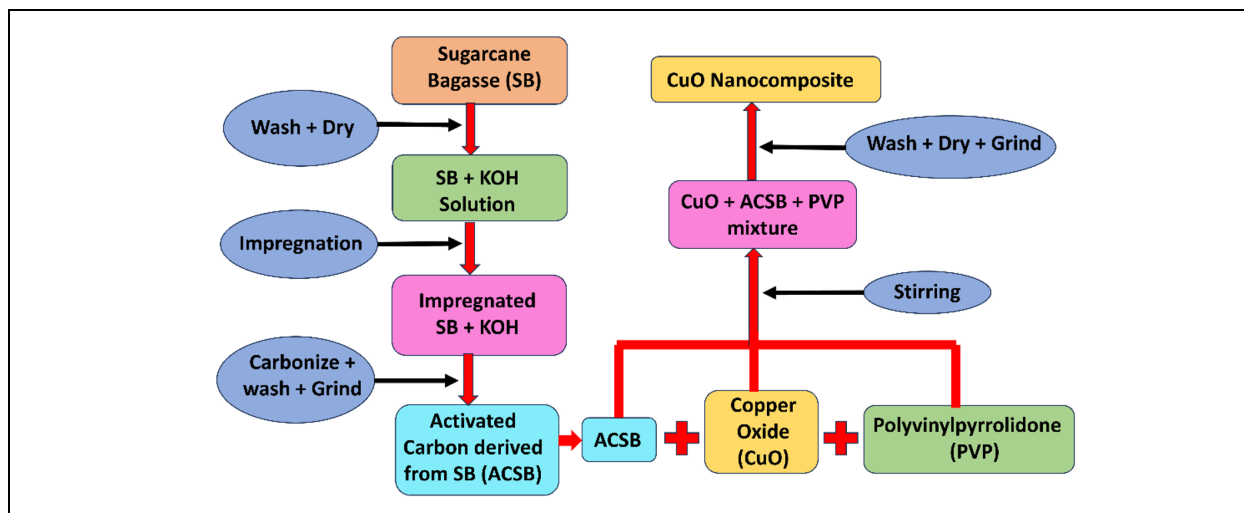


Fig. 3: Flowchart illustrating the synthesis of CuO nanocomposite using ACSB

3. RESULTS AND DISCUSSION

3.1 Characterization of Synthesized CuO Nanocomposites

In the present study, XRD, FTIR, and SEM were employed to systematically investigate the crystalline structure, functional groups, and surface morphology of the synthesized CuO nanocomposite samples. The selection of characterization techniques was guided by the need to elucidate the structural, chemical, and morphological features of the CuO nanocomposites. XRD analysis was carried out to confirm the formation of crystalline CuO nanoparticles, identify the phase composition, and evaluate their successful incorporation onto the activated carbon matrix. FTIR was employed to identify the functional groups present and to investigate

the possible interactions between CuO nanoparticles and the surface functionalities of the activated carbon. SEM was used to investigate the surface morphology, dispersion of CuO nanoparticles, and agglomerated behaviour, which are critical for antimicrobial activity. Collectively, these techniques provide complementary insights into the physicochemical properties of the CuO nanocomposites, which are essential for understanding their enhanced antimicrobial performance and potential biomedical applications.

3.2 X-ray Diffraction (XRD)

The crystalline structure of the synthesized CuO nanocomposite was analyzed using an X-ray diffractometer. The XRD patterns were recorded on a PANalytical EMPYREAN diffractometer with operating parameters of Cu K α ($\lambda=1.5405$ Å) radiation, 45 kV

operating voltage, 40 mA current, 1°/min scan rate, and 0.02° step size. Synthesized samples were placed in the XRD analyzer by loading them onto the metal slides. XRD patterns were recorded using a diffractometer over the 2θ range of 20°-80°. X'Pert HighScore Plus software was used to identify the phases. Data recorded from the XRD with Joint Committee on Powder Diffraction Standards (JCPDS) data and Debye–Scherrer equation (Ali *et al.* 2022) were used to calculate the nanoparticle size (*D*):

$$D = \frac{K\lambda}{\beta \cos \theta} \quad \dots (1)$$

where *K* is the shape factor (*K* = 0.9), *λ* is the X-ray wavelength, *β* is the FWHM, and *θ* is the Bragg angle.

