JournalsPub

International Journal of
Chemical Engineering and Processing

ISSN: 2455-5576
Volume 12, Issue 1, 2026
January–June
DOI (Journal): 10.37628/IJCEP

https://journals.stmjournals.com/ijocep/

Review IJCEP

Chemical Engineering Aspects of Carrageenan Hydrogel–Silver Composite Systems: Synthesis, Structure, and Performance

Sakshi Chaudhary[1], Bibhas K. Bhunia[2,*], Jayanand Manjhi[3]

Abstract

This review presents a green chemistry-driven strategy for the synthesis, design, and chemical engineering of carrageenan-based hydrogel matrices embedded with green-synthesized silver nanoparticles (AgNPs) for advanced biomedical and pharmaceutical applications. Silver nanoparticles were fabricated through an environmentally benign route employing natural biopolymeric reducing and stabilizing agents, eliminating the need for hazardous chemical reagents and minimizing ecological impact. The synthesized AgNPs were subsequently incorporated into κ-carrageenan hydrogel networks under controlled physicochemical conditions to achieve uniform dispersion and stable nanocomposite formation. Carrageenan, a naturally occurring sulfated polysaccharide derived from red seaweed, serves as an excellent hydrogel matrix due to its intrinsic biocompatibility, biodegradability, gel-forming capability, and bio-adhesive characteristics. Detailed evaluation of molecular-level interactions between carrageenan polymer chains and embedded AgNPs revealed significant modulation of hydrogel cross-linking density, viscoelastic behavior, swelling capacity, mechanical integrity, and controlled ion-release kinetics. The resulting nanocomposite hydrogels demonstrated enhanced physicochemical and biological functionality, including sustained silver ion release, structural stability, and broad-spectrum antimicrobial activity against representative Gram-positive and Gram-negative microorganisms. Furthermore, the integration of green nanoparticle synthesis with sustainable polymer network engineering provides a scalable and eco-conscious platform for next-generation biomaterials. The study emphasizes the potential of carrageenan–AgNP hydrogel systems as multifunctional materials suitable for diverse biomedical applications, including antimicrobial coatings, wound healing scaffolds, targeted drug delivery systems, biosensing interfaces, and regenerative tissue engineering. Overall, this review underscores the importance of combining green nanotechnology principles with advanced hydrogel design to develop safe, sustainable, and high-performance biomedical materials. Future studies should prioritize clinical validation, scalability, and long-term safety.

***Author for Correspondence**
Bibhas K. Bhunia
E-mail: bibhasmicro@gmail.com

[1]Research of Scholar, School of Biotechnology and Bioinformatics, Shobhit Institute of Engineering and Technology (Deemed-to-be-University), Meerut, Uttar Pradesh, India.
[2]Assistant Professor, Department of Life Sciences, Parul Institute of Applied Sciences, Parul University, Vadodara, Gujarat, India.
[3]Professor, School of Biotechnology and Bioinformatics, Shobhit Institute of Engineering and Technology (Deemed-to-be-University), Meerut, Uttar Pradesh, India.

Received Date: December 30, 2025
Accepted Date: January 28, 2026
Published Date: February 23, 2026

Citation: Bibhas K. Bhunia, Sakshi Chaudhary, Jayanand Manjhi. Chemical Engineering Aspects of Carrageenan

Keywords: Antimicrobial coating, carrageenan, hydrogel, silver nanoparticles, tissue engineering

INTRODUCTION

Nanotechnology has emerged as a key instrument for producing novel materials with a wide range of scientific and technological uses in recent years. When compared to their bulk materials, nanoparticles smaller than 100 nm have special characteristics such a high surface to volume ratio and strong reactivity [1]. Among noble metallic nanoparticles, silver nanoparticles are the subject of much research due to their remarkable characteristics [2].

They are mostly studied in colloidal systems because of their special electrical and, in particular, antibacterial properties [3]. Silver nanoparticles' antibacterial qualities have led to their incorporation into a variety of medical devices [4]. Green-synthesised AgNPs are becoming more popular because of their reduced toxicity, enhanced antibacterial activity, bioactive phytochemical cap, and environmental friendliness [5, 6]. There are several uses for green synthesised silver nanoparticles when they are incorporated into different substrates and matrices. A novel class of materials with a broad spectrum of applications has been created by combining hydrogels with nanoparticles. Naturally, the most important feature of hydrogel networks is their excellent suitability for both in situ and ex-situ nanoparticle formation [7].

The free space between the gel networks act as nanoscopic domains or pots that provide excellent growth of the nanoparticles without any aggregations due to their biocompatibility, adjustable porosity, and capacity to replicate the extracellular matrix (ECM), hydrogels are particularly interesting in biomedical engineering [8]. These characteristics make them appropriate for a variety of uses such as biosensors, tissue engineering scaffolds, drug delivery systems, wound dressings, and regenerative medicine. Additionally, their significance in therapeutic delivery has increased due to their capacity to encapsulate and release medicines, bioactive compounds, or nanoparticles in a regulated manner [9, 10]. Current developments focus on stimuli-responsive hydrogels, which enable intelligent biological applications by reacting to environmental cues like pH, temperature, enzymes, or light.

Hydrogels are an intriguing class of materials that have garnered significant interest in several scientific and technical fields [11]. Three-dimensional, hydrophilic polymeric networks known as hydrogels can absorb and hold large volumes of water or biological fluids without disintegrating. Their distinctive structure, which resembles real soft tissues in terms of mechanical strength and flexibility, is created by the physical or chemical crosslinking of polymer chains [12]. Hydrogels are a versatile and optimistic biomaterial that has become indispensable in a wide range of applications, from the biomedical and pharmaceutical fields to the environmental and industrial sectors, thanks to their remarkable water-absorbing properties and striking resemblance to natural living tissues [13]. Both natural polymers (such alginate, chitosan, carrageenan, gelatin, and cellulose) and synthetic polymers (like polyvinyl alcohol, polyethylene glycol, and polyacrylamide) can be used to create hydrogels [14–15]. Their mechanical qualities, biocompatibility, and degradability are all influenced by the polymer selection, which enables customization for certain biomedical requirements [16].

Within the pharmaceutical industry, Carrageenan hydrogels have garnered more interest than other carrageenan formulations. Carrageenan-based hydrogel beads have been the focus of much research because of their facile gelling forming ability, biodegradability, high water absorption, mucoadhesiveness, reversible gel formation at particular temperatures, and viscoelastic properties [75]. They have shown themselves to be a useful substrate for cell transplantation, differentiation, and spontaneous tissue regeneration. The addition of carrageenan as a biopolymer offers sufficient possibility for further research into the possibilities of this intriguing combination, given the well-established flexibility of hydrogels in tissue engineering and drug administration.

Natural hydrogels and green-synthesized nanoparticles have gained popularity due to the growing need for safe, efficient, and sustainable biomedical materials. Furthermore, by adding antibacterial, anti-inflammatory, or regenerative qualities, including nanoparticles – like green-synthesized silver nanoparticles – into hydrogels based on carrageenan has increased their functionality [17]. As a result, hydrogels provide enormous potential for resolving issues in biotechnology and healthcare by serving as a versatile platform that connects material science and biomedical innovation.

In this review, we have concentrated on the green production of silver nanoparticles using natural reducing agents, microorganisms, or plant extracts, which provides an environmentally friendly substitute and makes AgNPs safer for use in biomedical applications. By incorporating these AgNPs into hydrogels, particularly those made from the biopolymer carrageenan, novel applications in tissue engineering, drug delivery, wound healing, regenerative medicine, and antimicrobial coating were made possible.

GREEN SYNTHESIS OF SILVER NANOPARTICLES

The fast-developing area of nanotechnology has important ramifications for material science, agriculture, and medicine. Silver nanoparticles (AgNPs) have drawn a lot of interest among different nanomaterials because of their multifunctional biological potential, high surface-to-volume ratio, and broad-spectrum antibacterial qualities [18]. One of the most well-known metals, silver has been used medicinally for more than 2000 years due to its ability to eradicate a variety of pathogenic microbes, as well as its strong antimicrobial activity and ability to suppress germs in different ways. Additionally, silver is a key ingredient in many wound-healing treatments [19, 20]. Silver nanoparticles (Ag NPs) have drawn a lot of interest for their beneficial properties, such as exceptional bactericidal activity against a variety of pathogens, given the recent rise in antimicrobial resistance to many diseases [21]. Antimicrobial resistance is less common and silver-based products are less expensive. Silver nanoparticles (AgNPs) are presently utilized in many fields, including biological, food, medicinal, consumer, and industrial applications, due to their special qualities. AgNPs are made in a variety of ways, frequently with the purpose of examining their morphology or other physicochemical characteristics. It is suggested that silver nanoparticles, which are well-known antimicrobial agents, have anti-fungal, anti-inflammatory, anti-angiogenic, and anti-permeability properties. However, silver ions are currently being replaced by silver nanoparticles as an alternative antibacterial agent. Microbes are inhibited and killed by both silver ions and silver nanoparticles [22, 23].

