



Green Synthesized ZnO Incorporated *Sida cordifolia* /Alginate Hydrogel Scaffolds for Antibacterial Wound Healing Applications

Alagendran Subbarayalu¹, Rekha Anantharaman², Narendra Singh^{3*}, Ramesh Murugesan⁴, N. Sangeetha⁵ and Nagamalli Arasavalli⁶

¹Department of Research, Saveetha College of Nursing, Saveetha Institute of Medical and Technical Sciences, Thandalam, Chennai, TN, India

²Department of Obstetrics and Gynecology, Saveetha Institute of Medical and Technical Sciences, Chennai, TN, India

³Department of Electronics and Communication Engineering, Jaypee University of Engineering and Technology, Guna, MP, India

⁴Department of Electrical and Electronics Engineering, M. Kumarasamy College of Engineering, TN, India

⁵Department of Biochemistry, Kongu Arts and Science College, Nanjanapuram, Erode, TN, India

⁶Department of Electronics and Communication Engineering, Koneru Lakshmaiah Educational Foundation, AP, India

Received: 20.05.2026 Accepted: 15.06.2026 Published: 30.06.2026

*narendra52800@gmail.com



ABSTRACT

Natural fiber-based hydrogel scaffolds have emerged as promising biomaterials for antimicrobial dressing applications owing to their biodegradability, biocompatibility, and environmental sustainability. In this study, a novel multifunctional hydrogel scaffold was developed by integrating alkali-treated *Sida cordifolia* (SC) microfibers with calcium-crosslinked sodium alginate and green-synthesized zinc oxide (ZnO) nanoparticles derived using *Azadirachta indica* leaf extract. The novelty of this work lies in the synergistic combination of natural microfibers, alginate hydrogel networks, and in situ synthesized ZnO nanoparticles to achieve enhanced swelling, controlled biodegradation, and antibacterial performance within a single scaffold system. Structural and chemical analyses confirmed successful scaffold formation and ZnO nanoparticle incorporation. Swelling studies revealed that the optimized SCA-3/ZnO scaffold exhibited a maximum swelling capacity of approximately 5.8 g/g, indicating excellent water uptake behavior suitable for moist wound environments. In vitro biodegradation studies demonstrated controlled degradation, with a maximum weight loss of 48.7% after 385 h in phosphate-buffered saline. Dynamic light scattering analysis revealed nanoscale ZnO particles with an average hydrodynamic diameter of 6.26 nm, while zeta potential measurements showed a surface charge of -39.89 mV, indicating good colloidal stability. UV-Visible spectroscopy exhibited broad absorption features in the 430–460 nm region, attributed to phytochemical-mediated surface modification and interactions between ZnO nanoparticles and the hydrogel matrix. Antibacterial evaluation demonstrated significant inhibitory activity against both *Staphylococcus aureus* and *Escherichia coli*, with inhibition zones of 16 mm and 14 mm, respectively, for the optimized scaffold. These findings suggest that the developed SCA/ZnO hydrogel scaffold is a promising candidate for antimicrobial biomedical dressing applications and warrants further cytocompatibility and in vivo investigations.

Keywords: Zeta potential; Antibacterial activity; Biodegradability; UV spectroscopy; Dynamic light scattering.

1. INTRODUCTION

Antibacterial biomaterials are crucial in healthcare applications because of their multifunctional capacity to decrease infection rates, inhibit pathogenic bacteria, and enhance healing in clinical settings like surgical interventions and wound care. Wound healing is a complex biological process involving coordinated phases of hemostasis, inflammation, proliferation, and tissue remodeling. Disruptions to this cascade, particularly through bacterial infection, represent a significant clinical burden, contributing to chronic wound complications, increased morbidity, and prolonged hospitalization (Srivastava *et al.* 2025). The global prevalence of chronic and infected wounds has intensified the demand for advanced wound management

strategies that not only provide a physical barrier but also actively support tissue regeneration, modulate the inflammatory microenvironment, and prevent microbial colonization (Khan *et al.* 2025).

Conventional wound dressings, including gauze, foam, films, and hydrocolloids, offer basic wound coverage but are fundamentally limited in their capacity to manage infection, maintain appropriate moisture balance, and actively promote healing. These passive materials often fail in chronic wound settings due to inadequate antimicrobial activity, poor exudate absorption, and inability to support cellular regeneration (Rani *et al.* 2024). Hydrogel-based scaffolds have emerged as a next-generation alternative, owing to their high-water content, tissue-mimicking architecture, and

capacity to maintain a moist wound environment conducive to cell migration and proliferation. However, current hydrogel systems frequently suffer from mechanical fragility, rapid or uncontrolled biodegradation, poor structural integrity under mechanical loading, and insufficient antibacterial performance without additional bioactive agents (Shamshad *et al.* 2024). Moreover, strategies relying solely on polymeric matrices often lack sustained antimicrobial efficacy, highlighting the need for hybrid scaffold designs that synergistically integrate structural and bioactive components.

To address the antimicrobial limitations of conventional hydrogels, ZnO nanoparticles have been extensively investigated as bioactive additives due to their broad-spectrum antibacterial activity, antioxidant properties, and favorable biocompatibility (Saini *et al.* 2022). Their bactericidal mechanism operates through multiple pathways, including reactive oxygen species (ROS) generation, membrane disruption, and zinc ion release, enabling effective inhibition of both Gram-positive and Gram-negative bacteria, including multidrug-resistant strains (Tabe *et al.* 2026). Green synthesis routes, particularly those employing plant extracts, have gained considerable interest as eco-friendly and cost-effective alternatives to conventional chemical methods (Habeeb *et al.* 2025). Plant-mediated ZnO nanoparticles benefit from phytochemical capping agents that enhance particle stability, reduce agglomeration, and confer additional antioxidant and anti-inflammatory activity, making them particularly suitable for wound-healing applications (Kirubakaran *et al.* 2026). Doping strategies, such as Ag- or Cu-incorporation, have further been shown to augment antibacterial and antibiofilm efficacy by enhancing ROS production and disrupting bacterial electron transport chains (Sampath *et al.* 2022). Despite these merits, key translational challenges remain, including nanoparticle aggregation within polymeric matrices, cytotoxicity at elevated concentrations, and difficulties in achieving uniform dispersion and controlled release within scaffold systems (Abisha *et al.* 2025).

Among biopolymeric materials explored for wound dressing scaffolds, sodium alginate has attracted considerable interest due to its natural origin, biocompatibility, biodegradability, and capacity to form stable hydrogels through ionic crosslinking with divalent cations such as calcium ions (Thanjavur *et al.* 2025). Alginate hydrogels closely mimic the extracellular matrix (ECM) environment, supporting cell attachment, proliferation, and differentiation. Their high-water retention capacity maintains wound moisture, facilitates gas exchange, and creates conditions that accelerate re-epithelialization (Hadap *et al.* 2025). Furthermore, alginate's gelation behavior can be tuned to control scaffold porosity and degradation kinetics, making it a versatile platform for incorporating bioactive agents such

as nanoparticles or bioactive fibers (Thandavamoorthy *et al.* 2026). However, unmodified alginate hydrogels exhibit limited mechanical strength and reduced structural stability under physiological conditions, which restricts their standalone application in dynamic wound environments.

Natural cellulose-rich plant microfibers represent a promising class of reinforcing agents for hydrogel-based scaffolds, offering the dual advantage of mechanical strengthening and biocompatibility (Karthick and Sreenivasan, 2025). *Sida cordifolia*, a medicinal plant belonging to the Malvaceae family, yields bast fibers with high cellulose content, favorable aspect ratio, and inherent surface hydroxyl groups that promote interfacial bonding with polymeric matrices (Suresh *et al.* 2026). Alkali treatment of these fibers effectively removes lignin, hemicellulose, and surface impurities, increasing cellulose crystallinity and surface roughness — properties that enhance fiber–matrix adhesion and improve overall scaffold integrity (Mim *et al.* 2025). Beyond their structural role, cellulose microfibers enhance swelling behavior by increasing scaffold porosity and water absorption capacity, which is critical for exudate management in wound dressings (Bhakyalatha and Koppole, 2026). The renewable origin and biodegradability of *Sida cordifolia* fibers further align with the objective of developing sustainable biomaterials. Despite these attributes, their integration into alginate-ZnO composite scaffolds for wound-healing applications has not been systematically explored (Poorani *et al.* 2026).