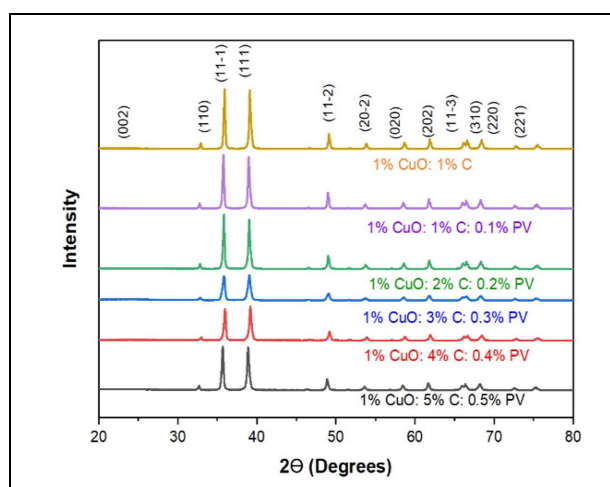


Fig. 4: XRD patterns of CuO nanocomposites at various mixing ratios

The XRD patterns of the synthesized CuO nanocomposites with different mixing ratios are shown in Fig. 4. The recorded patterns confirm the monoclinic crystal structure of CuO in all nanocomposite samples. The absence of additional diffraction peaks indicates the phase purity of the synthesized nanocomposites. Prominent diffraction peaks observed at 2θ values of 32.26°, 35.88°, 38.44°, 45.98°, 49.20°, 53.44°, 58.74°, 61.66°, 66.40°, 68.62°, and 73.06° correspond to the characteristic Bragg reflections. These peaks are indexed to the (110), (11-1), (111), (11-2), (20-2), (020), (202), (11-3), (310), (220), and (221) planes. The JCPDS card No. 00-048-1548 was used as a reference, confirming the monoclinic phase of CuO (Renuga *et al.* 2020). The activated carbon derived from sugarcane bagasse shows a peak at 2θ value of 23.36° corresponding to the (002) plane of disordered graphitic carbon, indicating its predominantly amorphous nature (Dwiyaniti *et al.* 2023).

The broadening of diffraction peaks suggests the presence of small crystallites in the synthesized samples. In general, an increase in crystallite size leads to sharper and more intense diffraction peaks, indicating

improved crystallinity and a higher degree of structural order. This indicates improved crystallinity, attributed to a reduction in lattice defects and microstrain, as evidenced by the sharper XRD peaks. According to the principles of X-ray diffraction, peak broadening is inversely related to crystallite size, confirming the formation of small crystallites (Bantikatta *et al.* 2023). The smaller CuO-NPs on activated carbon may show broader peaks due to nanoscale size and interaction with the activated carbon. As particle growth proceeds, CuO domains become more crystalline. It is observed that the diffraction peaks of the synthesized samples were slightly shifted toward higher 2θ angles compared with the reported values for undoped CuO (Paraguay-Delgado *et al.* 2022). This can be due to strong interfacial interactions between CuO-NPs and activated carbon. The average crystallite sizes of synthesized CuO-NPs were estimated using the Scherrer equation, and the corresponding crystallite sizes for different ratios are presented in Table 1. The values indicate nanoscale crystallite dimensions, which contribute to an increased surface area that is beneficial for antimicrobial and adsorption applications. The XRD peak intensities decreased with increasing activated carbon content up to the CuO: ACSB: PVP ratio of 1:3:0.3, while an increase in peak intensity was observed beyond this ratio.

XRD results thus confirm the successful synthesis of a hybrid nanocomposite, in which crystalline CuO nanoparticles are effectively anchored onto activated carbon derived from sugarcane bagasse. This structural integration is beneficial for enhancing functional performance in applications such as antimicrobial activity.

Table 1. Average crystalline size of CuO nanocomposites

CuO: ACSB: PVP	Average Crystalline Size, <i>D</i> (nm)
1: 1: 0.0	31.27
1: 1: 0.1	29.97
1: 2: 0.2	27.55
1: 3: 0.3	21.13
1: 4: 0.4	24.49
1: 5: 0.5	25.47

3.3 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was conducted on the synthesized nanocomposites to identify the presence of functional groups and the interaction between CuO nanoparticles and the activated carbon derived from sugarcane bagasse. Synthesized samples were scanned from 400 cm⁻¹ to 4000 cm⁻¹ range by loading samples on a holder (Nzilu *et al.* 2023). Equipment JASCO FT/IR-4700 Fourier Transform Infrared Spectrometry was used to obtain the FTIR spectra of the samples (Fig. 5).