AgNPs have historically been produced by chemical and physical processes including laser ablation, chemical reduction, and photochemical techniques [24]. However, these methods are rarely used since they frequently include hazardous byproducts, high energy consumption, and toxic chemicals, raising questions regarding biocompatibility and environmental sustainability. However, the green synthesis process, which incorporates different biological agents, provides a more environmentally benign way to produce nano-scale functional materials. Green synthesis of AgNPs is becoming increasingly popular due to its low cost, environmental friendliness, and capacity to safeguard human health [25]. Green synthesis has become a viable, affordable, and environmentally beneficial way to get around these restrictions. This method uses biological systems as reducing and stabilizing agents to produce AgNPs, including plant extracts, microorganisms (bacteria, fungi, algae), and biomolecules. Because phytochemicals like flavonoids, phenolics, tannins, terpenoids, and alkaloids not only convert silver ions (Ag^+) to metallic silver (Ag^+) but also cap and stabilize the nanoparticles, improving their biocompatibility and functional activity, plant-based synthesis is especially beneficial. Biocompatibility, less toxicity, eco-safety, and scalability are only a few benefits of green-synthesized AgNPs. Additionally, bioactive substances made from natural extracts are frequently applied to their surface, strengthening their antibacterial, antioxidant, and anti-inflammatory qualities [26]. These characteristics make them ideal for use in biological applications such as wound healing, drug delivery, tissue engineering, and antimicrobial coatings [27, 28]. As shown in Table 1, silver nanoparticles are synthesized from different biological sources such as plant extract, microbes, fungus and algae.

To improve the stability and biological performance of biomaterials such hydrogels, films, and scaffolds, research has recently concentrated more on incorporating green-synthesized AgNPs into these materials. This has created new opportunities for the creation of multifunctional nanocomposites that are safe, effective, and environmentally friendly in tackling urgent medical issues, including the emergence of antimicrobial resistance [29].

Table 1. Green Synthesis of silver nanoparticles from different biological sources.

S.N.	**Biological source**	**Outcomes**	**Reference**
	Plant-based material		

1	*Mikania cordata* leaves	The biosynthesized AgNPs exhibited significant bioactivities such as antioxidant and antimicrobial.	[30]
2	*Moringa oleifera* leaves	The results suggested that AgNPs prepared by green approach can be considered as an alternative antibacterial agent.	[98]
3	leaves of *Eugenia roxburghii* DC.	The AgNPs effectively inhibit biofilm formation and the biofilm-producing bacterial colonies.	[99]
4	leaf extract of *Cucumis prophetarum*	Shows good antibacterial activity and antiproliferative potential against selected cancer cell lines.	[100]
5	seed extract of *Tectona grandis*	Synthesized nanoparticles showed antimicrobial activity which was investigated by agar well diffusion method against *B. cereus*, *S. aureus*, and *E. coli*.	[101]
	Microbe-based material		
1	*Bacillus subtilis*	The antibacterial efficacy of silver bio-nanoparticles display a commitment for use as a strong agent to treat multidrug resistant microorganisms.	[102]
2	*Escherichia coli*	The antibacterial activity of silver nanoparticles synthesised using both pellet and supernatant against human pathogens.	[103]
3	*Lactobacillus bulgaricus*	The result showed that that AgNPs with size (30.65–100 nm) obtained from Lactobacillus bulgaricus were found to exhibit antibacterial activities against selected bacterial strains.	[104]
4	*Lactobacillus plantarum* and *Lactobacillus brevis*	The antibacterial activity of Ag-NPs was more potent against Gram-negative bacteria than Gram-positive bacteria.	[105]
5	*Bacillus licheniformis* TT01	X-ray diffraction (XRD) and transmission electron microscopy (TEM) revealed that the obtained AgNPs had a spherical shape and sizes ranging from 2 to 22 nm, in which particles from 2 to 10 nm appeared with the highest frequency.	[106]
	Fungus-based material		
1	*Aspergillus sydowii*	In the biological application of AgNPs, it shows effective antifungal activity against many clinical pathogenic fungi and antiproliferative activity to HeLa cells and MCF-7 cells in vitro.	[107]
2	*Trichoderma harzianum*	The antibacterial activities of synthesized nanosilver were evaluated against two bacteria; *Staphylococcus aureus* and *Klebsiella aeruginosa* and it was found that bacterial growth was significantly reduced in a dose dependent manner.	[108]
3	*Fusarium oxysporum*	we have observed that aqueous silver ions when exposed to the fungus Fusarium oxysporum are reduced in solution, thereby leading to the formation of an extremely stable silver hydrosol.	[109]
4	*Rhizopus stolonifer*	They have spherical form with an average size of 9.46 ± 2.64 nm. The AgNPs were characterized by UV-visible, XRD, TEM and FT-IR spectra.	[110]

5	*Fusarium semitectum*	Highly stable and crystalline silver nanoparticles are produced in solution by treating the filtrate of the fungus *F. semitectum* with the aqueous silver nitrate solution.	[111
	Algae-based material		
1	*Amphiroa rigida*	The biomimetic synthesized AR-AgNPs showed antibacterial activity against *Staphylococcus aureus* (21 ± 0.2 mm) and *Pseudomonas aeruginosa* (15 ± 0.2 mm). Further, the cytotoxic effects of AR-AgNPs against MCF-7 human breast cancer cells were observed through acridine orange-ethidium bromide and Hoechst staining.	[112]
2	*Ecklonia cava*	*Ecklonia cava* is an effective reducing agent for green synthesis of AgNPs with efficient antimicrobial, antioxidant, and anticancer activities.	[113]
3	*Asterarcys* sp.	*Staphylococcus aureus*, *Bacillus subtilis*, *Klebsiella pneumoniae*, and *Proteus vulgaris* were among the Gram positive and Gram-negative bacteria that were significantly inhibited by *Ast*-AgNPs.	[114]
4	*Graesiella emersonii* KNUA204	This study demonstrates that extracellular polymeric substances (EPS) from Graesiella emersonii KNUA204 enable the green synthesis of silver nanoparticles (AgNPs), offering a sustainable alternative to conventional methods.	[115]
5	*Padina pavonia*	The obtained nanoparticles exhibited high stability, rapid formation of the biogenic process (2 min–3 h), small size (49.58–86.37 nm) and variable shapes (spherical, triangular, rectangle, polyhedral and hexagonal). Preliminary characterization of nanoparticles was monitored by using UV-visible spectroscopy (UV-vis),	[116]

CARRAGEENAN HYDROGELS: STRUCTURE AND ROLE

Alginates, which are polymers from brown seaweeds that contain mannuronic acid and guluronic acid; agar, which is composed of polymers from red seaweeds that include D-galactose and 3,6-anhydro-L-galactose; and carrageenans are the three types of carbohydrate polymers from marine organisms that are currently used in commerce. Certain red seaweeds (Rhodophyta) include a type of polysaccharides called carrageenan [31]. The Rhodophyceae family of red seaweeds is the main source of carrageenan, a naturally occurring high-molecular-weight sulfated polysaccharide. Carrageenan is structurally composed of alternating units of 3,6-anhydro-D-galactose and D-galactose with different levels of sulfation, which affects its functional characteristics. The Irish vernacular term “carrageen,” which means “little rock,” is where the name “carrageenan” originates [32]. In Ireland, the extraction of these hydrophilic colloids from red seaweeds has been known since 1810. There is little information on the biosynthesis and genetics of carrageenan in seaweed cell walls, despite the fact that all seaweeds that produce it as their primary cell-wall component belong to Rhodophyta [33, 34].

Carrageenan is used by pharmaceutical companies as an anticoagulant, immunomodulatory, antihyperlipidemic, and anticancer substance [35]. Carrageenan was found to be a potent inhibitor of HPV infections in people that are acquired by sexual contact by Buck et al. and to be able to prevent the reproduction of the hepatitis A virus by Girond et al. Carrageenan has been used in a variety of compositions, including hydrogel beads, tablets, microcapsules, microspheres, and nanoparticles [36]. Building upon this foundation, scientists have investigated a various form of carrageenan-based hydrogels, including gradient hydrogels, interpenetrating polymer networks, floating hydrogels, nanogels, and bioinks for 3D bioprinting.

Glycosidic bonds between galactose and anhydrogalactose create a twisted helical assembly in the structural arrangement of carrageenan. Specifically, each d-galactose and 3,6-anhydro-d-galactose unit is bound by α-1,3 and β-1,4 glycoside linkages. Carrageenans are classified based on the degree of substitution on their free hydroxyl groups such as the inclusion of ester sulphate or the presence of 3,6-anhydride on the 4-linked residue. Kappa (κ), iota (ι), lambda (λ), mu (μ), nu (ν), and theta (θ) are the six fundamental forms of these polymers [37]. However, kappa (κ), iota (ι), and lambda (λ) carrageenans are particularly significant due to their unique gelling and viscoelastic properties. When potassium ions are present, kappa (κ), which is frequently employed in food products and biomedical scaffolds, creates strong, stiff gels. Each disaccharide unit has one sulphate group. In the biomedical field, it has good mechanical strength and is frequently utilised in wound dressings and scaffolds. When calcium ions are present, iota (ι) produces soft, elastic gels that are highly biocompatible and flexible [38]. Each disaccharide molecule has two sulphate groups. Lambda (λ) is mostly employed as a thickening and stabilizer because it doesn’t gel. Each disaccharide unit has three sulphate groups. mostly utilised in biomedical formulations, medicinal solutions, and beverages where viscosity improvement is needed [39].

Because of its biocompatibility, biodegradability, and structural resemblance to glycosaminoglycans found in the human extracellular matrix (ECM), carrageenan has recently drawn interest in biomedical engineering. Because of these characteristics, carrageenan-based hydrogels are ideal for tissue engineering scaffolds, medication delivery systems, and wound dressings. Carrageenan’s potential as a multifunctional biomaterial is further enhanced by its capacity to form ionic cross-links and encapsulate bioactive substances, including nanoparticles.