Although ZnO nanoparticles, alginate hydrogels, and natural microfibers have each been individually investigated for biomedical applications, their synergistic combination into a single multifunctional scaffold has not been reported. Existing studies have largely evaluated these components in isolation or in binary systems, leaving unresolved questions regarding the interplay between fiber reinforcement, nanoparticle distribution, hydrogel crosslinking, and antibacterial performance in composite wound dressings. Furthermore, limited attention has been paid to the role of alkali-treated natural microfibers in modulating nanoparticle dispersion, scaffold biodegradation, and wound-healing performance within calcium-crosslinked alginate matrices. This gap in knowledge motivates the development of a ternary composite scaffold that integrates all three components: green-synthesized ZnO nanoparticles, alkali-treated *Sida cordifolia* microfibers, and calcium-crosslinked sodium alginate to achieve a balance of antimicrobial efficacy, structural stability, moisture management, and cytocompatibility.

This research introduces an innovative biofunctional hydrogel scaffold by combining alkali-treated *Sida cordifolia* microfibers with calcium-ion

crosslinked sodium alginate and green-synthesized ZnO nanoparticles obtained from *Azadirachta indica* leaf extract. This study introduces a multifunctional natural fiber-based scaffold that integrates enhanced swelling capacity, controlled biodegradation, nanoscale ZnO dispersion, and broad-spectrum antibacterial efficacy, distinguishing it from traditional hydrogel systems that typically emphasize either polymeric matrices or nanoparticle incorporation alone. The study illustrates the synergistic effect of alkali-treated SC microfibers and alginate networks in enhancing nanoparticle distribution, structural stability, and antimicrobial efficacy, thus presenting a sustainable and sophisticated biomaterial option for wound healing and infection-preventive biomedical dressing applications.

2. MATERIALS AND METHODS

2.1 Materials

Fibers of *Sida cordifolia* (SC) and Fresh *Azadirachta indica* leaves employed in the study were collected from the forested regions adjacent to Anthiyur, Erode district, Tamil Nadu, India. Sodium alginate (alginic acid), Sodium hydroxide (NaOH), potassium dihydrogen phosphate (KH_2PO_4), zinc nitrate precursor, and calcium chloride (CaCl_2) were procured from Star Scientific Enterprises, Erode, Tamil Nadu, India. All reagents used in this experimental procedure were of analytical reagent grade and were used as obtained without purification. High-purity nanopure water was uniformly employed throughout all testing protocols.

2.2 NaOH Treatment for SC Fibers

Table 1. Comparative weight analysis of untreated and treated SC fibers

Alkali-treated Fiber Designation	Weight After NaOH Treatment (g)	Initial Fiber Weight (g)
SC-0	3.009	3.169
SC-1	3.12	3.156
SC-2	1.244	3.032
SC-3	0.874	3.107

The alkaline modification of *Sida cordifolia* (SC) fibers was conducted using sodium hydroxide (NaOH) solutions of varying concentrations. Alkali solutions were formulated by dissolving 1 g, 2 g, and 3 g of NaOH individually in 100 mL of deionized water to achieve 1%, 2%, and 3% (w/v) concentrations. Approximately 12 g of SC fibers was evenly divided into four groups of 3 g and placed into separate glass beakers. The control sample (SC-0) was immersed in 100 mL of distilled water without alkali treatment, whilst the other samples, labeled SC-1, SC-2, and SC-3, were immersed in 100 mL of 1%, 2%, and 3% NaOH solutions, respectively. The treatment procedure was performed for

one hour at ambient temperature. After alkali treatment, the fibers were rinsed three times with deionized water to remove leftover NaOH and surface contaminants, and dried under room conditions (Alam *et al.* 2023). The weights of treated fibers are detailed in Table 1.

2.3 Synthesis of Alginate-modified SC Fiber Scaffolds

Alginate-coated fiber scaffolds were produced by an ionic crosslinking technique. Initially, 2 g of sodium alginate were solubilized at 100 mL of nanopure water while maintaining continuous magnetic stirring to create a homogeneous polymeric solution. Subsequently, 2 g samples of each *Sida cordifolia* fiber were individually placed in Petri plates, and 10 mL of alginate solution was incorporated to ensure thorough surface impregnation of the fibers. The coated samples were kept undisturbed for 30 minutes to facilitate adequate adsorption of alginate onto the fiber surface. Subsequently, 5 mL of 1% calcium chloride (CaCl_2) solution was introduced to each sample to induce ionic gelation by Ca^{2+} -mediated crosslinking, resulting in the formation of hydrogel scaffold structures. The crosslinking reaction was extended for an additional 30 minutes. The synthesized *Sida cordifolia*/sodium alginate scaffolds labeled SCA-0, SCA-1, SCA-2, and SCA-3 were meticulously washed with distilled water to eliminate unreacted components and dried at room temperature.

2.4 Synthesis of Nucleation Agent

The nucleating medium was manufactured by an environmentally sustainable extraction process in accordance with published standards. Fresh *Azadirachta indica* leaves were first rinsed multiple times by deionized water to remove clinging impurities and air-dried for 24 hours. Approximately 15 grams of leaves were chopped into small fragments and combined with 100 mL of nanopure water. The resultant blend was heated to a boil and constantly agitated for 15 mins to facilitate the release of phytochemical contents into the aqueous medium. Following extraction, the solution was allowed to cool at room temperature and filtered to remove leftover plant material. The collected filtrate was stored at 4 °C and subsequently employed as the nucleating agent for additional experimental procedures.

2.5 Green Synthesis of ZnO-loaded Alginate/SC Hydrogels

A zinc precursor solution was prepared by dissolving 1 g of zinc nitrate hexahydrate [$\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$] in 100 mL of nanopure water, corresponding to a concentration of approximately 0.034 M. The solution was magnetically stirred at 250 rpm for 5 min until a clear and homogeneous solution was obtained. Approximately 10 mL of the produced

precursor solution was individually added to Petri dishes containing alginate-functionalized *Sida cordifolia* scaffolds and incubated for 24 hours to facilitate zinc ion transport and adsorption within the hydrogel matrix. Subsequently, the excess zinc nitrate solution was removed, and 10 mL of *Azadirachta indica* leaf extract was added to each scaffold system (Gunasekaran *et al.* 2026). The phytochemical constituents present in the leaf extract, including flavonoids, phenolic compounds, terpenoids, and reducing sugars, facilitated the nucleation, growth, and stabilization of ZnO nanoparticles within the hydrogel matrix. These bioactive compounds interact with adsorbed Zn^{2+} ions and promote the formation of ZnO nanostructures while

simultaneously acting as natural capping agents that minimize nanoparticle agglomeration. The pH of the zinc nitrate solution before extract addition was approximately 5.8, whereas the reaction medium attained a pH of approximately 7.2 following extract incorporation, indicating favorable conditions for ZnO nanoparticle formation and stabilization within the scaffold structure. After a reaction period of 2 h, the synthesized ZnO-incorporated scaffolds (SCA/ZnO) were collected and dried under ambient conditions. The formation of ZnO nanoparticles within the scaffold matrix was subsequently verified through XRD, FTIR, UV–Vis spectroscopy, DLS, zeta potential, and SEM analyses.