The presence of functional groups in samples was identified from the characteristic peaks in the FTIR spectrum, which correspond to specific absorption bands and stretching vibrations. The absorption band in the region of $480\text{--}580\text{ cm}^{-1}$ confirms the formation of Cu–O bonds, indicating the presence of CuO-NPs in the CuO nanocomposites. The absorption band in the region of $900\text{--}1100\text{ cm}^{-1}$ corresponds to C–O stretching vibrations of alcohols, ethers, or phenolic groups present in the activated carbon. The absorption band in the region of $1550\text{--}1620\text{ cm}^{-1}$ corresponds to C=O stretching vibrations of carbonyl groups. The absorption band in the region of $2850\text{--}2950\text{ cm}^{-1}$ is attributed to C–H stretching vibrations of aliphatic groups, suggesting the presence of residual organic components from the biomass precursor. The broad band observed between 3400 and 3800 cm^{-1} corresponds to O–H stretching vibrations, indicating hydroxyl groups or adsorbed moisture on the surface. Furthermore, slight shifts in wavenumber and changes in intensity of the –OH, C=O, and C–O bands were observed compared to activated carbon derived from sugarcane bagasse (Malool *et al.* 2021). Although the pattern of FTIR spectra remains unchanged for different sample ratios, a notable peak broadening is observed for the 1: 3: 0.3 ratio sample.

FTIR results indicate strong interactions between CuO nanoparticles and surface functional groups, suggesting effective bonding of CuO to activated carbon. Such interactions enhance the physicochemical properties of the composite, particularly for adsorption and antimicrobial applications.

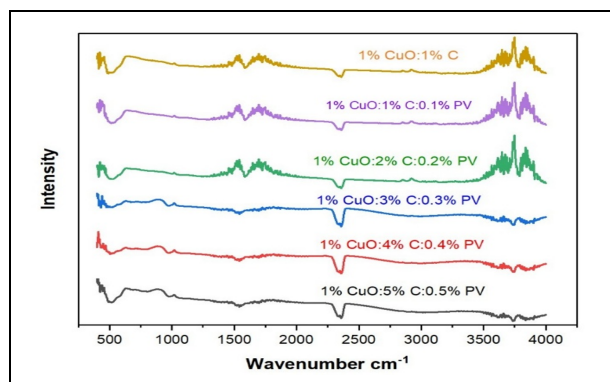
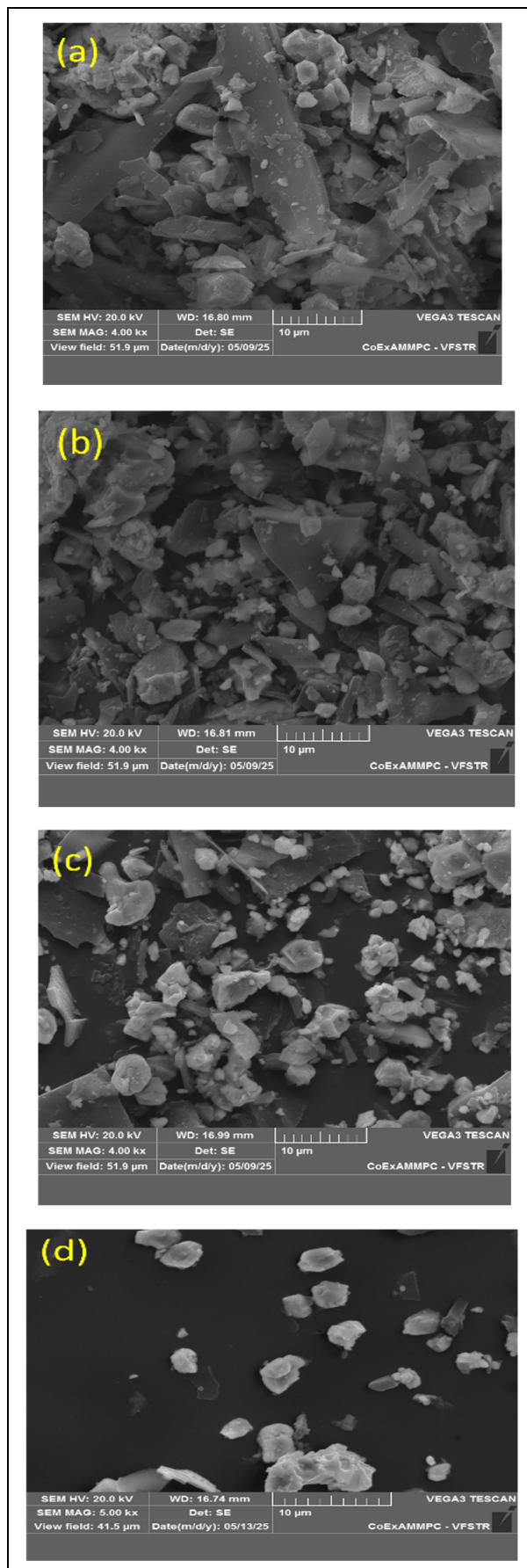