Carrageenan stands out as a promising candidate in the development of advanced biomaterials given the growing demand for sustainable and environmentally friendly biopolymers, especially when paired with nanotechnology techniques like the incorporation of silver nanoparticles for antimicrobial and regenerative applications [40].

INTEGRATION OF AGNPS INTO CARRAGEENAN HYDROGELS

Metal-based nanoparticles, including gold and silver, can be combined with polymer hydrogels to create hybrid materials. As long as the interactions between polymer and nanoparticles are weak, the addition of metal nanoparticles has minimal impact on the mechanical properties of the resulting nanocomposite hydrogels. In this instance, the polymer gel’s phase transition, thermosensitivity, and viscoelasticity are preserved while the nanoparticle’s characteristics – such as enhanced electrical conductivity, reaction to optical stimuli, enhanced antibacterial qualities, etc. – are incorporated into the gel [50].

Innovative biomaterial production made possible by recent developments in nanotechnology has resulted in the creation of nanogels for use in biomedical applications. Because of their promise for regulated and prolonged drug administration, which lessens side effects and improves therapeutic efficacy, nanogels have made tremendous strides [51]. Ensuring the stability of biomolecules within the delivery system is a critical component of drug carrier design, and nanogels provide an efficient way to improve this stability. The main characteristic of nanogels is their size, which is usually a few hundred nanometers and allows for effective and targeted interactions with cells and tissues [52]. Furthermore, different medicinal compounds, both hydrophilic and lipophilic, can functionalize the nanoparticle component of nanogels. Because of their high surface-to-volume ratio, these molecules can bind at high densities. Additionally, nanogels can be made to be stimuli-responsive systems, which enables regulated and targeted drug delivery [53]. Nanogels are thought to be one of the most promising systems since they combine the characteristics of hydrogels and nanoparticles.

Researchers are particularly interested in silver nanoparticle-incorporated hydrogels because of their superior antibacterial qualities and less toxicity for overcoming antibacterial resistance. Because silver has bactericidal capabilities against bacteria, it has been used as an antimicrobial for centuries to treat illness and prolong the shelf life of food products [41]. With the advancement of nanoscience and nanotechnology, silver, primarily in the form of silver nanoparticles (AgNPs) and AgNPs embedded hydrogels, has become an effective antibacterial agent for wound treatment in recent decades [42].

Silver nanoparticles (3–8 nm) give a range of polymer hydrogels electrical and antibacterial qualities. Silver cations may typically be attached to polymer hydrogels using carboxylic acid groups as a temporary anchoring agent. The silver is then reduced to create nanoparticles using sodium borohydride [54]. Although the nanoparticles are scattered throughout the hydrogel matrix, this preparation technique relies on the quantity of functional groups needed to stabilize the silver ions [55].

Excellent antibacterial qualities and the capacity to manage bacterial infections were shown by AgNPs integrated into hydrogels. By varying the quantity of crosslinkers and monomers in the hydrogel network and serving as a stabilizing medium, polymer-based hydrogels regulate the size and shape of the nanostructures [43]. Their ability to deliver a variety of bioactive molecules, such as proteins, medications, and vaccinations, has been thoroughly studied. Microemulsion, radical polymerization, physical mixing of prepared nanoparticles, and sonication are some of the techniques used to create nanogels. Either in situ polymer synthesis or the addition of the NP colloid to the polymer are used to load the NPs into porous hydrogels. Additionally, NPs are incorporated into hydrogels using a microwave radiation-based technique, and the hydrogel is stabilized by crosslinking with agents like KCl or $CaCl_2$.

Issues with AgNPs' dispersion frequently restrict their use as delivery vehicles. This drawback was significantly mitigated by the addition of AgNPs to hydrogels. By lowering the minimal inhibitory concentration (MIC) against Gram-positive bacterial and fungal (S. cerevisiae) strains while lowering the toxicity of AgNPs, different additives, such as the counterion of positively charged $Ag+$ within the hydrogel matrix, have demonstrated good antimicrobial activity in addition to avoiding nanoparticle dispersion problems [44].In a different study, Mirzajani et al. showed that AgNPs might damage the bacterial cell wall by interacting with the peptidoglycan layer in the S. aureus cell membrane and disrupting the β-1–4 bonds of N-acetylglucosamine and N-acetylmuramic acid of the glycan chain [45].

Another study found that the bacteria's internal and external production of free radicals, or reactive oxygen species (ROS), produced favorable antibacterial characteristics [46]. AgNPs-based hydrogels have been widely used for their antibacterial qualities, although their efficiency (more effective against Gramme − bacteria than Gramme + bacteria), safety, and stability (both chemical and physical instability) are still far below expectations [47].

The strong resilience of the peptidoglycan layer of the bacterial cell wall is the reason for the reduced efficacy against Gramme + bacteria. Therefore, when creating AgNP-based hydrogels, several crucial factors should be considered, including the antibacterial capacity against Gram-positive bacteria, the lowering of serum albumin, and the minimization of gene toxicity [48].

To guarantee the clinical potential of the hydrogels loaded with AgNPs, several eco-friendly synthesis techniques have been used to enhance their properties [49].

CHARACTERIZATION TECHNIQUES

Characterization is essential to maximize the performance of carrageenan-based hydrogels for biomedical applications and to describe the structure-property correlations of these hydrogels. To confirm the chemical structure of carrageenan, identify sulphate ester groups, and confirm hydrogel formation and intermolecular interactions following crosslinking or blending, physicochemical characterization techniques like Fourier transform infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR) are frequently used. The hydrogel network's crystalline or amorphous nature can be determined by X-ray diffraction (XRD), which also verifies that nanoparticles or other reinforcing agents were successfully included. The porous architecture, pore size distribution, and internal network homogeneity – all crucial factors controlling swelling, drug transport, and cell infiltration – are revealed through morphological characterization using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Studies on swelling and degradation under physiological settings are conducted to assess the hydrogels' stability, environmental reactivity, and ability to absorb water. For tissue engineering and drug delivery applications, mechanical and rheological analyses – such as oscillatory rheology and compression testing – evaluate gel strength, elasticity, viscoelastic behavior, and injectability. Additional information about thermal stability and composition can be obtained by thermal analysis methods like thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Different characterization techniques are shown in Table 2 [123].

Table 2. Characterization techniques for carrageenan-based hydrogels.

Technique	**Purpose**
UV-Vis Spectroscopy	Confirms AgNP synthesis (peak ~420 nm).
FTIR	Identifies functional groups involved in capping.
XRD	Determines crystalline structure of AgNPs.
SEM/TEM	Analyzes nanoparticle size and hydrogel morphology.
Swelling Ratio	Evaluates hydrogel's absorption capacity.
Mechanical Testing	Assesses strength for biomedical use.

BIOMEDICAL APPLICATIONS

Wound Healing

Recent advances in nanobiotechnology have produced a new class of hydrogel-based nanoparticles called nanogels, which hold a great deal of promise for improving wound healing. Because of their nanometric size, high water content, and elasticity, nanogels can, therefore, actively interact at the cellular and interstitial levels in a wound environment, improving drug delivery into the wound more successfully, speeding up healing, and decreasing the formation of scars. Cross-linked polymeric networks make up hydrogel-based nanoparticles known as nanogels, which have the ability to expand in aqueous solutions. Unlike other nanomaterials, nanogels have special benefits such biocompatibility and flexible drug delivery [56].

Haemostasis, inflammation, proliferation, and tissue remodeling are all steps in the very intricate and dynamic biological process of wound healing. Delayed or chronic wounds are frequently the result of these processes being disrupted by microbial infections, oxidative stress, or protracted inflammation [57]. Because of its capacity to maintain a moist wound environment, give controlled medication release, provide antimicrobial protection, and demonstrate great biocompatibility, nanogel-based wound dressings have drawn increased attention as a solution to these problems [58].

Because of its biodegradability, non-toxicity, hydrophilicity, and structural similarity to glycosaminoglycans found in the extracellular matrix (ECM), carrageenan, a naturally occurring sulfated polysaccharide extracted from red seaweeds, has become a promising biopolymer for nanogel fabrication in wound healing applications. Nanogels have adjustable gel strength, elasticity, and viscosity depending on the type of carrageenan (κ-, γ-, or λ-), enabling customization for various wound-healing needs [59].

