Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 4, 2026
January–December
DOI (Journal): 10.37591/JoPC

Research JoPC

Preparation and Characterization of Clay-Based Hybrid Membranes for Antibacterial Biodegradable Polymer Wound Dressings

Snehal Masurkar[1,*], S. K. Mohite[2], Sheeth Toppo[3]

Abstract

Recent developments in the field of polymer chemistry have resulted in many new forms of Hybrid polymer. This has further revolutionized the application of polymer chemistry in numerous fields. In this research, we manufactured clay-based hybrid membrane by adding clay to the biodegradable matrix of chitosan polymer. It is widely known that microbial and pathogenic organisms are responsible for wound hampering infections such as impetigo. They can spread in bodily fluids and skin, enter the blood through wounds and slow down the healing and repair of tissues. Clay has long historical use as a therapeutic agent with potential use in biomedical applications. Its safe composition, along with its large surface area, availability, and ability to exchange cations make it attractive. This design increases structural and biocompatibility and wound-healing efficiency. The hybrid membranes are a combination of clays, hydraulic ionizing agents – called Zwitterions, silver and terbinafine hydrochloride (TBH). This combination yields both antibacterial as well as antifungal action. The biodegradable polymer serves as a supporting framework, and the clay helps to control the releasing of antimicrobial agents to prevent the growth of pathogens. We evaluated the antimicrobial efficacy employing a zone of inhibition assay against prevalent skin wound pathogens; these hybrid clay membranes were strongly antimicrobial against Candida albicans, Escherichia coli, and Staphylococcus aureus. Our output suggests that these hybrid clay membranes are affordable, scalable, and suitable for powerful and useful treatment of microbial infections. In wound healing solution these membranes provide an advance point of care solution.

Keywords: Hybrid polymer, polymer characterization, biodegradable polymer, Chitosan polymer

INTRODUCTION

Infection caused by microbes from wounds, burns, and foodborne illnesses represent 12% of deaths globally, particularly affecting low- and middle-income nations bearing the brunt of them [1]. A recent study, this time a large one, found that five germs, *S. aureus*, *Pseudomonas aeruginosa, Escherichia coli*, *Klebsiella pneumoniae*, *S. aurereus*, were responsible for over half of all bacteria-related deaths, with *Staphylococcus aureus* alone being responsible for more than 1.1 million deaths [2]. These infections are very contagious in humans and animals and have been the cause of millions of birds being lost to the poultry and farming industry to diseases caused by bacteria and viruses [3].

The level of surface wounds affects the upper body surface while acute wounds are more serious and can become infected with bacteria or fungi [4].

***Author for Correspondence**
Snehal Masurka
E-mail id: smasurkar51@outlook.com

[1]Associate Professor, Department of Microbiology, Krishna Institute of Science and Technology, Krishna Vishwa Vidyapeeth (Deemed to be University), Karad, Satara, Maharashtra, India
[2]Principal, Department of Pharmaceutical Chemistry, Rajarambapu College of Pharmacy, Kasegaon, Maharashtra, India
[3]Assistant Professor, Department of Home Science, Kolhan University, Chaibasa, Jharkhand, India

Received Date: May 19, 2026
Accepted Date: May 29, 2026
Published Date: June 06, 2026

Citation: Snehal Masurkar, S. K. Mohite, Sheeth Toppo. Preparation and Characterization of Clay-Based Hybrid Membranes for Antibacterial Biodegradable Polymer Wound Dressings. Journal of Polymer & Composites. 2026; 14(Special Issue 4): S13–S20p.

Staphylococcus aureus (Saveis) and *Escherichia coli* (*E. coli*) are probably the most common bacteria of human body [5]. *S. aureus* is the most common cause of surgical infection [6]. Though usually benign residents of the body, when bacteria enter the bloodstream through a wound, they have the potential to lead severe infections and secrete their enzymes which spread damage to nearby tissues [7].