Fig. 5: FTIR spectra of CuO nanocomposites

3.4 Scanning Electron Microscopy (SEM)

SEM analysis was employed to obtain information on the surface morphology and particle agglomeration behavior of the synthesized samples. The analysis was performed using a TESCAN VEGA 3 instrument (TESCAN Brno S.R.O., Czech Republic). The morphological features of all synthesized samples were recorded as black-and-white micrographs at magnifications up to $33,000\times$ (Mote *et al.* 2023), and the corresponding SEM images are presented in Fig. 6.



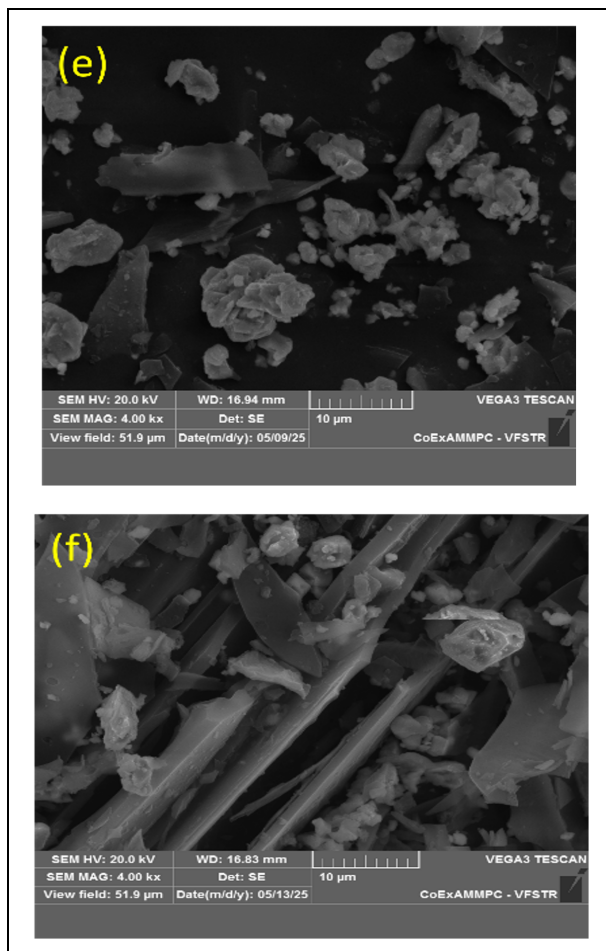


Fig. 6: SEM micrographs of CuO nanocomposite samples: (a) 1: 1: 0.0 (b) 1: 1: 0.1 (c) 1: 2: 0.2 (d) 1: 3: 0.3 (e) 1: 4: 0.4 and (f) 1: 5: 0.5

SEM images of samples with varying ratios reveal a heterogeneous morphology, where CuO nanoparticles are distributed over the surface of activated carbon. The activated carbon exhibits a porous and irregular structure, providing abundant anchoring sites for CuO nanoparticles. Additionally, the activated carbon particles display a flake-like or layered morphology with random orientation (Somyanonthanakun *et al.* 2023). Upon incorporation, CuO-NP particles are distributed over the surface of activated carbon, often occupying pores and surface cavities. The presence of CuO-NPs can be identified as brighter contrast regions compared to the darker carbon background. A relatively uniform dispersion of CuO-NPs indicates effective interaction between the components. This uniform dispersion observed in the SEM images correlates with broadened XRD peaks, suggesting smaller crystallite sizes. Consequently, the synthesized nanocomposites exhibit a porous and rough surface morphology. The rough and heterogeneous surface morphology enhances antimicrobial performance by facilitating the interaction between bacteria and the nanocomposite surface. The dispersed CuO nanoparticles promote Cu^{2+} ion release

and reactive oxygen species (ROS) generation. These combined effects lead to membrane disruption, oxidative stress, and inhibition of microbial growth (Menichetti *et al.* 2023). SEM image corresponding to 1: 3: 0.3 ratio sample shows a relatively uniform dispersion of CuO-NPs on activated carbon, whereas other ratios exhibit flake-like structures with random orientations.