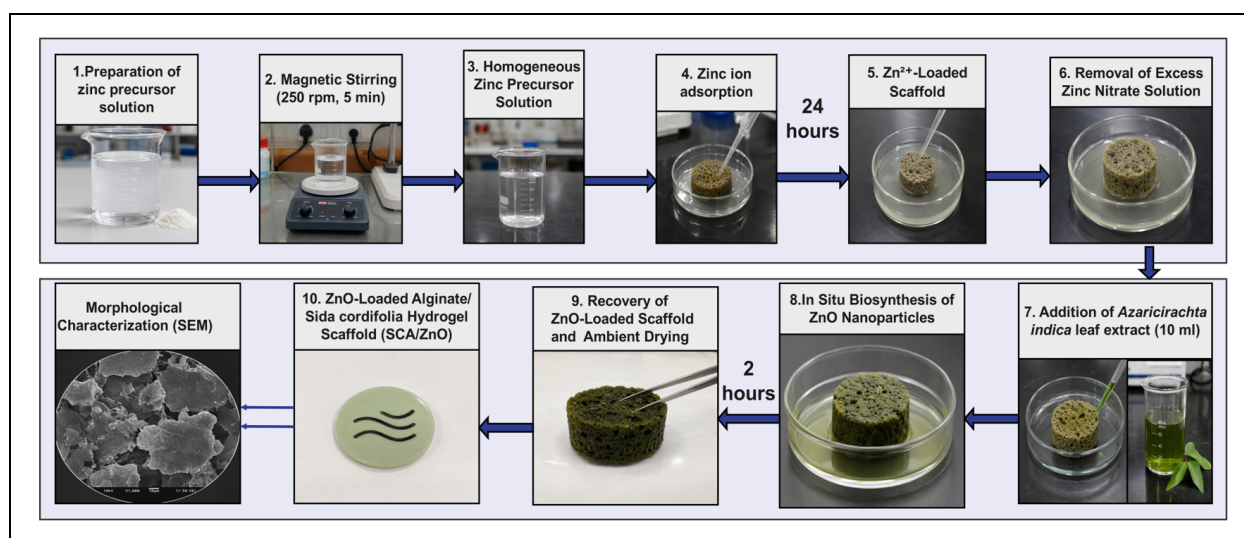


Fig. 1: Green synthesis of ZnO-loaded alginate/Sc hydrogels

2.6 Characterizations

Fourier transform infrared (FTIR) was utilized to analyze chemical interactions and functional groups at different stages of scaffold creation, specifically SC, SCA, and SCA/ZnO samples. Spectral analysis was conducted utilizing a Bruker Tensor 27 FTIR spectrometer in the wavenumber range of 400–4000 cm^{-1} . X-ray diffraction examinations were executed to verify crystalline characteristics and the formation of ZnO nanoparticles within the hydrogel matrix. The SCA and SCA/ZnO scaffolds were systematically analyzed over a 2θ range of 5° – 80° utilizing a Bruker D8 Advance diffractometer. Ultraviolet–visible (UV–Vis) spectroscopy of the SCA/ZnO hydrogel scaffolds was conducted utilizing a Thermo Fisher Multiskan SkyHigh spectrophotometer. To evaluate the optical characteristics and stability of ZnO nanoparticles released from the hydrogel matrix, 0.05 g of each scaffold was immersed in nanopure water for 24 and 120 h. The resulting suspension was analyzed using UV–Vis spectroscopy. DLS and zeta potential analyses were performed using aqueous nanoparticle suspensions obtained from scaffold extracts to determine particle size distribution,

polydispersity index, and colloidal stability. Dynamic light scattering measurements were used to ascertain the polydispersity index and zeta potential of the ZnO nanoparticles suspended in aqueous solution. The surface morphology of untreated fibers, alkali-modified fibers, and manufactured hydrogel scaffolds was examined by scanning electron microscopy (SEM). SEM examinations were utilized to assess the distribution and effective integration of ZnO nanoparticles within the hydrogel scaffold structure. Prior to SEM analysis, the samples were gold sputter-coated and examined at an accelerating voltage of 10–15 kV to evaluate surface morphology and nanoparticle distribution.

2.7 Swelling Ratio

Swelling characteristics of hydrogel scaffolds were assessed using gravimetric analysis. The initial dry mass of each scaffold sample (W_0) was measured before immersion in 10 mL of nanopure water at $20 \pm 1^\circ\text{C}$. Following a 24-hour incubation period, swollen hydrogels were meticulously extracted from the medium, and the surplus surface water was delicately absorbed with tissue paper. Hydrated scaffolds were subsequently

weighed (W), and swelling capacity (Sg/g) was calculated using the appropriate equation (1):

$$S_{g/g} = (W - W_0)/W_0 \quad \dots (1)$$

2.8 Degradation and Swelling Activity

The engineered scaffold prototypes was subsequently evaluated for their swelling behavior at phosphate-buffered saline solution with pH 7.4. Initial dry weight of the hydrogel samples (W_0) was recorded, followed by immersion of the samples at 25 mL of phosphate-buffered saline, maintained at 37 °C for 360 hours. At specified time intervals, scaffolds were meticulously extracted from the solution, and surplus phosphate-buffered saline adhering to scaffold surfaces was delicately eliminated by filter paper. The swollen specimen was then weighed (W), and the swelling capacity (Sg/g) was calculated using the appropriate equation (2).

$$S_{g/g} = \frac{(W - W_0)}{W_0} \quad \dots (2)$$

The PBS solution consisted of NaCl, KCl, KH_2PO_4 , and Na_2HPO_4 and was adjusted to pH 7.4. In vitro biodegradation characteristics of the ZnO-infused hydrogel scaffolds were examined by submerging the samples with an initial dry weight designated as W_0 in 25 mL of phosphate-buffered saline at 37 °C for durations of 48, 264, and 385 hours. At predetermined time intervals, the scaffolds were removed from the PBS medium, washed thoroughly with nanopure water to remove residual salts, and then dried at ambient temperature. The ultimate dry weight of deteriorated scaffolds (W_d) was subsequently measured, and percentage weight loss was calculated using the appropriate equation (3):

$$WL(\%) = \left[\frac{W_0 - W_d}{W_0} \right] \times 100 \quad \dots (3)$$

2.9 Antimicrobial Activity

Antibacterial efficacy of synthesized hydrogel scaffolds were evaluated for Gram-negative *Escherichia coli* (*E. coli*) and Gram-positive *Staphylococcus aureus* (*S. aureus*) by agar diffusion technique (Kumar *et al.* 2024). The ZnO-free SCA scaffold was used as the negative control. Circular scaffold discs (10 mm diameter) were used for antibacterial testing. Streptomycin (10 µg/disc) served as the positive control. New bacterial cultures were cultivated on Muller–Hinton (MH) agar medium, and the microbial suspension was calibrated to a 1 McFarland turbidity of about 1×10^8 CFU/mL to ensure inoculum concentration. Sterile cotton swabs were utilized to distribute bacterial suspension over the complete surface of MH plates, creating a homogeneous bacterial lawn. The produced hydrogel samples, along with streptomycin as the positive control, were meticulously placed on Petri plates and incubated at

37 °C for 1 day. Subsequent to incubation, antibacterial efficacy was assessed by measuring the diameter of inhibitory zones surrounding the scaffold samples. Prior to antibacterial testing, the hydrogel scaffolds were sterilized under UV irradiation for 30 min on both sides and stored in sterile conditions until use. *E. coli* and *S. aureus* were selected as representative Gram-negative and Gram-positive bacteria commonly associated with wound infections

3. RESULTS AND DISCUSSION

Alkali treatment of *Sida cordifolia* (SC) fibers led to a reduction in original weight, as illustrated at table 1 and Figure 2(a).

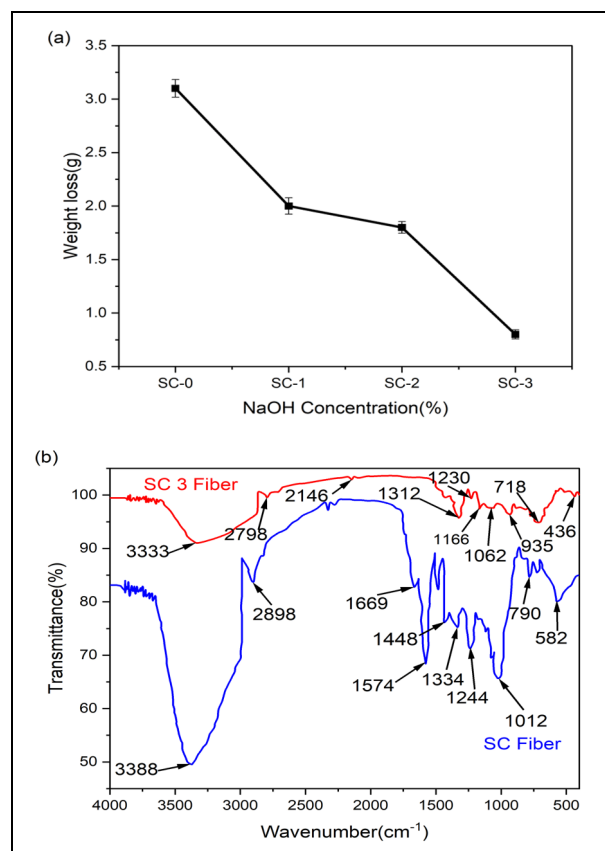


Fig. 2: (a) Weight reduction of deionized water- and alkali-treated SC fibers and (b) FTIR analysis of SC fibers

Moreover, an elevation in NaOH concentration at alkali treatment resulted in a continuous increase in fiber weight reduction. The detected mass loss is mostly attributable to the removal of surface contaminants and non-cellulosic components, including lignin, hemicellulose, pectin, waxes, and other amorphous substances found in *Sida cordifolia* fibers. The delignification efficacy of NaOH is recognized to enhance with escalating treatment intensity, aligning with the results seen in this study. This effect is primarily attributed to the ability of NaOH to dissolve and remove the binding constituents surrounding the cellulose

microfibrils, thereby enhancing cellulose exposure and reducing the overall fiber diameter. Moreover, elevated alkali concentrations may facilitate partial hydrolysis of cellulose chains, hence augmenting the total weight loss of treated fibers. The observed weight reduction is consistent with the removal of non-cellulosic constituents such as hemicellulose, pectin, waxes, and partial lignin during alkali treatment.