Effective moisture retention, which is crucial for fibroblast migration and cell proliferation, and regulated drug distribution made possible by ionic interactions of sulphate groups within the polymer network are two benefits of carrageenan-based nanogels in wound care [60]. These nanogels show strong antibacterial action and prevent biofilm formation when combined with antimicrobial agents such silver nanoparticles (AgNPs), antibiotics, or plant-derived bioactives [61, 62]. Additionally, by imitating the extracellular matrix, carrageenan nanogels enhance tissue regeneration, angiogenesis, and collagen deposition. According to recent research, carrageenan–AgNP nanogels greatly improve wound contraction and epithelialization in animal models while exhibiting potent antibacterial activity against common wound pathogens like *Escherichia coli, Staphylococcus aureus,* and *Pseudomonas aeruginosa* [63]. Specifically, the soft, elastic gel structure of ß-carrageenan-based nanogels allows good adhesion to wound surfaces without producing damage during dressing replacement. When taken as a whole, these characteristics make carrageenan-based nanogels platforms for enhanced wound care that are eco-friendly, sustainable, and multipurpose. In vitro tests of K-carrageenan hydrogels prepared for wound healing applications using poly (N-vinyl-2-pyrrolidone), potassium chloride, and polyethylene glycol revealed excellent results, including effective fluid absorption, high elasticity, flexibility, soft texture, good mechanical strength, good transparency, and adhesion to the wound surface with a painless removal [64]. This hydrogel will have a better chance of being approved if it can pass testing for gas permeability, water evaporation control, bacterial infection prevention, and biocompatibility in both in vitro and in vivo investigations. The initial findings demonstrated that this CG form satisfies some of the most crucial ideal dressing characteristics, including high elasticity, flexibility, painless removal, good transparency and mechanical strength, and efficient fluid absorption [65]. The ideal wound dressing must be bio-compatible, bio-adherent to the wound surface and non-adhesive to the wound bed, painless and trauma-free to remove, easy to apply and replace, biodegradable, affordable, elastic but resistant, semi-permeable (allows gas exchange but prevents microorganisms) and compatible with therapeutic agents. Along with protecting against mechanical, bacterial, infectious, and thermal factors, it should also relieve pain and create a moist wound environment. It should also have debridement activity, non-toxic and non-antigenic qualities, high absorption of excess exudate, and healing/re-epithelialization capability. Because biopolymers are biodegradable, bioactive, and encourage tissue regeneration and wound healing through cell migration and proliferation, they are among the most widely utilised materials that combine most of these advantages. “Smart” biomaterials have applications in soft electronics, drug delivery, regenerative medicine, 4D bioprinting, artificial life, and synthetic biology.

Because they alter their characteristics and release kinetics, biomaterial-based wound dressings can contain medications and antibiotics. In addition to moisturizing dry wounds and/or absorbing liquids and exudates from wet ones, biomaterials employed in wound healing should support autolytic debridement. Additionally, the healing process would be quicker and more seamless if they stimulate angiogenesis in poorly perfused wounds, modify the immune cells within the wound, and increase the migration and invasion of fibroblasts and keratinocytes, thereby preventing or treating a potential infection.

AgNPs stop bacterial infections, and carrageenan keeps the site wet, which encourages the production of collagen and re-epithelialization [66].

Drug Delivery

Nanogels are cross-linked polymeric networks at the nanoscale that have a high-water content, adjustable porosity, and superior drug-loading capability. Nanogels have drawn a lot of interest in improved drug delivery systems because of their capacity to encapsulate therapeutic molecules, shield them from enzymatic or chemical degradation, and allow for regulated and targeted release (Oh et al., 2009 [67]). The three main forms of carrageenan, a sulfated polysaccharide derived from red seaweeds, are κ-, ¾-, and λ-carrageenan. Each of these forms exhibits unique sulfation patterns and gelation behaviors, enabling the rational design of nanogels with customized drug delivery characteristics (Necas & Bartosikova, 2013 not in bib). Strong ionic interactions with positively charged medications, proteins, or nanoparticles are made possible by carrageenan’s negatively charged sulphate groups, which improve colloidal stability and drug encapsulation effectiveness [68–73].

Compared to separate delivery methods, the incorporation of nanoparticles into hydrogel matrix has synergistic benefits. While the hydrogel network acts as a barrier against degradation and quick removal, extending therapeutic efficacy, nanoparticles contained in hydrogels enhance drug stability, inhibit premature release, and enable sustained and localized distribution. Additionally, by functionalizing nanoparticles with certain ligands and creating hydrogels that react to environmental triggers like pH, temperature, or enzyme activity, nanoparticle–hydrogel composites can be produced for targeted and stimuli-responsive drug delivery [72–76]. This method improves treatment efficacy and lowers off-target effects by enabling targeted medication release at inflammatory or sick tissues.

Because of their hydrophilic matrix and ionic functional groups, carrageenan-based nanogels have a high drug-loading capacity that makes it possible to effectively encapsulate both hydrophilic and hydrophobic medicines. Their cross-linked structure facilitates sustained and regulated medication release, which lowers the frequency of doses and increases patient compliance. Carrageenan is a food-grade, pharmaceutically approved polysaccharide that exhibits good biocompatibility and low toxicity, making it appropriate for use in biomedical applications. These nanogels are adaptable carriers that can deliver proteins, peptides, antibiotics, anticancer medicines, small-molecule medications, and natural bioactives. Applications include protein or peptide delivery through enhanced mucoadhesion and bioavailability; transdermal delivery via hydrogel patches; anticancer therapy utilizing the enhanced permeability and retention (EPR) effect; and oral drug delivery, where pH-responsive swelling protects acid-sensitive drugs.

While κ-carrageenan nanogels have shown sustained antibiotic release with prolonged antimicrobial efficacy, recent studies have shown that κ-carrageenan nanogels co-loaded with doxorubicin and curcumin exhibit enhanced cytotoxicity towards cancer cells while reducing systemic toxicity. All things considered, carrageenan-based nanogels are a versatile and sustainable drug delivery system whose promise in cancer therapy, antimicrobial treatment, and regenerative medicine is greatly increased by their integration with nanotechnology [77–81].

Drug delivery systems (DDS), which provide targeted distribution, controlled release, and increased drug bioavailability, are essential for successful treatment outcomes. Because of their high-water content and adjustable characteristics, hydrogels have become a promising DDS. Therapeutic compounds are frequently transported using nanogels. To minimize the amount of carrier needed, an effective nanodelivery system should have a high drug-loading capacity. Because of its chemical makeup, which has been verified by in vivo research in animal models, nanogel-based drug delivery formulations increase the efficacy and safety of many medications, including some anti-cancer medications. Targeted administration of medications with high therapeutic efficacy and anticipated low toxicity to adjacent tissues is part of cancer treatment. The following list of benefits is guaranteed by nanogel technology: cancer, autoimmune disorders, diabetes, opthalmic, neurodegenerative, and anti-inflammatory action.

Advanced drug delivery systems can be developed by combining the characteristics of metal nanoparticles with carrageenan hydrogels. Hezaveh et al. investigated the effects of nanoparticles on drug release properties in the gastrointestinal system using modified kappa-carrageenan nanocomposite hydrogels. They discovered that adding magnetic and silver nanoparticles to carrageenan hydrogels produced varied drug releases across the GI tract, suggesting the possibility of controlled drug delivery. Carrageenan has been found to be a good choice for vaginal, oral, transdermal, pulmonary, ophthalmic, and drug delivery applications [82–86].

Tissue Engineering

By combining biomaterials, bioactive compounds, and cells, tissue engineering seeks to replace or regenerate damaged tissues to restore normal physiological function. Choosing the right biomaterial is crucial because it needs to be biocompatible, biodegradable, have the right amount of mechanical strength, and be able to replicate the natural extracellular matrix (ECM). Because of their innate bioactivity and ECM-like characteristics, natural polymers have drawn more attention to tissue engineering applications.

Because of their high-water content, ionic sulphate groups, adjustable mechanical properties, and ability to incorporate growth factors, medications, or nanoparticles, carrageenan-based nanogels offer a flexible substrate for tissue engineering. Negatively charged sulphate groups promote cellular signaling and tissue regeneration by improving cell adhesion, proliferation, and growth factor binding. Additionally, by choosing particular carrageenan types, the mechanical properties of carrageenan nanogels can be customized; for example, κ-carrageenan creates strong, rigid gels that are appropriate for bone tissue engineering, while γ-carrageenan creates softer, more elastic matrices that resemble cartilage and neural tissues [87–91].

Additionally, carrageenan-based nanogels facilitate the regulated distribution of bioactive substances that promote angiogenesis, osteogenesis, and tissue remodeling such as cytokines, bone morphogenetic protein-2 (BMP-2), and vascular endothelial growth factor (VEGF). These nanogels exhibit outstanding biocompatibility and have been demonstrated to promote fibroblast, osteoblast, and chondrocyte proliferation without causing cytotoxic effects. Additionally, adding nanoparticles to carrageenan nanogels – such as silver nanoparticles (AgNPs), hydroxyapatite, zinc oxide, or gold nanoparticles – improves their antimicrobial activity, osteoconductivity, and angiogenesis, increasing their potential as sophisticated scaffolds for tissue engineering.

According to recent research, κ-carrageenan/hydroxyapatite nanogel composites greatly enhance osteoblast proliferation and bone matrix mineralization in vitro, underscoring its potential for use in bone tissue engineering. Similarly, ß-carrageenan-based nanogels have shown extracellular matrix deposition and chondrogenic differentiation, which makes them attractive options for cartilage regeneration. The addition of green-synthesized nanoparticles to carrageenan nanogels enhances their eligibility for multifunctional tissue engineering scaffolds by producing synergistic antibacterial and regenerative properties.

All things considered, carrageenan-based nanogels offer a biocompatible, versatile, and sustainable biomaterial platform for tissue engineering, with uses in the regeneration of bone, cartilage, skin, neurones, and blood vessels. They are useful materials in the development of regenerative medicine because of their ECM-mimicking qualities, adjustable mechanics, and ability to distribute bioactive substances [92–94].