SEM analysis confirms the formation of a well-integrated nanocomposite with a heterogeneous morphology and a relatively uniform distribution of CuO-NPs on activated carbon. This morphology is highly favorable for antibacterial applications.

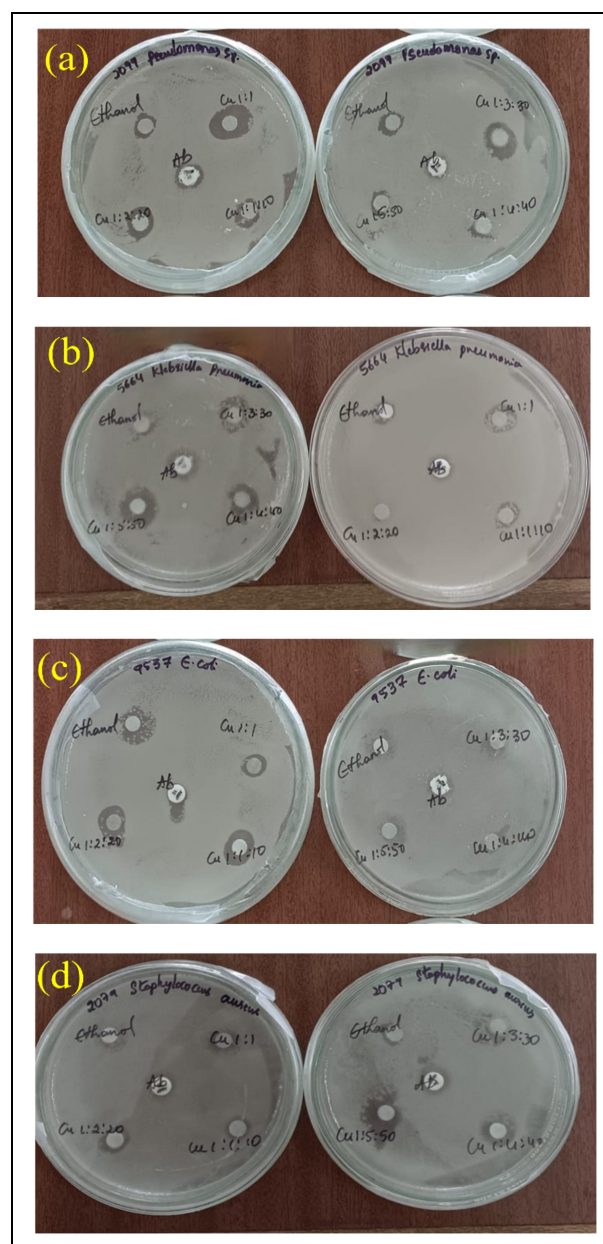


Fig. 7: ZOI of synthesized CuO nanocomposites against different bacteria: (a) *Pseudomonas* sp., (b) *K. pneumoniae*, (c) *E. coli* and (d) *S. aureus*

3.5 Antimicrobial Activity

Antimicrobial tests were conducted on the synthesized CuO nanocomposite samples to determine the antimicrobial potential against four different bacteria. Antimicrobial activity was evaluated using the ZOI. Antimicrobial activity was assessed against *Staphylococcus aureus*, a gram-positive bacterium, and *Pseudomonas* sp., *Klebsiella pneumoniae*, and *Escherichia coli*, a gram-negative bacterium, using a modified disc diffusion method (Bauer *et al.* 1966). Fresh bacterial cultures were cultivated in nutrient broth and incubated at 35 ± 2 °C in a shaking incubator at 160 rpm to promote active bacterial growth. Following incubation, 100 μ L of each standardized bacterial suspension was uniformly spread on MHA (Muller–Hinton agar) plates using a sterile glass spreader to form a consistent bacterial lawn (Azam *et al.* 2012). Sterile 6 mm Whatman filter paper discs were saturated with 20 μ L of nanoparticle suspensions (equivalent to 50 μ g/disc) and carefully placed on the inoculated agar surfaces. Ethanol was employed as the negative control, while a standard penicillin disc served as the positive control to assess comparative antimicrobial performance. All plates were incubated at 35 ± 2 °C for 24 h, after which the zones of inhibition were carefully measured in mm using a digital vernier caliper (Moniri *et al.* 2019). The effect of growth inhibition of CuO nanocomposites on MHA plates was evaluated by measuring the ZOI; the clear zones around the discs (Fig. 7) indicate the absence of