FTIR spectra for untreated and alkali-modified *Sida cordifolia* fibers are illustrated in Fig. 2(b). The untreated SC fibers exhibit a large absorption band at 3338 cm^{-1} , which corresponds to O–H stretching linked to cellulose and hemicellulose components. Peaks at 2898 cm^{-1} and 1448 cm^{-1} correspond to CH_2 bending vibrations and C–H stretching from cellulose-based structures. An absorption peak at 1669 cm^{-1} corresponds to carbonyl (C=O) or ester groups mostly linked to lignin components, whilst the bands at 1574 and 1334 cm^{-1} indicate aromatic C=C vibrations, thus confirming the existence of lignin at fiber matrix. Supplementary peaks identified at 1244 , 1012 , 790 , and 582 cm^{-1} were attributed to C–H vibrations of hemicellulose/cellulose, C–O–C stretching of lignin, C–O/C–C stretching associated with aliphatic ether groups or lignin acetyl, and C–C vibrations, respectively. In the case of SC-3 fibers, significant peak shifting and a decrease in peak intensity were observed following alkali treatment, signifying the elimination of waxes and amorphous contaminants. The absorption band at 3333 cm^{-1} indicates alterations in hydroxyl stretching of cellulose, while peaks at 2798 and 2146 cm^{-1} correspond to C–H stretching of cellulose chains. The band at 1312 cm^{-1} indicates alterations in aromatic C=C stretching due to partial lignin elimination, while the peak at 1230 cm^{-1} corresponds to CH_2 bending differences arising from structural modifications of lignin. The absorption peak at 1116 cm^{-1} signifies modifications in C–O stretching vibrations resulting from the alkali treatment process.

The production of SCA/ZnO hydrogel scaffolds was conducted using a multistep process. Initially, *Sida cordifolia* fibers were isolated and then functionalized with sodium alginate by a CaCl_2 -mediated ionic gelation process, wherein Ca^{2+} ions facilitated the creation of stable crosslinked hydrogel networks through interactions with alginate chains. In the subsequent phase, the produced *Sida cordifolia*/alginate (SCA) hydrogels were submerged in a zinc nitrate solution to enable the integration of zinc ions into the hydrated hydrogel matrix. Thereafter, the zinc ion-embedded hydrogels were subjected to treatment with *Azadirachta indica* leaf extract, serving as a natural stabilizing and capping agent, facilitating in-situ biogenesis of ZnO nanoparticles inside the scaffold structure. The phytochemical components in the leaf extract, such as flavonoids, terpenoids, and other phenolic compounds, facilitated the reduction and nucleation processes

essential for the creation of ZnO nanoparticles in the hydrogel matrix.

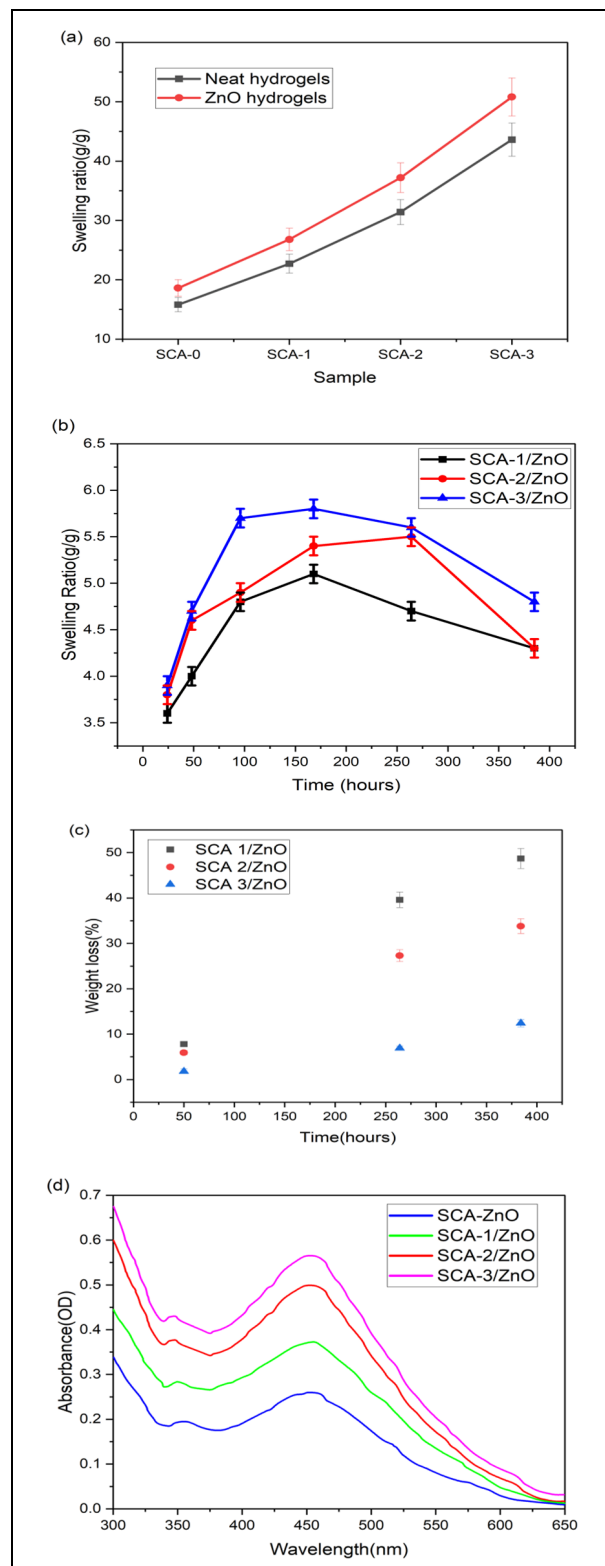


Fig. 3: (a) Swelling performance of hydrogel (b) characteristics of ZnO hydrogels and (c) In vitro biodegradation

The synthesis and integration of ZnO nanoparticles into the hydrogel scaffolds were significantly affected by the swelling characteristics of the formulated hydrogel systems, as illustrated in Fig. 3. The results depicted in Fig. 3(a) demonstrate that alkali-treated hydrogel scaffolds exhibited significantly enhanced swelling capacity relative to the untreated SCA hydrogels. Of all the manufactured samples, the SCA-3 hydrogel exhibited the most superior swelling performance compared to the other scaffold formulations. Compared with the untreated scaffold, the swelling capacity increased progressively with alkali treatment intensity, indicating improved hydrophilicity and water absorption characteristics.

The augmented swelling behavior was mostly linked to the elevated NaOH concentration utilized in the treatment of *Sida cordifolia* fibers. Elevated alkali concentrations enhance the exposure and activation of cellulose-based groups in fibers, consequently augmenting their interaction and compatibility at hydrophilic alginate chains. The synthesized hydrogels demonstrated enhanced water absorption capacity, leading to superior swelling performance. Furthermore, the ZnO-infused hydrogel scaffolds exhibited superior swelling ratios compared to the unmodified hydrogels. This behavior is ascribed to the synthesis of ZnO nanoparticles within the SCA hydrogel matrix following the treatment of zinc ion-loaded scaffolds with *Azadirachta indica* extract, which serves as a natural stabilizing and capping agent. In-situ synthesis of ZnO NPs enhanced the hydrogel network, consequently augmenting the water absorption capacity of scaffolds. The enhanced swelling may be associated with increased scaffold porosity and hydrophilic interactions generated by fiber modification and nanoparticle incorporation. The swelling properties are particularly beneficial for biological applications like wound dressings, tissue engineering scaffolds and drug delivery systems. The swelling behavior of ZnO-loaded hydrogels was subsequently examined in PBS medium at 37 °C for a duration of 385 hours, as depicted in Fig. 3(b). Of the created samples, the SCA-3/ZnO scaffold had the greatest swelling capacity in comparison to the SCA-2/ZnO and SCA-1/ZnO scaffolds. The greater swelling behavior was attributed to increased functionalization of alginate at alkali-treated SC microfibers, resulting at more porous and hydrophilic three-dimensional structure. The swelling ratio of the chosen scaffolds rose steadily until 168 hours, after which a steady decline occurred because of hydrolytic destruction of alginate and SC microfibers in the PBS medium, resulting in partial collapse of the hydrogel structure.