Creating functional substitutes for damaged organs and tissues is the aim of tissue engineering. Because they serve as scaffolding to promote the growth of new tissues and cell proliferation, biomaterials are crucial in this field. Due to their high-water content and tissue-like properties, hydrogels are particularly attractive for this function. The creation of numerous biomaterials has led to notable developments in the field of tissue engineering. Carrageenan hydrogel has become one of these promising options. Ossa evaluated the injectability of hydroxyapatite nanorod-based carrageenan-based injectable bone substitutes and found that they had good injectability.

Although nanogels have been extensively studied for medication delivery, their use in tissue engineering is still relatively new. Controlled distribution of growth factors and other active ingredients that can encourage cell adhesion, direct cell differentiation, and direct tissue creation is also necessary for regenerative medicine. Compared to conventional tissue engineering materials, hydrogels provide a few advantages. In terms of mechanical, chemical, and biological characteristics, they can be made to resemble the natural environment of various tissues. To promote tissue regeneration, they can also be tailored to transport various bioactive substances, including growth factors, cytokines, and medications. In tissue engineering, a variety of hydrogels, including synthetic and natural hydrogels, have been utilised to replicate different kinds of tissues such as skin, cartilage, bone, and nerve tissue [95–99].

As is widely known, appropriate scaffolds that promote cell adhesion and proliferation as well as control the delivery of active ingredients that can promote cell differentiation and tissue creation are necessary for regenerative medicine. The controlled, stepwise release of active substances, such as growth factors, cytokines, or other morphogenetic factors, and the fine tuning of the scaffold's texture and mechanical properties, which are also crucial for controlling cell behavior, are two important levels at which nanogels may be relevant.

In addition to supporting cell attachment and proliferation when paired with growth factors, nanogels offer scaffolding for the regeneration of skin, cartilage, bone, insertable discs, and soft tissues [100–105].

Antimicrobial Coatings

The need for innovative antimicrobial coatings that are efficient, biocompatible, and environmentally sustainable has increased due to the quick development of antimicrobial resistance (AMR) and the rising prevalence of infections linked to medical devices. In addition to being non-toxic, biodegradable, and compatible with biomedical surfaces, an ideal antimicrobial coating should prevent bacteria adherence and biofilm development [84]. Carrageenan functions as a sophisticated antimicrobial delivery system appropriate for thin-film coatings when it is prepared into nanogels. Antimicrobial compounds such silver nanoparticles (AgNPs), zinc oxide (ZnO), antibiotics, and essential oils can be effectively encapsulated and released over time thanks to the high surface area, water-retention capacity, and negatively charged sulphate groups of carrageenan nanogels [106–111].

Broad-spectrum antimicrobial activity against Gram-positive and Gram-negative bacteria, such as Escherichia coli and Staphylococcus aureus, as well as fungal pathogens, such as Candida species, is greatly increased when metal nanoparticles are incorporated into carrageenan nanogels. Furthermore, on biomedical surfaces, nanogel-based coatings successfully limit microbial adhesion and biofilm development, which is crucial for reducing chronic and device-associated infections.

Additionally, controlled and sustained release of antimicrobial drugs is made possible by carrageenan-based nanogels, extending therapeutic efficacy and lowering the frequency of dosing. Because carrageenan is a food- and pharmaceutical-grade polysaccharide, it has good biocompatibility and can be used in implant coatings, surgical sutures, wound dressings, and catheters. According to recent research, κ-carrageenan nanogel films loaded with AgNPs dramatically lower bacterial load while remaining compatible with fibroblasts and keratinocytes, which speeds up wound healing. Comparably, carrageenan–ZnO nanogel coatings have demonstrated extended antibacterial action with low cytotoxicity, underscoring its promise for biological devices that are resistant to infection [112–117].

All things considered, carrageenan-based nanogels offer a sustainable and multipurpose antimicrobial coating approach that blends controlled antimicrobial release, biocompatibility, and infection prevention. A next-generation approach to lowering microbial contamination and battling AMR in hospital settings is provided by its integration with nanotechnology.

Since bacterial biofilms exhibit a high resistance to antibiotics and biomaterial-associated infections are infamously persistent and challenging to eradicate, bacterial attachment and subsequent biofilm formation on implant surfaces pose a serious problem from both an economic and healthcare perspective. The development of surface coatings to stop initial bacterial adherence and biofilm formation as a substitute platform has received a lot of attention in recent decades due to the growing issue of antibiotic resistance. These antimicrobial surface coatings are primarily based on three strategies: an antibacterial (bactericidal) strategy that kills bacteria either before or after they meet the surface, an antifouling strategy that can drastically reduce the amount of initial bacterial attachment, and a third strategy based on triggered bacterial detachment. Some techniques create multifunctional surfaces by combining methodologies [118–121].

Regardless of the substrate material, colloidal particles are recognised to have exceptional ability to form well-organized films based on their physical adsorption capabilities.

Surface coverings using hard colloidal particles, like polystyrene nanoparticles, have been attempted numerous times. However, because of the limited particle-surface contact point, these coatings were discovered to be unstable under physiological conditions. According to this perspective, nanogels may adhere to surfaces firmly and produce impressively homogeneous coatings because they are soft, malleable colloidal particles. Physical adsorption makes it simple to create nanogel-based surface coatings without the need for harsh chemical processes like grafting or covalent binding.

Furthermore, by simply adjusting the chemical functions of the adsorbed nanogel particles, the properties of the nanogel-coated surface can be changed.

Nanogels offer a lot of promises such as antibacterial and/or antifouling coatings for medical implants. They are strong candidates as antimicrobial surface coatings due to their advantages, which include high water content, suitable chemical and physical structures, superior mechanical capabilities, and excellent biocompatibility.

By rejecting the bacteria and so reducing the formation of biofilms, antifouling surfaces are intended to decrease the initial bacterial attachment. These surface coatings are typically made with hydrogels, which can produce a hydration layer in an aqueous environment, aside from zwitterion-based surfaces and polymer brush coatings. Because of their affinity for water and ability to produce a hydration layer that acts as a physical barrier against bacterial adherence and protein adsorption, hydrogels have been employed in the field of biomaterials.

Strong hydration qualities can be exhibited by antifouling hydrogel surfaces in physiological settings like serum or salt solutions. As previously stated, hydrogels having a nano-sized feature exhibit behaviors comparable to those of nanogels. The superior tunable-chemical characteristics and film-forming capabilities of hydrogel-inspired nanogels have led to the development of numerous applications in the biomedical area, including antifouling surfaces [122–123].

LIMITATIONS AND CHALLENGES

The clinical translation of nanoparticle–hydrogel systems for antimicrobial delivery is still exceedingly difficult, despite tremendous advancements and encouraging laboratory-scale outcomes. The translational gap between experimental success and clinical application is highlighted by the fact that no antibacterial nanoparticle–hydrogel composite has been commercially available to far and only a few numbers have progressed into clinical trials. Concerns about in vivo safety, long-term toxicity, biodegradation, and clearance of the hydrogel matrix and the integrated nanomaterials, especially for internal or injectable applications, are significant barriers to clinical translation. Longer residence durations and delayed clearance may cause immunological reactions or chronic inflammation, despite the fact that hydrogels are typically thought of as biocompatible and biodegradable. Furthermore, careful control over gelation kinetics is essential for injectable or in situ-forming nanoparticle–hydrogel systems to guarantee appropriate localization, mechanical integrity, and therapeutic efficacy at the target site.

Nanomaterials' unexpected in vivo behavior adds to the challenge of their therapeutic translation. Because of their interactions with proteins and biomolecules in physiological settings, nanoparticles are prone to aggregation, which can change their stability, biodistribution, and targeting efficacy [96]. Because non-biodegradable nanoparticles can accumulate in organs and cause chronic toxicity and long-term negative effects, safety considerations are especially important. These elements make regulatory approval more difficult and need for thorough pharmacokinetic and toxicological testing.

Before being widely used in clinical and industrial settings, several material-specific issues need to be resolved, despite the fact that carrageenan-based nanogels have shown significant promise in drug delivery, wound healing, tissue engineering, and antibacterial applications. While γ-carrageenan gels are rather soft, pure κ-carrageenan gels are frequently brittle, which limits their mechanical stability under physiological settings and affects their longevity as scaffolds, coatings, or implantable biomaterials. Because carrageenan nanogels are extremely sensitive to pH and ionic strength, they may cause excessive swelling, shrinkage, or destabilization in biological fluids, which could jeopardize in vivo repeatability and controlled drug release. Furthermore, because carrageenan is a naturally occurring polymer, its molecular weight and sulfation patterns vary from batch to batch, making standardization and large-scale production difficult.

Concerns about long-term clinical use have also been raised questioning the safety of highly sulfated carrageenan types, especially λ-carrageenan, which may cause cytotoxic effects or inflammatory reactions at high doses. The efficacy of carrageenan nanogels for extended drug administration or tissue regeneration may be further diminished by rapid breakdown under physiological settings. Furthermore, carrageenan's encapsulation efficacy for hydrophobic compounds is still limited, making sustained and targeted delivery difficult, even if it is quite effective for ionic loading of hydrophilic medicines. Lastly, it is still challenging to produce carrageenan-based nanogels on a large scale with consistent physicochemical properties. The absence of standardized manufacturing procedures, high production costs, and contradictory safety reports pose major obstacles to regulatory approval by organisations like the FDA and EMA.