Although bacteria are one of the main causes of chronic nonhealing wounds, fungi are also significant contributors [8]. Fungal infections pose dangerous threats in critical care particularly chronic and surgical wounds [6]. Almost one quarter of chronic wounds are fungal infected [9] is widely reported in chronic wounds is Candida (*Candida albicans* [*C. albicans*]) yeast-like fungus [10]. *C. albicans* is naturally found in different areas of the body such as the digestive system, reproductive organs, oral region, and outer body surface [11]. In the case of fungal infections can complicate skin wounds and the wound-healing process, forming organisms that are not easily destroyed by conventional treatment in so-called biofilms [12].

Current wound dressings products are composed of various materials including, hydrogels, fiber-based scaffolds, hydrocolloids, carbon derived structure, bioactive glass, film layers prepared from either natural or artificial origins [13–15]. Many of these dressings have antimicrobial agents – like metal nanoparticles or antibiotics – to enhance the antibacterial activity [14–16]. Although there are artificial materials this need for supplementary, cost-effective solutions is growing. Environmentally friendly, sustainable materials that do not involve toxicity, easy to use in harsh conditions, appropriately packaged, and well-biodegradable are key requirements [17]. Biodegradable polymers have been very interesting for wound dressings due to their biocompatibility, degradation, and tissue regeneration support. Natural polymers, like chitosan, alginate, and gelatin and the synthetic polymers, polycaprolactone and polylactic acid provide moisture-retention, oxygen-permeability and structural support. Chitosan is interesting in particular since it is naturally antibacterial, non-toxic and promotes cell adhesion and proliferation. Biodegradable matrices also have the potential to incorporate antimicrobial agents, which can be used to release at a sustained rate at the site of the wound. However, biodegradable polymers lack often mechanical strength and structural stability; the presence of clay minerals add on to these characteristics in hybrid composites [18]. Mylsamy B, Aruchamy K, Shanmugam SK, Palanisamy S, Ayrilmis N. Improving performance of composites: Natural and synthetic fibre hybridisation techniques in composite materials–A Review. Materials Chemistry and Physics. 2025 Apr 1;334:130439.

Clays find a range of applications in the therapeutic and biomedical sectors, as they are biocompatible, richly available, have a large surface area, and promote the flow of oxygen and moisture through pores. Bentonite and sepiolite have a distinctive property that allows their modification with biodegradable polymers and organic agents to produce hybrid membranes with improved mechanical resilience, stability and antimicrobial properties for wound dressings [19, 20]. Elements – like iron, magnesium, and potassium in clays – also help in recovery process [21, 22].

Antibiotics are the most common type of antibacterials used in wound dressings, followed using antimicrobial materials such as metallic elements and oxide-based nanomaterials [16]. Silver based compounds in ionic and nanoparticles are favored as antibacterial agents while treating these different classes of antifungal groups we use, such as polyenes, echinocandins, and allylamines azole, and that include dermatophytes [10]. Terbinafine hydrochloride (TBH) is an allylamine with oral and topical action, which is effective against different types of fungi, even at low concentrations [22]. With the proper dosage and duration, silver acts as an effective antiseptic with powerful antibacterial activity against microorganisms present in wound. Research findings indicate that both silver ions and nanocrystalline silver may control the spread of antibiotic-resistant organisms when used wisely and reduce the need for antibiotics to be taken systemically, and therefore, reduce treatment time and cost [23].

We intend to show off hybrid clay composite membrane as an affordable antimicrobial treatment by engineering clays, betaine, silver ion and TBH as environmentally benign ingredients to develop an efficient membrane with effective antibacterial and antifungal properties. Bentonite and sepiolite served as host clay for the synthesize of the composites. The non-toxic, one of the non-toxic surfactants, betaine, which is a non-toxic compound, binds to the interlayer or surface of the clay and helps to adsorb the antimicrobial agent. Ag-apatite-bentonite membrane prepared by Cation Exchange Resorption. Membranes composed of silver-infused apatite-bentonite were created by incorporating silver ions into bentonite clay. These materials effectively targeted both Gram-positive and Gram-negative bacteria, including *E. coli* and *S. aureus*, but did not exhibit any antifungal properties. On the other hand, TBH–betaine–bentonite composites proved to be effective against fungal organisms. Finally, Ag–TBH–betaine–bentonite composite materials were obtained, in which silver, TBH and betaine have been used in combination with ambient to deliver antibacterial and antifungal activity.