Figure 3(c) illustrates the in vitro biodegradation characteristics of ZnO-loaded hydrogel scaffolds at PBS medium at 37 °C. The SCA-1/ZnO scaffold demonstrated the highest degradation rate among the generated samples, with an approximate

weight loss of 48.7% after 385 hours of incubation. The SCA-2/ZnO and SCA-3/ZnO scaffolds exhibited relatively reduced degradation rates, attributable to increased alginate crosslinking density and greater stabilization of ZnO nanoparticles inside the hydrogel matrix. The diminished degradation propensity of these scaffolds suggests that enhanced alginate functionalization and nanoparticle integration have led to increased structural stability after extended exposure to PBS medium. The reduced degradation rate observed for SCA-3/ZnO may be attributed to increased crosslinking density and stronger scaffold stabilization resulting from improved fiber–alginate interactions. The effective production and integration of ZnO nanoparticles into the SCA hydrogel matrix were also validated by UV–Visible spectroscopy. Figure 3(d) illustrates the presence of discrete absorption bands within the wavelength range of 430–460 nm, indicative of optical absorption associated with ZnO nanoparticles integrated inside the nanocomposite hydrogel scaffolds. Furthermore, the strength of the absorption peaks augmented with greater interaction between alginate and SC fibers, signifying enhanced nanoparticle incorporation inside the hydrogel matrix. The red-shifted absorption band may be influenced by phytochemical capping agents, particle aggregation, and interactions between ZnO nanoparticles and the hydrogel matrix. The X-ray diffraction patterns depicted in Fig. 4(a-c) exhibited large diffraction peaks ranging from 21.73° to 15.71° (2 θ), corresponding to the (111) and (002) planes linked to cellulose within the hydrogel system. In Fig. 4(b), an extra diffraction peak at 2 θ = 12.33° was attributed to the alginate biopolymer structure in the scaffold matrix. Following the introduction of ZnO nanoparticles, a little peak shift in the reflections of cellulose and alginate was noted in Fig. 4(c), attributable to interactions between the polymeric network and ZnO nanoparticles. Moreover, supplementary low-intensity diffraction peaks emerged at 2 θ values of 33.87°, 38.90°, 62.36°, and 74.35°, corresponding to (111), (200), (220), and (311) planes of ZnO nanocrystals, thereby validating the successful synthesis of ZnO nanoparticles within the SCA-3/ZnO hydrogel scaffold by the green synthesis method. The diffraction peaks were assigned according to standard ICDD/JCPDS reference data for hexagonal ZnO. The average crystallite size of the ZnO nanoparticles embedded within the SCA-3/ZnO hydrogel scaffold was estimated using the Debye–Scherrer equation. Based on the broadening of the characteristic ZnO diffraction peaks, the crystallite size was found to be approximately 18–25 nm, confirming the nanoscale nature of the synthesized ZnO particles. The relatively small crystallite size provides a larger surface area and promotes stronger interfacial interactions between the ZnO nanoparticles and the alginate–cellulose hydrogel network, thereby contributing to the enhanced antibacterial activity and structural stability of the scaffold. Similarly, UV–Vis spectra confirmed enhanced UV and visible light absorption of the ZnO-Cu@CQD

nanocomposite due to successful CQD incorporation into the Cu-doped ZnO matrix. The improved optical response supports its enhanced antibacterial and photocatalytic activity (Joseph *et al.* 2025).

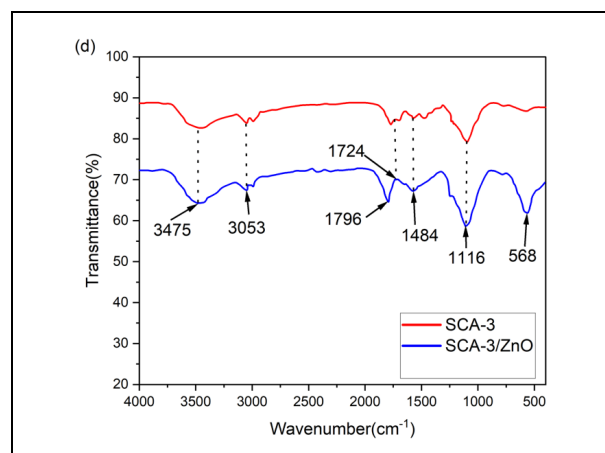
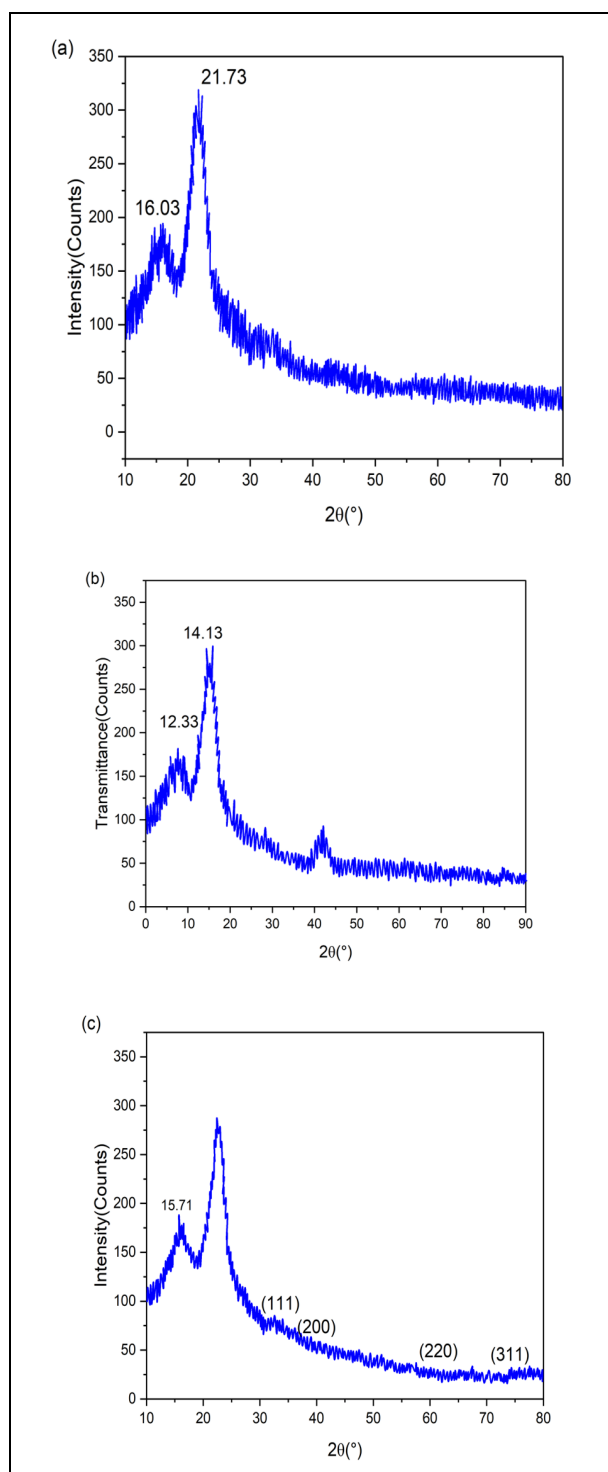
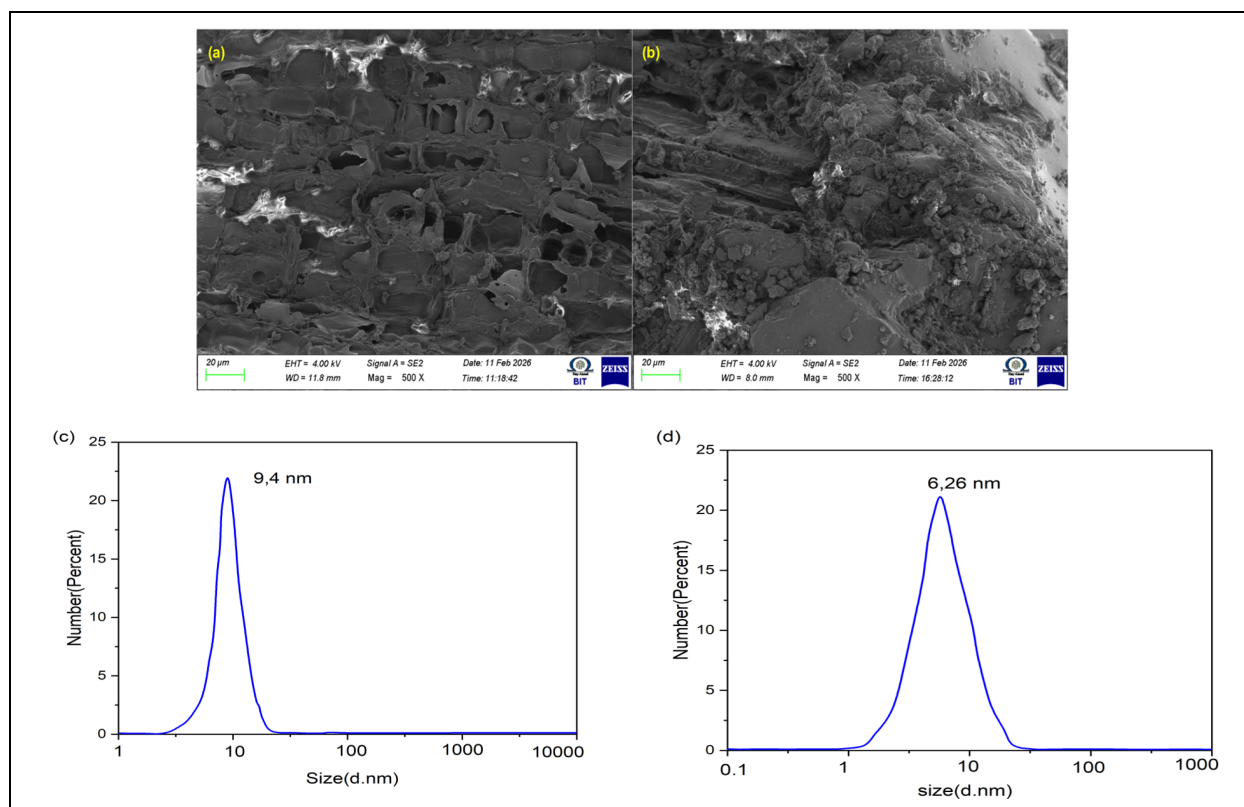