microbial growth, thereby providing a measure of the antimicrobial efficacy of the tested samples (Gudkov *et al.* 2024). In this study, each experiment was conducted in triplicate, and the average inhibition zone diameter was documented for each treatment and presented in Table 2. A larger inhibition zone indicates greater sensitivity of the test microorganism to the nanocomposite, thereby reflecting its higher antimicrobial effectiveness (Bin *et al.* 2012). Among the four bacterial strains tested, *Pseudomonas* sp. showed zones of inhibition of 10 mm and 11 mm for the 1:3:0.3 and 1:1:0.0 ratios, respectively, which were comparable to those of the standard penicillin antibiotic disc under identical conditions (Yifira *et al.* 2025). The concentration to be used should be selected based on the treatment conditions and clinical requirements.

Antimicrobial activity confirms the synergistic mechanism involving ROS generation, Cu^{2+} ion release, and direct membrane interaction. CuO-NPs induce oxidative stress through ROS production, leading to lipid peroxidation, protein denaturation, and DNA damage. Simultaneously, released Cu^{2+} ions penetrate microbial cells and disrupt enzymatic and genetic functions. The activated carbon enhances this activity by providing a high surface area for nanoparticle dispersion and facilitating the adsorption of microbial cells, thereby increasing the contact between CuO nanoparticles and pathogens. This synergistic effect results in efficient inhibition and destruction of microbial cells.

Table 2: Antimicrobial activity of synthesized CuO nanocomposites against different bacteria

Microorganisms	ZOI in mm for Different CuO: ACSB: PVP Ratios						Penicillin
	1: 1: 0.0	1: 1: 0.1	1: 2: 0.2	1: 3: 0.3	1: 4: 0.4	1: 5: 0.5	
<i>Pseudomonas</i> sp.	11	3	5	10	1	1	3
<i>K. pneumoniae</i>	4	3	0	8	5	9	3
<i>E. coli</i>	5	8	8	1	0	4	0
<i>S. aureus</i>	3	3	3	3	4	7	0

4. CONCLUSION

This study successfully demonstrated the synthesis of CuO nanocomposites using activated carbon derived from sugarcane bagasse in six different composition ratios. The integration of CuO-NPs with activated carbon was confirmed through comprehensive physicochemical characterization. XRD analysis revealed the crystalline nature of CuO, with characteristic diffraction peaks, and peak broadening indicated nanoscale crystallite dimensions and successful dispersion over the activated carbon. FTIR confirmed the presence of functional groups such as hydroxyl, carbonyl, and Cu–O bonds, highlighting the interaction between CuO-NPs and the activated carbon surface.

SEM images revealed a heterogeneous morphology with a relatively uniform distribution of CuO nanoparticles on the activated carbon, providing a high surface area conducive to enhanced activity. The synthesized CuO nanocomposites exhibited significant antimicrobial activity against the tested bacterial strains, as evidenced by measurable zones of inhibition (ZOI) in the disc diffusion assay. This enhanced antibacterial performance can be attributed to the synergistic effect of CuO-NPs and the porous activated carbon, which facilitates effective microbial contact, generation of reactive oxygen species, and disruption of bacterial cell membranes. Among the synthesized samples, the 1: 3: 0.3 (CuO: ACSB: PVP) ratio exhibited the most favorable results in XRD, FTIR, and SEM analyses. A ZOI of 10 mm was observed

against *Pseudomonas* sp. in the antimicrobial assay, whereas the remaining three bacterial strains exhibited comparatively lower inhibitory responses. This indicates that the 1:3:0.3 ratio exhibited enhanced antimicrobial effectiveness, particularly against *Pseudomonas* sp.

Overall, this study highlights the potential of CuO nanocomposites synthesized using activated carbon derived from sugarcane bagasse. The use of an eco-friendly, cost-effective biomass precursor makes the synthesized CuO nanocomposite an efficient antimicrobial material. The combined structural, chemical, and morphological properties contribute to its promising application in biomedical and antimicrobial coating systems. While nanocomposites represent sustainable and effective antimicrobial materials, previous studies (Ma *et al.* 2017; Hassanen *et al.* 2021; Nasaj *et al.* 2024) have highlighted their strong potential for biomedical applications. However, addressing challenges related to toxicity, scalability, and stability is critical for real-world implementation. Future research could focus on safe design strategies, process standardization, clinical safety, and long-term performance evaluation before large-scale therapeutic applications can be realized.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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