In our studies, we revealed that the viscosity, storage moduli and flow stresses of the clays functionalized with the redox agents are higher because of the creation of three-dimensional networks and a result of higher aggregation due to intercalation [24]. Rheological analyses investigated the interactions of betaine molecules with bentonite slurry and the effect on slurry structure and properties of bentonite clay. We found that the addition of small, pH-sensitive, eco-friendly betaines, such as trimethyl glycine, grants substantial improvement in rheological performance compared to unmodified clays which is a great alternative to long-chain surfactants that are currently used to functionalize clays.

Chitosan is a biodegradable biocompatible polymer that is popular for biomedical use because it is hydrophilic and naturally antimicrobial. Clay minerals have high surface area, ion-exchange capacity and good mechanical properties which make them suitable for drug delivery applications, wound healing, etc. Combining chitosan and clay polymers results in biodegradable polymer–clay nanocomposites that improve mechanical strength, stability and controlled drug release. These are the hybrids that are getting more attention in antimicrobial wound dressings, thanks to the better compatibility, therapy persistence and prevention of infections that they achieve.

MATERIALS, SYNTHESIS, AND TESTING

Materials Used

Bentonite and sepiolite clays were used as the primary mineral components in this study. Phosphate buffered saline (PBS) was used to keep the physiological condition during the experiments. Silver nitrate, betaine and terbinafine hydrochloride (TBH) were used as functional agents in the composite preparation. All materials were used as received, and no additional processing and purification steps were performed. Deionized water was used for all the work for solution preparation and washing.

The antibacterial wherefore of the materials was tested against *Staphylococcus aureus* (ATC 6538) and *Escherichia coli* (ATC 25922). Antifungal activity was determined on *Candida albicans* (ATCC MYA 4441). These strains were from a certified culture repository. Prior using all growth media and buffer solutions used for this purpose were sterilized by autoclaving at 121°C and 15 psi for 30 min to maintain aseptic condition.

Preparation of Clay-Based Composite

Bentonite Clay Composite

A composite, which used a membrane mix that contained bentonite clay and betaine, was prepared to increase functional characteristics. First, 3.5 g of sodium bentonite was combined with 55 ml of deionized water and stirred constantly for 24 hours to ensure complete hydration and expansion of the layers of clay. The suspension was then purified by centrifugation at 8000 rpm 3 times, of which deionized water was used to wash and remove the remaining impurities. Following purification, 0.58 g of betaine was added to the clay suspension along with 10 mL of deionized water, and the mixture was stirred for an additional 24 hours to ensure consistent interaction between betaine and the clay structure.

The suspension prepared was then uniformly applied onto a glass surface utilizing an automatic film coater that operated at a speed of 2 mm/s. The coated film was then placed in an oven at 60°C for 4 hours to ensure adequate membrane formation. Following the drying process, the membrane was gently removed from the glass surface and identified as the Betaine/Bentonite Clay Composite Membrane (BB-CC (M)). Circular samples measuring 6 mm in diameter were cut for antibacterial testing. Each membrane sample weighed approximately 2.5 mg and had a thickness of about 50 µm.

Silver–Betaine Functionalized Bentonite Composite Membrane

Composite membranes of betaine and bentonite loaded with silver were created using an ion-exchange technique, where silver ions replaced the sodium ions found in bentonite. To create the samples, four different amounts of silver nitrate (0.4 g, 0.8 g, 1.2 g, and 1.6 g) were utilized while keeping the quantities of bentonite (3.5 g) and betaine (0.58 g) constant. First, bentonite was dispersed in deionized water, after which the appropriate amount of silver nitrate was added to the mixture. The resulting suspension was stirred continuously for 24 hours to facilitate adequate ion exchange between sodium ions and silver ions.