Fig. 4: (a) XRD pattern of SCN3, (b) XRD pattern of SCA3, (c) XRD pattern of SCA3/ZnO hydrogels and (d) FTIR spectra of hydrogels

Figure 4(d) shows the FTIR spectra of alginate functionalized SCA-3 fibers and biosynthesized SCA-3/ZnO hydrogel scaffold. The wide absorption peak in the SCA-3 sample at 3475 cm^{-1} is for O-H stretching vibrations of hydroxyl groups belonging to alginate and cellulose-rich fibers of *Sida cordifolia*. These hydroxyl groups play a crucial role in forming intermolecular hydrogen bonds, hence enhancing the stability and integrity of the hydrogel network. After functionalization of alginate, obvious changes in the characteristic absorption peaks indicate strong interactions between alginate chains and the surface of the microfibers. The strong bands at 3053 cm^{-1} indicated C-H stretching vibrations, and the 1724 cm^{-1} band was assigned to the carbonyl ($\text{C}=\text{O}$) stretching of polysaccharide and lignocellulosic components in the SCA-3 scaffold. The peak at 1484 cm^{-1} is attributed to COO^- symmetric stretching and cellulose/lignin structural vibrations. Moreover, the typical absorption band at 1116 cm^{-1} was attributed to the C-O-C vibration of polysaccharide chains, while the absorption band at 568 cm^{-1} corresponds to Zn-O stretching vibrations, confirming successful ZnO incorporation within the hydrogel scaffold. Figure 5 further depicts the SEM micrographs of alginate-functionalized microfibers (SCA-2) and ZnO nanoparticle-embedded alginate-functionalized fibers (SCA-2/ZnO). Comparatively, FTIR spectra confirmed the successful incorporation of ZnO nanoparticles through characteristic shifts in functional group vibrations, indicating strong interactions within the hydrogel network. Similar spectral changes observed in the SCA/ZnO scaffold further verified the effective integration of green-synthesized ZnO nanoparticles into the alginate-*Sida cordifolia* matrix (Palem *et al.* 2024).

SEM analyses confirmed the successful fabrication of SCA/ZnO hydrogel scaffolds integrated with ZnO nanoparticles. The SCA/ZnO scaffold effectively incorporated ZnO nanoparticles into the alginate-functionalized microfibre matrix, whereas the SCA-3/ZnO scaffold displayed a smoother morphology and a more uniform dispersion of nanoparticles inside the hydrogel structure. The better distribution can be linked to greater alkali treatment, which augmented the activation of microfibre surfaces and promoted stronger interactions with alginate chains. As a result, the SCA-3/ZnO scaffold exhibited enhanced interfacial compatibility among alginate, *Sida cordifolia* microfibers, and ZnO nanoparticles within the hydrogel matrix. DLS measurements indicated that the hydrodynamic particle sizes (Fig. 5c and d) were approximately 9.4, 8.2, 7.1, and 6.26 nm for the SCA/ZnO, SCA-1/ZnO, SCA-2/ZnO, and SCA-3/ZnO scaffolds, respectively. DLS measures the hydrodynamic diameter of nanoparticles in suspension, whereas SEM evaluates particle morphology in the dry state; therefore, differences between DLS and SEM particle sizes are expected. Furthermore, the DLS results represent nanoparticles extracted from the hydrogel system and may not exactly reflect the particle dimensions within the

scaffold matrix. Zeta potential analysis (Fig. 5e and f) revealed values of -30.39 , -37.84 , -31.5 , and -39.89 mV for SCA/ZnO, SCA-1/ZnO, SCA-2/ZnO, and SCA-3/ZnO, respectively. The negative surface charge signifies improved colloidal stability by electrostatic repulsion among nanoparticles, therefore reducing agglomeration tendencies. The polydispersity index (PDI) values for the SCA/ZnO, SCA-1/ZnO, SCA-2/ZnO, and SCA-3/ZnO scaffolds were 0.48, 0.43, 0.39, and 0.35, respectively, indicating moderately polydisperse nanoparticle populations with acceptable colloidal stability within the hydrogel systems. Antibacterial efficacy of synthesized hydrogel scaffolds were subsequently assessed by agar plate diffusion assays, with inhibition zones recorded after 24 hours of incubation, as depicted in Fig. 6. In prior studies, SEM analysis revealed that the green-synthesized ZnO nanoparticles possessed nearly spherical morphology with slight agglomeration and well-distributed surface structures. The nanoparticles exhibited an average particle size ranging from 88.5 to 90.2 nm, confirming successful nanoscale formation through the *Sida cordifolia*-mediated synthesis process (Siddiqui *et al.* 2026).



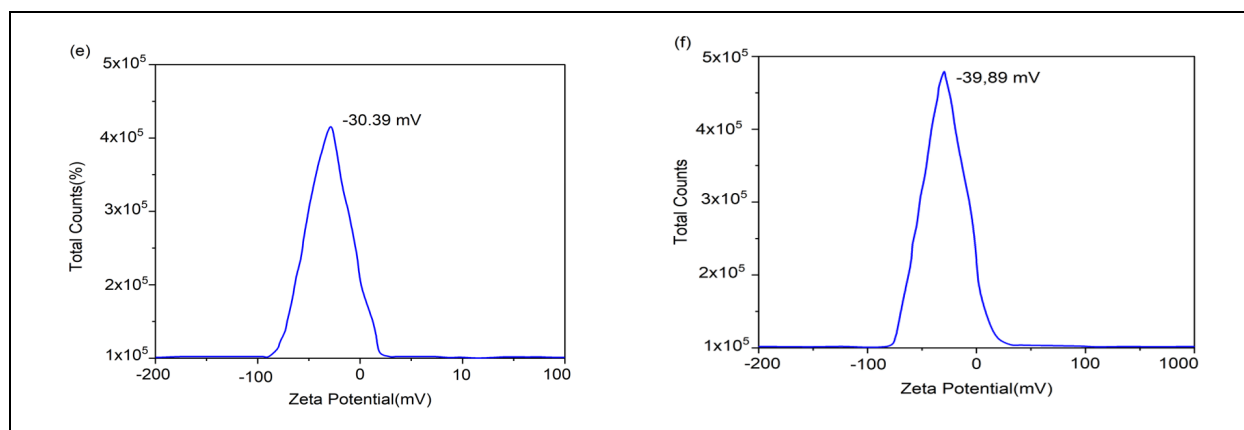


Fig. 5: SEM micrographs of (a) SCA/ZnO and (b) SCA3/ZnO hydrogel scaffolds, DLS size distribution of (c) SCA/ZnO and (d) SCA3/ZnO, and zeta potential analysis of (e) SCA/ZnO and (f) SCA3/ZnO