FUTURE DIRECTIONS

Because of its special qualities – such as high-water content, biocompatibility, biodegradability, and adjustable drug release behavior – nanoparticle-incorporated hydrogels have a wide range of extremely intriguing prospects. The capacity to accurately control drug release kinetics, which can be set in accordance with the intended therapeutic outcome, is one of these hybrid systems' most important advantages in drug administration. Because of this characteristic, hydrogels loaded with nanoparticles are especially well suited for long-term and sustained drug delivery applications, particularly in the management of inflammatory and chronic illnesses. By preserving localized drug concentrations, the inclusion of nanoparticles to hydrogel matrix not only minimizes systemic side effects but also increases drug bioavailability and the physicochemical stability of both medicines and nanoparticles.

Furthermore, by functionalizing nanoparticles or creating responsive hydrogel networks that interact specifically with particular cells or tissues, hydrogels containing nanoparticles can be designed for targeted drug delivery. This kind of targeted delivery lowers the possibility of antimicrobial resistance linked to subtherapeutic medication concentrations while simultaneously improving therapeutic efficacy and reducing off-target exposure. These systems are quite adaptable and can be made to work with medications that have different molecular sizes, charges, and solubilities. A variety of antimicrobial agents, such as antibiotics, antifungal agents, and antiviral drugs, can be delivered on-demand and site-specific thanks to the development of stimuli-responsive hydrogels, which react to pH, temperature, enzymes, or redox conditions.

Future research avenues for carrageenan-based systems include polymer blending and crosslinking techniques, such as mixing carrageenan with chitosan, alginate, or polyethylene glycol (PEG), to enhance mechanical stability and obtain more precise control over drug release profiles. It is anticipated that nanoparticle reinforcement using hydroxyapatite, zinc oxide, or silver nanoparticles will further improve structural performance and antimicrobial efficiency. A possible path for next-generation biomedical materials is the creation of smart carrageenan hydrogels with stimuli-responsive behavior, 3D-printed carrageenan–AgNP scaffolds, and hybrid composites containing bioactive peptides or herbal extracts. To ensure long-term safety, biodegradability, and therapeutic efficacy prior to successful clinical translation, however, thorough in vivo research, standardization of raw materials, scalable production procedures, and carefully planned clinical trials are crucial.

All things considered, hydrogels containing nanoparticles – especially those based on carrageenan – represent a flexible and potent platform for the future creation of sophisticated antimicrobial drug delivery systems. Significant advancements in their functionality, design, and practical biomedical applications are anticipated because of ongoing interdisciplinary research.

CONCLUSION

In this review, we began by defining biomaterials and outlining the essential properties required for their effective application in tissue engineering and regenerative medicine. We then explored the various formats in which biomaterials are utilized, with a focused emphasis on carrageenan-based hydrogels. A major strength of this review is its comprehensive and up-to-date discussion on the biomedical applications of carrageenan-based hydrogels. The integration of green-synthesized silver nanoparticles into carrageenan hydrogels has shown significant promise in antimicrobial and regenerative biomedical applications. The natural, biocompatible, and eco-friendly nature of both components makes this composite a potent alternative to synthetic materials. With further optimization, these systems may revolutionize future biomedical devices, dressings, and delivery platforms.

REFERENCES

1. Meher A, Tandi A, Moharana S, Chakroborty S, Mohapatra SS, Mondal A, et al. Silver nanoparticle for biomedical applications: A review. Hybrid Adv. 2024;6(100184):100184. Available from: http://dx.doi.org/10.1016/j.hybadv.2024.100184.
2. Rana A, Yadav K, Jagadevan S. A comprehensive review on green synthesis of nature-inspired metal nanoparticles: Mechanism, application and toxicity. J Clean Prod. 2020;272(122880):122880. Available from: http://dx.doi.org/10.1016/j.jclepro.2020.122880.
3. Bruna T, Maldonado-Bravo F, Jara P, Caro N. Silver nanoparticles and their antibacterial applications. Int J Mol Sci. 2021;22(13):7202. Available from: http://dx.doi.org/10.3390/ijms22137202.
4. Roy A, Bulut O, Some S, Mandal AK, Yilmaz MD. Green synthesis of silver nanoparticles: Biomolecule-nanoparticle organizations targeting antimicrobial activity. RSC Adv. 2019;9(5):2673–702. Available from: http://dx.doi.org/10.1039/c8ra08982e.
5. Prabhu S, Poulose EK. Silver nanoparticles: Mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. Int Nano Lett. 2012;2(1). Available from: http://dx.doi.org/10.1186/2228-5326-2-32.
6. Aguilar-Garay R, Lara-Ortiz LF, Campos-López M, Gonzalez-Rodriguez DE, Gamboa-Lugo MM, Mendoza-Pérez JA, et al. A comprehensive review of silver and gold nanoparticles as effective antibacterial agents. Pharmaceuticals (Basel). 2024;17(9):1134. Available from: http://dx.doi.org/10.3390/ph17091134.
7. Aldakheel FM, Sayed MME, Mohsen D, Fagir MH, El Dein DK. Green synthesis of Silver Nanoparticles loaded hydrogel for wound healing; Systematic review. Gels. 2023;9(7):530. Available from: http://dx.doi.org/10.3390/gels9070530.
8. Ross-Murphy SB, McEvoy H. Fundamentals of hydrogels and gelation. Br Polym J. 1986;18(1):2–7. Available from: http://dx.doi.org/10.1002/pi.4980180103.
9. Liu B, Chen K. Advances in hydrogel-based drug delivery systems. Gels. 2024;10(4):262. Available from: http://dx.doi.org/10.3390/gels10040262.
10. Toh WS, Loh XJ. Advances in hydrogel delivery systems for tissue regeneration. Mater Sci Eng C Mater Biol Appl. 2014;45:690–7. Available from: http://dx.doi.org/10.1016/j.msec.2014.04.026.
11. Hoffman AS. Hydrogels for biomedical applications. Adv Drug Deliv Rev. 2012;64:18–23. Available from: http://dx.doi.org/10.1016/j.addr.2012.09.010.
12. Tibbitt MW, Anseth KS. Hydrogels as extracellular matrix mimics for 3D cell culture. Biotechnol Bioeng. 2009;103(4):655–63. Available from: http://dx.doi.org/10.1002/bit.22361.
13. Holback H, Yeo Y, Park K. Hydrogel swelling behavior and its biomedical applications. In: Biomedical Hydrogels. Elsevier; 2011. p. 3–24.
14. Zhao L, Zhou Y, Zhang J, Liang H, Chen X, Tan H. Natural polymer-based hydrogels: From polymer to biomedical applications. Pharmaceutics. 2023;15(10):2514. Available from: http://dx.doi.org/10.3390/pharmaceutics15102514.

15. Kumar AC, Erothu H. Synthetic Polymer Hydrogels. In: Biomedical Applications of Polymeric Materials and Composites. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA; 2016. p. 141–62.
16. Satchanska G, Davidova S, Petrov PD. Natural and synthetic polymers for biomedical and environmental applications. Polymers (Basel). 2024;16(8):1159. Available from: http://dx.doi.org/10.3390/polym16081159.
17. Azizi S, Mohamad R, Abdul Rahim R, Mohammadinejad R, Bin Ariff A. Hydrogel beads bio-nanocomposite based on Kappa-Carrageenan and green synthesized silver nanoparticles for biomedical applications. Int J Biol Macromol. 2017;104(Pt A):423–31. Available from: http://dx.doi.org/10.1016/j.ijbiomac.2017.06.010.
18. Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. J Adv Res. 2016;7(1):17–28. Available from: http://dx.doi.org/10.1016/j.jare.2015.02.007.
19. Nqakala ZB, Sibuyi NRS, Fadaka AO, Meyer M, Onani MO, Madiehe AM. Advances in nanotechnology towards development of silver nanoparticle-based wound-healing agents. Int J Mol Sci. 2021;22(20):11272. Available from: http://dx.doi.org/10.3390/ijms222011272.
20. Rodrigues AS, Batista JGS, Rodrigues MÁV, Thipe VC, Minarini LAR, Lopes PS, et al. Advances in silver nanoparticles: a comprehensive review on their potential as antimicrobial agents and their mechanisms of action elucidated by proteomics. Front Microbiol. 2024;15:1440065. Available from: http://dx.doi.org/10.3389/fmicb.2024.1440065.
21. Ankush K, Vishakha V, Anjana D, Kamal J, Sanjay K, Rohit B. A review on silver nanoparticles focusing on applications in biomedical sector. Int J Pharm Sci Dev Res. 2022;8(1):057–63. Available from: http://dx.doi.org/10.17352/ijpsdr.000043.
22. Lara HH, Garza-Treviño EN, Ixtepan-Turrent L, Singh DK. Silver nanoparticles are broad-spectrum bactericidal and virucidal compounds. J Nanobiotechnology. 2011;9(1):30. Available from: http://dx.doi.org/10.1186/1477-3155-9-30.
23. Mohamed A, Dayo M, Alahmadi S, Ali S. Anti-inflammatory and antimicrobial activity of silver nanoparticles green-synthesized using extracts of different plants. Nanomaterials (Basel). 2024;14(17):1383. Available from: http://dx.doi.org/10.3390/nano14171383.
24. Zahoor M, Nazir N, Iftikhar M, Naz S, Zekker I, Burlakovs J, et al. A review on silver nanoparticles: Classification, various methods of synthesis, and their potential roles in biomedical applications and water treatment. Water (Basel). 2021;13(16):2216. Available from: http://dx.doi.org/10.3390/w13162216.
25. Zhang X-F, Liu Z-G, Shen W, Gurunathan S. Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. Int J Mol Sci. 2016;17(9):1534. Available from: http://dx.doi.org/10.3390/ijms17091534.
26. Muslim MRF, Chabib L, Suryaningsih BE, Hayati F, Annisa V. Green-synthesized silver nanoparticle hydrogels for biofilm-infected wounds: Bridging sustainability and clinical translation. Front Pharmacol. 2025;16(1694144):1694144. Available from: http://dx.doi.org/10.3389/fphar.2025.1694144.
27. Velmani S, Sholkamy EN, Ruba P, Kanaga S, Balamurugan V, Tarighat MA, et al. Eco-friendly synthesis and biomedical potential of silver nanoparticles using Pandanus dubius extract. Sci Rep. 2025;15(1):39940. Available from: http://dx.doi.org/10.1038/s41598-025-23717-1.
28. Gharari Z, Hanachi P, Sadeghinia H, Walker TR. Eco-friendly green synthesis and characterization of silver nanoparticles by Scutellaria multicaulis leaf extract and its biological activities. Pharmaceuticals (Basel). 2023;16(7):992. Available from: http://dx.doi.org/10.3390/ph16070992.
29. Elmehalawy NG, Zaky MMM, Eid AM, Fouda A. Eco-friendly synthesis of silver nanoparticles: Multifaceted antioxidant, antidiabetic, anticancer, and antimicrobial activities. Sci Rep. 2025;15(1):37349. Available from: http://dx.doi.org/10.1038/s41598-025-22154-4.
30. Khatun M, Khatun Z, Karim MR, Habib MR, Rahman MH, Aziz MA. Green synthesis of silver nanoparticles using extracts of Mikania cordata leaves and evaluation of their antioxidant, antimicrobial and cytotoxic properties. Food Chem Adv. 2023;3(100386):100386. Available from: http://dx.doi.org/10.1016/j.focha.2023.100386.