The suspension was subjected to centrifugation at 8000 rpm and rinsed with deionized water to eliminate any unreacted ions and contaminants. The purified material was then combined with 0.58 g of betaine in 10 mL of deionized water and stirred for 24 hours to guarantee even incorporation. The resulting suspension was applied onto glass plates using an automated film coater and dried at 60°C for 4 hours. After drying, the membranes were carefully peeled off and designated as silver–betaine–bentonite composites, labeled according to the concentration of silver nitrate: Ag(1)-BB-CC(M), Ag(2)-BB-CC(M), Ag(3)-BB-CC(M), and Ag(4)-BB-CC(M). Each membrane sample weighed approximately 2.5 mg and had a thickness of around 50 µm.

TBH–Betaine Functionalized Bentonite-Based Composite Pellets

The composites of Bentonite Clay TBH–Betaine were created by incorporating 3.5 g of bentonite into 50 ml of deionized water. The mixture was shaken for 24 hrs, centrifuged three times at 8000 rpm, and washed with deionized water. The slurry was transferred to another container and combined with ready prepared TBH solutions in the form of methanol. The TBH–clay suspensions were shaken for a further 24 hr. at ambient temperature, then applied onto glass plates and allowed to dry in a vacuum oven for 24 hours. at 60°C. The resulting powders were collected and worse pressed into pellets. Terbinafine hydrochloride (TBH)–betaine–bentonite composite pellets were prepared using different concentrations of TBH. Three formulations were developed and designated as TBH(1)-BB-CC(P), TBH(2)-BB-CC(P), and TBH(3)-BB-CC(P). The TBH solutions were prepared by dissolving 50 mg, 100 mg, and 150 mg of TBH in 5 mL of methanol, respectively. These solutions were then incorporated into the betaine–bentonite composite to form pellet structures. The resulting composite pellets were uniform in shape, with each pellet having an approximate mass of 200 mg and a thickness of about 2.6 mm. These pellets were further used for antifungal evaluation and related experimental studies.

Silver–TBH–Betaine Modified Bentonite Composite Pellets

A hybrid nanocomposite was created by combining silver, terbinafine hydrochloride (TBH), betaine, and bentonite through a solution-based preparation technique. First, 0.3 g of silver nitrate was added to a suspension of 3.5 g bentonite in 50 ml deionized water with good mixing. Next, a TBH solution was made by dissolving 50 mg TBH in 5 mL methanol and added to the mixture. The resulting suspension was stirred for 24 hours to ensure an interaction of all components in the suspension; the solid material was then isolated by centrifugation. Then 0.58 g of betaine was added to the collected material and mixed to homogenize the material. The final mixture was evenly spread on a glass plate and dried in an oven for 4 hours at 60°C to obtain the composite material. After drying, the material was ground into powder and formed into circular pellets (diameter of 6.2 mm and weight of approximately 200 mg and thickness approximately 2.6 mm). These samples were named Ag-TBH-betaine-bentonite composite pellets (Ag-TBH-BB-CC(P)).

Preparation of Sepiolite Composite Materials

Betaine–Sepiolite composite membranes were prepared following the procedure developed for betaine–bentonite system except replacing bentonite with sepiolite. The membrane obtained was called

BS-CC(M) and was used as a reference to evaluate sepiolite-based formulations. Each BS-cc(M) membrane's weight was approximately 5 mg and its thickness was approximately 70 um. Composites that include silver and sepiolite were also developed in the membrane and pellet formats. For these, 0.3 g silver nitrate was combined with 3.5 g sepiolite and 2.5 g betaine with the same synthesis process as the betaine–bentonite membranes and TBH–bentonite pellets. The membrane samples were labelled Ag-BS-CCM while the pellets were labelled Ag-TBH-BS-CCP. Each pellet was about 200 mg in mass, 2.6 mm thick and 6.2 mm in diameter. Detailed information of prepared samples is all provided in Table1.