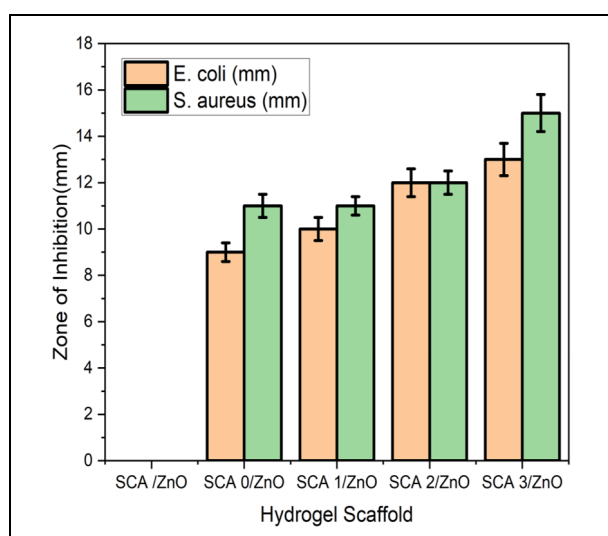


Fig. 6: Antibacterial performance of hydrogel scaffolds against (a) *Escherichia coli* and (b) *Staphylococcus aureus*

The SCA and SCA-3 hydrogel scaffolds devoid of ZnO inclusion were employed as control samples, whilst commercial chloramphenicol discs acted as the standard reference for antibacterial evaluation. The SCA-3/ZnO hydrogel scaffold exhibited the highest antibacterial activity among the developed scaffolds. This augmented activity is predominantly attributed to enhanced nanoparticle dispersion and reduced particle size, as validated by DLS analysis. Antibacterial efficacy of ZnO NPs was primarily affected by parameters like surface area, shape, particle size, surface charge, and the capacity for reactive oxygen species formation. The antibacterial efficacy of ZnO nanoparticles mostly stems from the generation of reactive oxygen species, which can cause oxidative harm to bacterial membranes, nucleic acids, and proteins. Moreover, the nanoscale size of ZnO particles enhances their contact with bacterial cell surfaces, augmenting membrane permeability and interrupting vital cellular functions. The release of zinc ions disrupts microbial metabolic and respiratory

functions, hence improving antibacterial efficacy. These mechanisms are proposed based on previous literature reports and were not directly investigated in the present study. The widths of the inhibition zones against *E. coli* were ranked as follows: SCA-3/ZnO > SCA-2/ZnO > SCA-1/ZnO > SCA/ZnO > SCA-3/SCA, with corresponding measurements of 14, 13, 12, 10, and 0 mm, respectively. In a similar manner, the inhibition zones against *S. aureus* were recorded in the following order: SCA-3/ZnO > SCA-2/ZnO > SCA-1/ZnO > SCA/ZnO > SCA-3/SCA, with measurements of 16, 13, 12, 12, and 0 mm, respectively. The findings demonstrate that ZnO nanoparticles exhibited marginally enhanced antibacterial efficacy against *S. aureus* in comparison to *E. coli*, potentially attributable to variations in bacterial cell wall architecture and vulnerability to nanoparticle-induced membrane rupture. In accordance with established antibacterial assessment standards, inhibition zones above 1 mm are deemed indicative of significant antibacterial efficacy. Consequently, the synthesized SCA/ZnO nanocomposite hydrogel scaffolds may be considered effective antibacterial biomaterials for inhibiting harmful microorganisms. The antibacterial performance observed in the present study is comparable to several previously reported ZnO-based antimicrobial hydrogel and wound-dressing systems. According to previous research that, the SCA/ZnO scaffold exhibited strong antibacterial activity against both *S. aureus* and *E. coli*, attributed to the synergistic interaction between green-synthesized ZnO nanoparticles and *Sida cordifolia* microfiber-reinforced alginate matrix. This eco-friendly scaffold demonstrated effective bacterial inhibition while offering a sustainable alternative to chemically synthesized antibacterial hydrogel systems (Liu *et al.* 2024). The improved swelling behavior, enhanced structural stability, and antibacterial performance correlate with the structural modifications observed through FTIR, XRD, and SEM analyses. The successful incorporation of ZnO nanoparticles and improved fiber–alginate interactions contributed to the overall functional performance of the developed hydrogel scaffold.

4. CONCLUSION

This study successfully developed a novel biofunctional hydrogel scaffold by integrating alkali-treated *Sida cordifolia* microfibers, calcium-crosslinked sodium alginate, and green-synthesized ZnO nanoparticles derived from *Azadirachta indica* leaf extract. The combined effects of fiber surface modification, alginate crosslinking, and ZnO nanoparticle incorporation contributed to improved scaffold structure, enhanced water absorption, controlled biodegradation, and antibacterial performance. The optimized SCA-3/ZnO scaffold exhibited a maximum swelling capacity of approximately 5.8 g/g, while the SCA-1/ZnO scaffold showed the highest degradation rate with a weight loss of 48.7% after 385 h in PBS medium. Furthermore, the SCA-3/ZnO scaffold demonstrated moderate antibacterial activity against *Staphylococcus aureus* and *Escherichia coli*, with inhibition zones of approximately 16 mm and 14 mm, respectively. The principal scientific contribution of this work lies in demonstrating the synergistic integration of natural cellulose-rich microfibers, alginate hydrogel networks, and green-synthesized ZnO nanoparticles within a single scaffold system, resulting in improved physicochemical and antimicrobial properties. Structural characterization through FTIR, XRD, SEM, DLS, and zeta potential analyses confirmed successful scaffold formation and ZnO nanoparticle incorporation, which correlated with the observed swelling, degradation, and antibacterial behaviors. Although the developed scaffold exhibited promising antimicrobial performance, this study did not include cytocompatibility, hemocompatibility, antibiofilm, cell proliferation, or in vivo wound-healing evaluations. Therefore, the present findings support the potential use of the scaffold as an antimicrobial dressing material rather than confirming its suitability for wound-healing or broader biomedical applications. Future investigations should focus on biocompatibility assessment, cell viability and proliferation studies, antibiofilm evaluation, hemocompatibility analysis, and in vivo wound-healing experiments to establish the biological safety and clinical applicability of the developed hydrogel scaffold.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons

Attribution (CC BY) license
(<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Abisha, M. M., Usha, D., Ashwin, B. M. and Dennison, M. S., Integrating microwave-assisted green synthesis, DFT simulations, and biological activity evaluation of copper-doped zinc oxide nanoparticles, *Sci. Rep.*, 15(1), 19348(2025).
<https://doi.org/10.1038/s41598-025-03922-8>
- Alam, P., Imran, M., Ahmed, S., Majid, H. and Akhtar, A., Chitosan Nanoparticles for Enhanced Delivery of *Sida cordifolia* Extract: Formulation, Optimization and Bioactivity Assessment, *Pharma.*, 16(11), 1561 (2023).
<https://doi.org/10.3390/ph16111561>
- Bhakyalatha, M. and Koppole, K., Plant extract-mediated ecofriendly synthesis of zinc oxide nanoparticles and investigation of their photocatalytic, antibacterial and antibiofilm properties, *Appl. Phy. A: Mater. Sci. Proce.*, 132(3), 162(2026).
<https://doi.org/10.1007/s00339-026-09301-y>
- Gunasekaran, R., Jyotsnika, K., Kannan, K. and Sivaperumal, P., Unlocking the bioactive potential: ZnO NPs synthesized from *Chaetomorpha linum* aqueous extract, *Next Nanotechnol.*, 9, 100346(2026).
<https://doi.org/10.1016/j.nxnano.2025.100346>
- Habeeb, R. K., Abad, W. K. and Abd, A. N., Preparation of ZnO nanoparticles from *Juglans regia* dry husk extract for biomedical applications, *J. Biosafety Biosecurity*, 7(1), 1–8(2025).
<https://doi.org/10.1016/j.jobbb.2024.10.004>
- Hadap, A., Panse, V. R. and Tereshchuk, S., Investigation of Aloe vera mediated ZnO-β-CD nanocomposite for photocatalysis and antimicrobial applications, *Sci. Rep.*, 15(1), 22871(2025).
<https://doi.org/10.1038/s41598-025-05231-6>
- Joseph, S. R., Sebastian, L. and Mythili, U., Transforming crustacean waste into a powerful antibacterial nanocomposite: unveiling the synergistic potential of novel copper-doped zinc oxide-carbon dot nanocomposite, *Biomass Convers. Biorefine.*, 15(2), 2837–2855 (2025).
<https://doi.org/10.1007/s13399-023-05189-3>
- Karthick, J. and Sreenivasan, V. S., Enhanced photocatalytic and antibacterial performance of ZnO and ZnS synthesized using natural fuel: Influence of green synthesis, particle size, and morphology, *Ind. J. Chem. Technol.*, 32(6), 710–722 (2025).
<https://doi.org/10.56042/ijct.v32i6.21749>