31. Selby HH, Whistler RL. Seaweed polysaccharides. In: Industrial Gums: Polysaccharides and Their Derivatives. New York: Academic Press; 1993.
32. Van De Velde F, Rollema HS, Tromp RH, Vliegenthart JFG. Molecular ordering of κ-carrageenan. Carbohydrate Research. 2002;337(10):827–35.
33. De Ruiter GA, Rudolph B. Carrageenan biotechnology. Trends Food Sci Technol. 1997;8(12):389–95. Available from: http://dx.doi.org/10.1016/s0924-2244(97)01091-1.
34. Stanley N. Production, properties and uses of carrageenan. Production and utilization of products from commercial seaweeds. FAO Fisheries Technical Paper. 1987;288:116-46.
35. Wijesekara I, Pangestuti R, Kim S-K. Biological activities and potential health benefits of sulfated polysaccharides derived from marine algae. Carbohydr Polym. 2011;84(1):14–21. Available from: http://dx.doi.org/10.1016/j.carbpol.2010.10.062.
36. Girond S, Crance JM, Van Cuyck-Gandre H, Renaudet J, Deloince R. Antiviral activity of carrageenan on hepatitis A virus replication in cell culture. Res Virol. 1991;142(4):261–70. Available from: http://dx.doi.org/10.1016/0923-2516(91)90011-q.
37. Nanaki S, Karavas E, Kalantzi L, Bikiaris D. Miscibility study of carrageenan blends and evaluation of their effectiveness as sustained release carriers. Carbohydr Polym. 2010;79(4):1157–67. Available from: http://dx.doi.org/10.1016/j.carbpol.2009.10.067.
38. Campo VL, Kawano DF, Silva DB da Jr, Carvalho I. Carrageenans: Biological properties, chemical modifications and structural analysis – A review. Carbohydr Polym. 2009;77(2):167–80. Available from: http://dx.doi.org/10.1016/j.carbpol.2009.01.020.
39. van de Velde F. Structure and function of hybrid carrageenans. Food Hydrocoll. 2008;22(5):727–34. Available from: http://dx.doi.org/10.1016/j.foodhyd.2007.05.013.
40. Thakur S, Govender T, Kumar P. Progress in carrageenan-based drug delivery systems. Carbohydrate Polymers. 2016;150:194–208.
41. Silver LL. Multi-targeting by monotherapeutic antibacterials. Nat Rev Drug Discov. 2007;6(1):41–55. Available from: http://dx.doi.org/10.1038/nrd2202.
42. Van Nguyen C, Matsagar BM, Ahamad T, Alshehri SM, Chiang W-H, Wu KC-W. Unraveling the highly selective nature of silver-based metal–organic complexes for the detection of metal ions: The synergistic effect of dicarboxylic acid linkers. J Mater Chem C Mater Opt Electron Devices [Internet]. 2020 [cited 2025 Dec 18];8(15):5051–7. Available from: https://pubs.rsc.org/en/content/articlelanding/2020/tc/c9tc07078h.
43. El-Sherif H, El-Masry M, Kansoh A. Hydrogels as template nanoreactors for silver nanoparticles formation and their antimicrobial activities. Macromol Res. 2011;19(11):1157–65. Available from: http://dx.doi.org/10.1007/s13233-011-1109-0.
44. Dutta S, Shome A, Kar T, Das PK. Counterion-induced modulation in the antimicrobial activity and biocompatibility of amphiphilic hydrogelators: influence of in-situ-synthesized Ag-nanoparticle on the bactericidal property. Langmuir. 2011;27(8):5000–8. Available from: http://dx.doi.org/10.1021/la104903z.
45. Mirzajani F, Ghassempour A, Aliahmadi A, Esmaeili MA. Antibacterial effect of silver nanoparticles on Staphylococcus aureus. Res Microbiol. 2011;162(5):542–9. Available from: http://dx.doi.org/10.1016/j.resmic.2011.04.009.
46. Kim JS, Kuk E, Yu KN, Kim J-H, Park SJ, Lee HJ, et al. Antimicrobial effects of silver nanoparticles. Nanomedicine. 2007;3(1):95–101. Available from: http://dx.doi.org/10.1016/j.nano.2006.12.001.
47. Taglietti A, Diaz Fernandez YA, Amato E, Cucca L, Dacarro G, Grisoli P, et al. Antibacterial activity of glutathione-coated silver nanoparticles against Gram positive and Gram negative bacteria. Langmuir . 2012;28(21):8140–8. Available from: http://dx.doi.org/10.1021/la3003838.
48. Yang C, Jung S, Yi H. A biofabrication approach for controlled synthesis of silver nanoparticles with high catalytic and antibacterial activities. Biochem Eng J. 2014;89:10–20. Available from: http://dx.doi.org/10.1016/j.bej.2013.12.008.
49. Zepon KM, Marques MS, da Silva Paula MM, Morisso FDP, Kanis LA. Facile, green and scalable method to produce carrageenan-based hydrogel containing in situ synthesized AgNPs

for application as wound dressing. Int J Biol Macromol. 2018;113:51–8. Available from: http://dx.doi.org/10.1016/j.ijbiomac.2018.02.096.

50. Ahmad N, Bukhari SNA, Hussain MA, Ejaz H, Munir MU, Amjad MW. Nanoparticles incorporated hydrogels for delivery of antimicrobial agents: developments and trends. RSC Adv. 2024;14(19):13535–64. Available from: http://dx.doi.org/10.1039/d4ra00631c.
51. Oh JK, Drumright R, Siegwart DJ, Matyjaszewski K. The development of microgels/nanogels for drug delivery applications. Prog Polym Sci. 2008;33(4):448–77. Available from: http://dx.doi.org/10.1016/j.progpolymsci.2008.01.002.
52. Soni G, Yadav KS. Nanoemulsions and nanogels for drug delivery. J Controlled Release. 2016;243:1–18.
53. Vinogradov SV, Bronich TK, Kabanov AV. Nanosized cationic hydrogels for drug delivery: Preparation, properties and interactions with cells. Adv Drug Deliv Rev. 2002;54(1):135–47. Available from: http://dx.doi.org/10.1016/s0169-409x(01)00245-9.
54. Vimala K, Samba Sivudu K, Murali Mohan Y, Sreedhar B, Mohana Raju K. Controlled silver nanoparticles synthesis in semi-hydrogel networks of poly(acrylamide) and carbohydrates: A rational methodology for antibacterial application. Carbohydr Polym. 2009;75(3):463–71. Available from: http://dx.doi.org/10.1016/j.carbpol.2008.08.009.
55. Lustosa AKMF, de Jesus Oliveira AC, Quelemes PV, Plácido A, da Silva FV, Oliveira IS, et al. In situ synthesis of silver nanoparticles in a hydrogel of carboxymethyl cellulose with phthalated-cashew gum as a promising antibacterial and healing agent. Int J Mol Sci. 2017;18(11). Available from: http://dx.doi.org/10.3390/ijms18112399.
56. Tayebi-Khorrami V, Fadaei MS, Dabbaghi MM, Azimi E, Kalalinia F, Fadaei MR, et al. Overview of the application of nanogels in wound healing. J Drug Deliv Sci Technol. 2025;112(107268):107268. Available from: http://dx.doi.org/10.1016/j.jddst.2025.107268.
57. Guo S, Dipietro LA. Factors affecting wound healing. J Dent Res. 2010;89(3):219–29. Available from: http://dx.doi.org/10.1177/0022034509359125.
58. Kabanov AV, Vinogradov SV. Nanogels as pharmaceutical carriers: Finite networks of infinite capabilities. Angew Chem Int Ed Engl. 2009;48(30):5418–29. Available from: http://dx.doi.org/10.1002/anie.200900441.
59. Popescu C, Iordan M, Cristian B. Structure and properties of carrageenan. Polym Chem. 2007;27–32.
60. Li L, Ni R, Shao Y, Mao S. Carrageenan and its applications in drug delivery. Carbohydr Polym. 2014;103:1–11. Available from: http://dx.doi.org/10.1016/j.carbpol.2013.12.008.
61. Abdelghany AM. Antimicrobial and wound healing efficiency of silver nanoparticle-loaded biopolymer hydrogels. Materials Science & Engineering C. 2021;118.
62. Ahmed TA, Aljaeid BM. Preparation, characterization, and potential application of chitosan, alginate, and carrageenan-based nanogels in wound healing. International Journal of Biological Macromolecules. 2020;164:137–54.
63. Ribeiro MP, Espiga A, Silva D. Development of antibacterial alginate-carrageenan hydrogel films incorporated with silver nanoparticles. Carbohydrate Polymers. 2019;203:256–67.
64. Khoo ZX, Teoh JEM, Liu Y, Chua CK, Yang S, An J, et al. 3D printing of smart materials: A review on recent progresses in 4D printing. Virtual Phys Prototyp. 2015;10(3):103–22. Available from: http://dx.doi.org/10.1080/17452759.2015.1097054.
65. Şen M, Avci EN. Radiation Synthesis of Poly(N-Vinyl-2-Pyrrolidone)-κ-Carrageenan Hydrogels and Their Use in Wound Dressing Applications. I. Preliminary Laboratory Tests. J Biomed Mater Res Part A. 2005;74:187–96.
66. Das S, Baker AB. Biomaterials and nanotherapeutics for enhancing skin wound healing. Front Bioeng Biotechnol. 2016;4:82. Available from: http://dx.doi.org/10.3389/fbioe.2016.00082.
67. Kabanov AV, Vinogradov SV. ChemInform abstract: Nanogels as pharmaceutical carriers: Finite networks of infinite capabilities. ChemInform. 2009;40(41). Available from: http://dx.doi.org/10.1002/chin.200941278.
68. Yegappan R, Selvaprithiviraj V, Amirthalingam S, Jayakumar R. Carrageenan based hydrogels and nanogels for drug delivery. Int J Biol Macromol. 2018;122:1220–33.