Table 1. Experiment details of experiments performed on clay composite samples.

Sample	Abbreviation	Physical form	Application
Betaine–Bentonite Clay Composite	BB-CC (M)	Membrane	Control.
Ag–Betaine–Bentonite Clay Composite	Ag (1)-BB-CC (M)	Membrane	Antibacterial.
	Ag (2)-BB-CC (M)	Membrane	Antibacterial.
	Ag (3)-BB-CC (M)	Membrane	Antibacterial.
	Ag (4)-BB-CC (M)	Membrane	Antibacterial.
TBH–Betaine–Bentonite Clay Composite	TBH (1)-BB-CC (P)	Pellet	Antifungal.
	TBH (2)-BB-CC (P)	Pellet	Antifungal.
	TBH (3)-BB-CC (P)	Pellet	Antifungal.
Ag–TBH–Betaine–Bentonite Clay Composite	Ag-TBH-BB-CC (P)	Pellet	Antibacterial, Antifungal.
Betaine–Sepiolite Clay Composite	BS-CC (M)	Membrane	Control.
Ag–Betaine–Sepiolite Clay Composite	Ag-BS-CC (M)	Membrane	Antibacterial.
Ag–TBH–Betaine–Sepiolite Clay Composite	Ag-TBH-BS-CC (P)	Pellet	Antibacterial, Antifungal.

Evaluation of Antimicrobial Activity of Clay Composites

The capability of the clay composite materials against some microbial strains including *C. albicans*, *S. aureus*, and *E. coli* was determined using the zone of inhibition (ZOI) method. First, all strains were grown in LB broth or YEM broth and incubated at 38°C while continuously agitated at 160 rpm for better growth. The optical density (OD) of the cultures was determined at 600 nm wavelength (OD600) with a UV–visible spectrophotometer (Cary-60, Agilent Technologies) to monitor the cell density. Before testing, all the composite samples were exposed to ultraviolet light for 22 min to eliminate potential contamination. The microbial suspensions were then diluted to an optical density of 0.2. About 55 tempting (phantom) microliter solution prepared from the cultured culture was uniformly spread on the LB agar or YEM agar plates, so that we can obtain the same amount of bacterial layer. Sterilized clay discs and control samples of similar size (6.2 mm diameter) were carefully placed on the surface of the agar on sterile forceps. Incubation of the plates took place at a temperature of 38°C for 24h. After incubation, the antibacterial effectiveness was scored by measuring the surrounding clear zones around each sample which indicated by inhibition of microbial proliferation. Measurements were made in millimeters and results given as the mean zone size with standard deviation from several repetitions (n > or equal to 2).

Chitosan–Clay

Applying eco-friendly ingredients or in particular bio-waste derived materials is also becoming more and more important for various applications. Chitosan is a natural polysaccharide with a great number of properties and potential applications [25]. Structurally, it is made up of random units of beta-(1->4) linked D-(1->2) glucose that is either deacetylated or N-acetylated.

Chitosan can be obtained from cell wall wastes of fungi. The biocompatible and biodegradable nature of it makes it a safe biomaterial for humans, animals and environment [26]. Such synonyms are deacetyl chitin and poly-(D) glucosamine, referring to its structure and ways of formation [27].

The degree of Deacetylation (DD) has a critical effect on the properties of chitosan. Commercial chitosan usually has a DD of 75–90 per cent and a molecular weight (MW) of 60–2000 kDa [28]; Based on MW, the chitosan is categorized into low MW (<160 kDa), medium MW (160–700 kDa) and high MW chitosan (MW > 700 kDa) [29].

Chitosan's biodegradability is a result of its vulnerability to hydrolysis by the proteolytic enzyme, lysozyme which is typically found in human tissue as well as lipase (which can be found in saliva, gastric and pancreatic secretion). The degradation product of enzymes is non-toxic in nature [30].