- Khan, S., Ullah, A., Ahmad, I., Sher, A., Rehman, G., Hayat, K., Ahmad, M., Shah, S. K. and Gunnella, R., Therapeutic potential of green-synthesized ZnO from *Azadirachta indica*: a study on anti-diabetic, anti-inflammatory, and anti-bacterial activities, *J. Sol-Gel Sci. Technol.*, 116(2), 1581–1596(2025).
<https://doi.org/10.1007/s10971-025-06938-8>
- Kirubakaran, D., Bupesh, G., Wahid, J. B. A., Murugeswaran, R., Ramalingam, J., Arokiyaraj, S., Sivasakthi, V. and Panigrahi, J., Green Synthesis of Zinc Oxide Nanoparticles Using *Acmella caulirhiza* Leaf Extract: Characterization and Assessment of Antibacterial, Antioxidant, Anti-inflammatory and Hemolytic Properties, *Biomed. Mater. Dev.*, 4(1), 552–573 (2026).
<https://doi.org/10.1007/s44174-025-00283-8>
- Kumar, P., Gautam, S., Bansal, D. and Kaur, R., Starch-based antibacterial food packaging with ZnO nanoparticle, *J. Food Sci. Technol.*, 61(1), 178–191(2024).
<https://doi.org/10.1007/s13197-023-05834-9>
- Liu, H., Yang, Y., Deng, L., Shen, Z., Huang, Q., Shah, N. G., Chen, W., Zhang, Y., Wang, X., Yu, L. and Chen, Z., Antibacterial and antioxidative hydrogel dressings based on tannic acid-gelatin/oxidized sodium alginate loaded with zinc oxide nanoparticles for promoting wound healing, *Int. J. Bio. Macromol.*, 279, 135177(2024).
<https://doi.org/10.1016/j.ijbiomac.2024.135177>
- Mim, J. J., Sarker, M. A. H., Maksudur Rahman, S. M., Hasan, M. J., Alom, M. S., Islam, S. and Hossain, N., Green synthesis, characterization, and in vitro biomedical applications of *Diospyros blancoi* synthesized copper and zinc oxide nanoparticles, *Res. Surf. Interf.*, 21, 100656(2025).
<https://doi.org/10.1016/j.rsufi.2025.100656>
- Palem, R. R., Kim, B. J., Baek, I., Choi, H., Suneetha, M., Shimoga, G. and Lee, S. H., In situ fabricated ZnO nanostructures within carboxymethyl cellulose-based ternary hydrogels for wound healing applications, *Carbohydr. Polym.*, 334, 122020 (2024).
<https://doi.org/10.1016/j.carbpol.2024.122020>
- Poorani, K., Rajkumar, M., Prajapati, B. G., Velmani, S., Sudha, P. N., Shanmugarathinam, A. and Paliwal, H., Biofabrication of *Leucas aspera*-Mediated Chitosan–Zinc Oxide Nanocomposites for In Vitro Antioxidant, Antibacterial, Anti-Inflammatory and Wound-Healing Properties, *Pharma.*, 18(3), 390(2026).
<https://doi.org/10.3390/pharmaceutics18030390>
- Rani, N., Yadav, S., Mushtaq, A., Rani, S., Saini, M., Rawat, S., Gupta, K., Saini, K. and Maity, D., *Azadirachta indica* peel extract-mediated synthesis of ZnO nanoparticles for antimicrobial, supercapacitor and photocatalytic applications, *Chem. Pap.*, 78(6), 3687–3704 (2024).
<https://doi.org/10.1007/s11696-024-03340-6>
- Saini, M., Yadav, S., Rani, N., Mushtaq, A., Rawat, S., Saini, K. and Maity, D., Biosynthesized zinc oxide nanoparticles using seed and bark extract of *Azadirachta indica* for antibacterial, photocatalytic and supercapacitor applications, *Mater. Sci. Eng. B*, 282, 115789(2022).
<https://doi.org/10.1016/j.mseb.2022.115789>
- Sampath, S., Bhushan, M., Saxena, V., Pandey, L. M. and Singh, L. R., Green synthesis of Ag doped ZnO nanoparticles: study of their structural, optical, thermal and antibacterial properties, *Mater. Technol.*, 37(13), 2785–2794(2022).
<https://doi.org/10.1080/10667857.2022.2075307>
- Shamshad, A., Ijaz, S., Arooj, I. and Tahir, S., Characterization and Sustainable Applications of Multifunctional, Non-Genotoxic ZnO-NPs Biofabricated by Organic Biomass Extract of *Nostoc* sp. SI-SN, *BioNanoSci.*, 14(5), 5527–5549(2024).
<https://doi.org/10.1007/s12668-024-01601-y>
- Siddiqui, M. A., Azam, M., Shabaaz Begum, J. P., Kumar, S., Prasad, R., Alomary, M. N., Ansari, M. A., Alharbi, H. O. A. and Alhumaidi, M. S., Phytofabrication of Zinc Oxide Nanoparticles Using *Sida cordifolia* L. and Their Biomedical Applications, *Bioinorg. Chem. Appl.*, 2026(1), 6531769(2026).
<https://doi.org/10.1155/bca/6531769>
- Srivastava, N., Ganapathy, K., Pathak, J. and Tadepalli, S., Exploring the Versatile Biocidal and Biocompatible Attributes of Chitosan-L-Tartaric Acid-Zinc Oxide Nanoparticles: Insights into Structural, Optical, and Biomedical Applications, *J. Inorg. Organomet. Polym. Mater.*, 35(12), 10182–10194(2025).
<https://doi.org/10.1007/s10904-025-03907-0>
- Suresh, U., Panneerselvam, C., Aziz, A. T., Srinivasan, M. K., Hassan, M. M., Alasmari, A. and Mohammedsaleh, Z. M., Synthesis, characterisation and evaluation of polyethylene glycol- β -cyclodextrin–curcumin–zinc oxide nanoparticles for mosquitocidal, antibacterial and anticancer applications, *Sci. Rep.*, 16(1), 2658(2026).
<https://doi.org/10.1038/s41598-025-32059-x>
- Tabe, M. B., Isbilen, O., Walker, J. N. and Cinar, E., Zingiber officinale-mediated zinc oxide nanoparticles: antimicrobial activity against multidrug-resistant bacteria, *BMC Complement. Med. Therapies*, 26(1), 88(2026).
<https://doi.org/10.1186/s12906-026-05281-x>
- Thandavamoorthy, R., Devarajan, Y. and Mehar, K., Synthesis of ZnO Nanoparticles from *Pergularia daemia* Fibre: Potential for Caries Prevention and Infection Control, *Int. Dent. J.*, 76(2), 109396(2026).
<https://doi.org/10.1016/j.identj.2025.109396>
- Thanjavur, N., Lakshmi, B. A., Bugude, L., Theyagarajan, K. and Kim, Y. J., Bio-capped ZnO nanoparticles formulated from *Prosopis juliflora* gum: Phytochemical characterization and therapeutic potential, *Int. J. Bio. Macromol.*, 334, 149092(2025).
<https://doi.org/10.1016/j.ijbiomac.2025.149092>