Preparation and Structural Analysis of Chitosan–Clay

The solution intercalation, in-place polymerization, and melted intercalation methods are generally used for the development of bio-nanocomposites made from polymer and clay. These techniques insert the polymer chain between the layers of clay and result in a homogeneous dispersion of clay particles onto a biodegradable polymer matrix. The composites exhibit enhanced mechanical strength and enhanced stability and controlled drug delivery. They can be cast in thin films or made into scaffolds for use in wound dressing. Characterization by XRD, SEM, FTIR and thermal analysis was done to study their structure, morphology, and physicochemical properties.

Statistical Analysis

All experiments were conducted three times unless stated otherwise. The outcomes are shown as the average value along with the relevant standard deviation (mean ± S.D.). A two-tailed Student's t-test was used for statistical assessment to evaluate the significance of differences between groups. A p-value of less than 0.05 was deemed statistically significant. The significance levels are denoted as ns (not significant) for $p > 0.06$, for $p < 0.06$, for $p < 0.02$, for $p < 0.002$, and for $p < 0.0002$.

RESULT

Production of Antimicrobial Clay-Infused Composites

Bentonite composites were produced by interlayer sodium ions in the clay structure being replaced by silver ions that endow antibacterial activity. Antifungal composites were based on terbinafine hydrochloride (TBH) that was adsorbed in bentonite surface via intercalation or surface attachment [31]. tiny betaine molecules also inserted themselves, leading to expanding the layers and also accommodating both silver and TBH. The mechanism of adsorption is primarily influenced by the electrostatic forces between the positively charged TBH and the negatively charged surface of the clay material [32].

Composites based on sepiolite were created by adsorbing silver ions (Ag^+) and TBH onto the surface of the elongated sepiolite structure. The negatively charged surface of sepiolite enables it to engage with positively charged TBH via electrostatic interactions, leading to enhanced adsorption [33]. The resulting composites were evaluated against microorganisms in skin wounds and their zones of inhibition. TBH inclusion disrupted the layers making free-standing membranes impossible and so all powders were compacted to pellets which were used as scaffolds.

CONCLUSION

This research showcases a simple yet efficient technique for creating clay-based composites with antimicrobial properties by combining sepiolite and bentonite with TBH and silver ions. The resulting membranes showed significant inhibitory effects against *E. coli*, and *C. albicans*, *S. aureus* highlighting their potential use in antimicrobial applications. The synthesis route presented in the study is a sequential synthesis route for antibacterial, antifungal and dual-action application. Bentonite is plate-like and sepiolite is fibrous/rod-shaped clay system proved to be effective when loaded with silver gram-negative bacteria and against gram-positive or TBH (against fungi). The combination has protection from bacterial and fungal pathogens, which fight bacteria with silver ions and fungus with TBH. Burn victims at increased risk of infection WHO estimates that 11 million burn patients experience complications and result in greater than 180 000 worldwide deaths annually. The control of infection is a worldwide priority. The market for wound care was worth $22.06 billion in 2023, and is expected to be worth $30 billion by 2029, providing the impetus for the development of materials to resist disease-causing microbes and limit their penetration. Our findings highlight clay-based composites as promising wound care solutions, i.e., biocompatible composites which are low-cost and have low-toxic antimicrobial functionalization. Furthermore, they provide a prolonged release of antimicrobial substances, necessary for ongoing defense against microbial colonization, thereby decreasing the likelihood of infections and bolstering public health initiatives. We plan upon taking these research findings into the further development of treatments against scars, burns, and chronic skin diseases and the optimization of these composites for clinical testing in animal models. Biodegradable polymer–clay hybrid membranes based on chitosan and natural clays have great potential for antibacterial wound dressings. These hybrids have the combined properties of chitosan (compatibility with living tissues, biodegradability, film-forming capacity and inherent antimicrobial properties) and clay minerals (high surface area, ion-exchange capacity and mechanical properties). Adding clay to a polymer matrix increases structural stability and can create controlled release of antimicrobial agents which will increase infection control and wound-healing efficiency. Such composites are a safe, sustainable and fruitful solution to advanced wound care and further biomedical applications.

REFERENCES

1. Bhattarai S, Sharma BK, Subedi N, Ranabhat S, Baral MP. Burden of serious bacterial infections and multidrug-resistant organisms in an adult population of Nepal: A comparative analysis of minimally invasive tissue sampling informed mortality surveillance of community and hospital deaths. Clin Infect Dis. 2021;73(Suppl 5):S415–S421.
2. Vos T, Lim SS, Abbafati C, Abbas KM, Abbasi M, Abbasifard M, et al. Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: A systematic analysis for the Global Burden of Disease Study 2019. Lancet. 2020 Oct 17;396(10258):1204-22.
3. Hernández AC. Poultry and avian diseases. In: Van Alfen NK, editor. Encyclopedia of Agriculture and Food Systems. Vol. 4. San Diego (CA): Academic Press; 2014. p. 504–520.
4. Simões D, Miguel SP, Ribeiro MP, Coutinho P, Mendonça AG, Correia IJ. Recent advances on antimicrobial wound dressing: A review. Eur J Pharm Biopharm. 2018;127:130–141.
5. Bowler PG, Duerden BI, Armstrong DG. Wound microbiology and associated approaches to wound management. Clin Microbiol Rev. 2001;14(2):244–269.
6. Uberoi A, McCready-Vangi A, Grice EA. The wound microbiota: Microbial mechanisms of impaired wound healing and infection. Nat Rev Microbiol. 2024;22(8):507–521.
7. Sun A, He X, Li L, Li T, Liu Q, Zhou X, et al. An injectable photopolymerized hydrogel with antimicrobial and biocompatible properties for infected skin regeneration. NPG Asia Mater. 2020;12(1):25.
8. Ge Y, Wang Q. Current research on fungi in chronic wounds. Front Mol Biosci. 2023;9:1057766.
9. Gil J, Solis M, Higa A, Davis SC. Candida albicans infections: A novel porcine wound model to evaluate treatment efficacy. BMC Microbiol. 2022;22(1):45.
10. Rewak-Soroczyńska J, Sobierajska P, Targońska S, Piecuch A, Grosman L, Rachuna J, et al. New approach to antifungal activity of fluconazole incorporated into the porous 6-anhydro-α-L-galacto-β-D-galactan structures modified with nanohydroxyapatite for chronic-wound treatments: In vitro evaluation. Int J Mol Sci. 2021;22(6):3112.
11. Nobile CJ, Johnson AD. Candida albicans biofilms and human disease. Annu Rev Microbiol. 2015;69:71–92.
12. Heald AH, O'Halloran DJ, Richards K, Webb F, Jenkins S, Hollis S, et al. Fungal infection of the diabetic foot: Two distinct syndromes. Diabet Med. 2001;18(7):567–572.
13. Ghimire S, Sarkar P, Rigby K, Maan A, Mukherjee S, Crawford KE, et al. Polymeric materials for hemostatic wound healing. Pharmaceutics. 2021;13(12):2127.
14. Dreifke MB, Jayasuriya AA, Jayasuriya AC. Current wound healing procedures and potential care. Mater Sci Eng C Mater Biol Appl. 2015;48:651–662.
15. Nowotnick AG, Xi Z, Jin Z, Khalatbarizamanpoor S, Brauer DS, Löffler B, et al. Antimicrobial biomaterials based on physical and physicochemical action. Adv Healthc Mater. 2024;13(32): 2402001.

16. Chernousova S, Epple M. Silver as antibacterial agent: Ion, nanoparticle, and metal. Angew Chem Int Ed Engl. 2013;52(6):1636–1653.
17. Karypidis M, Karanikas E, Papadaki A, Andriotis EG. A mini-review of synthetic organic and nanoparticle antimicrobial agents for coatings in textile applications. Coatings. 2023;13(4):693.
18. Mylsamy B, Aruchamy K, Shanmugam SK, Palanisamy S, Ayrilmis N. Improving performance of composites: natural and synthetic fibre hybridisation techniques in composite materials—A review. Mater Chem Phys. 2025;334:130439.
19. de Oliveira LH, de Lima IS, dos Santos AN, Trigueiro P, Barreto HM, Cecília JA, et al. Monitoring the antimicrobial activity of bentonite-chlorhexidine hybrid. Mater Today Commun. 2023;34:105352.
20. Ongprayoon T, Nuangchamnong R, Yanumet N. Antimicrobial resistance of clay polymer nanocomposites. Appl Clay Sci. 2013;86:179–184.
21. Gordienko MG, Palchikova VV, Kalenov SV, Belov AA, Lyasnikova VN, Poberezhniy DY, et al. Antimicrobial activity of silver salt and silver nanoparticles in different forms against microorganisms of different taxonomic groups. J Hazard Mater. 2019;378:120754.
22. Paskiabi FA, Bonakdar S, Shokrgozar MA, Imani M, Jahanshiri Z, Shams-Ghahfarokhi M, et al. Terbinafine-loaded wound dressing for chronic superficial fungal infections. Mater Sci Eng C Mater Biol Appl. 2017;73:130–136.
23. Woodmansey EJ, Roberts CD. Appropriate use of dressings containing nanocrystalline silver to support antimicrobial stewardship in wounds. Int Wound J. 2018;15(6):1025–1032.
24. Sarkar P, Ghimire S, Vlasov S, Mukhopadhyay K. Effect of clay-zwitterionic interactions in controlling the viscoelastic properties in organomodified clays. iScience. 2023;26(12).
25. Silva-Castro I, Martín-Ramos P, Matei PM, Fernandes-Correa M, Hernández-Navarro S, Martín-Gil J. Eco-friendly nanocomposites of chitosan with natural extracts, antimicrobial agents, and nanometals. In: Thakur VK, Thakur MK, Kessler MR, editors. Handbook of Composites from Renewable Materials. Hoboken (NJ): Wiley; 2017. p. 35–60.
26. Kean T, Thanou M. Biodegradation, biodistribution and toxicity of chitosan. Adv Drug Deliv Rev. 2010;62(1):3–11.
27. Rowe RC, Sheskey PJ, Quinn ME, editors. Handbook of Pharmaceutical Excipients. 5th ed. London: Pharmaceutical Press; 2006.
28. Seyfarth F, Schliemann S, Elsner P, Hipler UC. Antifungal effect of high- and low-molecular-weight chitosan hydrochloride, carboxymethyl chitosan, chitosan oligosaccharide and N-acetyl-D-glucosamine against Candida albicans, Candida krusei and Candida glabrata. Int J Pharm. 2008; 353(1–2):139–148.
29. Mishra M, editor. Handbook of Encapsulation and Controlled Release. Boca Raton (FL): CRC Press; 2015.
30. Safdar R, Omar AA, Arunagiri A, Regupathi I, Thanabalan M. Potential of chitosan and its derivatives for controlled drug release applications: A review. J Drug Deliv Sci Technol. 2019;49:642–659.
31. Thakral S, Kim K. Small-angle scattering for characterization of pharmaceutical materials. Trends Anal Chem. 2021;134:116144.
32. Sun B, Zhang M, Zhou N, Chu X, Yuan P, Chi C, et al. Study on montmorillonite-chlorhexidine acetate-terbinafine hydrochloride intercalation composites as drug release systems. RSC Adv. 2018;8(38):21369–21377.
33. Yang F, Wang A. Recent researches on antimicrobial nanocomposite and hybrid materials based on sepiolite and palygorskite. Appl Clay Sci. 2022;219:106454.