69. Hoare TR, Kohane DS. Hydrogels in drug delivery: Progress and challenges. Polymer (Guildf). 2008;49(8):1993–2007. Available from: http://dx.doi.org/10.1016/j.polymer.2008.01.027.
70. Li J, Mooney DJ. Designing hydrogels for controlled drug delivery. Nat Rev Mater. 2016;1(12). Available from: http://dx.doi.org/10.1038/natrevmats.2016.71.
71. Peppas NA, Hilt JZ, Khademhosseini A, Langer R. Hydrogels in biology and medicine: From molecular principles to bionanotechnology. Adv Mater. 2006;18(11):1345–60. Available from: http://dx.doi.org/10.1002/adma.200501612.
72. Gonçalves C, Pereira P, Gama M. Self-Assembled Hydrogel Nanoparticles for Drug Delivery Applications. Materials. 2010;3:1420–60.
73. Sultana F, Manirujjaman M, Haque MI-U-, Arafat M, Sharmin S. An overview of nanogel drug delivery system. J Appl Pharm Sci. 2013; Available from: http://dx.doi.org/10.7324/japs.2013.38.s15.
74. Pacheco-Quito E-M, Ruiz-Caro R, Veiga M-D. Carrageenan: Drug delivery systems and other biomedical applications. Mar Drugs. 2020;18(11):583. Available from: http://dx.doi.org/10.3390/md18110583.
75. Hezaveh H, Muhamad II. The effect of nanoparticles on gastrointestinal release from modified κ-carrageenan nanocomposite hydrogels. Carbohydr Polym [Internet]. 2012;89(1):138–45. Available from: http://dx.doi.org/10.1016/j.carbpol.2012.02.062.
76. Obrien FJ. Biomaterials & scaffolds for tissue engineering. Materials Today. 2011;14:88–95.
77. Yegappan R, Selvaprithiviraj V, Amirthalingam S, Jayakumar R. Carrageenan based hydrogels and nanogels for tissue engineering and drug delivery applications. Int J Biol Macromol. 2018;122:1220–33.
78. Li J, Mooney DJ. Designing hydrogels for controlled drug delivery and tissue regeneration. Nature Reviews Materials. 2016;1.
79. Grimaudo MA, Concheiro A, Alvarez-Lorenzo C. Nanogels for regenerative medicine. J Control Release. 2019;313:148–60. Available from: http://dx.doi.org/10.1016/j.jconrel.2019.09.015.
80. González M, Ossa EA. Injectable carrageenan-based hydroxyapatite nanorod composites for bone tissue engineering. Mater Sci Eng C. 2017;78:1075–85.
81. Chen Q, He Y, Li Q, Yang K, Sun L, Xu H, et al. Intelligent design and medical applications of antimicrobial hydrogels. Colloids Interface Sci Commun [Internet]. 2023;53(100696):100696. Available from: http://dx.doi.org/10.1016/j.colcom.2023.100696.
82. Du C, Huang W. Progress and prospects of nanocomposite hydrogels in bone tissue engineering. Nanocomposites. 2022;8(1):102–24. Available from: http://dx.doi.org/10.1080/20550324.2022.2076025.
83. Francolini I, Donelli G. Prevention and control of biofilm-based medical-device-related infections. FEMS Immunol Med Microbiol [Internet]. 2010;59(3):227–38. Available from: http://dx.doi.org/10.1111/j.1574-695X.2010.00665.x.
84. Yegappan R, Selvaprithiviraj V, Amirthalingam S, Jayakumar R. Carrageenan based hydrogels and nanogels for biomedical and antimicrobial applications. Int J Biol Macromol. 2018;122:1220–33.
85. Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. Biotechnol Adv. 2009;27(1):76–83. Available from: http://dx.doi.org/10.1016/j.biotechadv.2008.09.00.
86. Talsma SS. Biofilms on medical devices. Home Healthc Nurse. 2007;25(9):589–94. Available from: http://dx.doi.org/10.1097/01.NHH.0000296117.87061.14.
87. Tan R, Yoo J, Jang Y. Engineering approaches to create antibacterial surfaces on biomedical implants and devices. In: Racing for the Surface. Cham: Springer International Publishing; 2020. p. 313–40.
88. Schmidt S, Hellweg T, von Klitzing R. Packing density control in P(NIPAM-co-AAc) microgel monolayers: Effect of surface charge, pH, and preparation technique. Langmuir. 2008;24(21):12595–602. Available from: http://dx.doi.org/10.1021/la801770n.

89. Schubert J, Chanana M. Coating matters: Review on colloidal stability of nanoparticles with biocompatible coatings in biological media, living cells and organisms. Curr Med Chem [Internet]. 2018;25(35):4553–86. Available from: http://dx.doi.org/10.2174/0929867325666180601101859.
90. Saxena S, Spears MW Jr, Yoshida H, Gaulding JC, García AJ, Lyon LA. Microgel film dynamics modulate cell adhesion behavior. Soft Matter. 2014;10(9):1356–64. Available from: http://dx.doi.org/10.1039/C3SM52518J.
91. Wang Y, Guo L, Dong S, Cui J, Hao J. Microgels in biomaterials and nanomedicines. Adv Colloid Interface Sci. 2019;266:1–20. Available from: http://dx.doi.org/10.1016/j.cis.2019.01.005.
92. Hu B Innovative Center for Flexible Devices (iFLEX), School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore chenxd@ntu edu sg, Owh C, Chee PL, Leow WR, Liu X, Wu Y-L, et al. Supramolecular hydrogels for antimicrobial therapy. Chem Soc Rev. 2018;47(18):6917–29. Available from: http://dx.doi.org/10.1039/c8cs00128f.
93. Schmidt S, Zeiser M, Hellweg T, Duschl C, Fery A, Möhwald H. Adhesion and mechanical properties of PNIPAM microgel films and their potential use as switchable cell culture substrates. Adv Funct Mater. 2010;20(19):3235–43. Available from: http://dx.doi.org/10.1002/adfm.201000730.
94. Keskin D, Zu G, Forson AM, Tromp L, Sjollema J, van Rijn P. Nanogels: A novel approach in antimicrobial delivery systems and antimicrobial coatings. Bioact Mater. 2021;6(10):3634–57. Available from: http://dx.doi.org/10.1016/j.bioactmat.2021.03.004.
95. Ventola CL. Progress in nanomedicine: Approved and investigational nanodrugs. P T. 2017;42(12):742–55.
96. Monopoli MP, Walczyk D, Campbell A, Elia G, Lynch I, Bombelli FB, et al. Physical-chemical aspects of protein corona: relevance to in vitro and in vivo biological impacts of nanoparticles. J Am Chem Soc. 2011;133(8):2525–34. Available from: http://dx.doi.org/10.1021/ja107583h.
97. Tobacman JK. Review of harmful gastrointestinal effects of carrageenan in animal experiments. Environ Health Perspect. 2001;109(10):983–94. Available from: http://dx.doi.org/10.1289/ehp.01109983.
98. Asif M, Yasmin R, Asif R, Ambreen A, Mustafa M, Umbreen S. Green synthesis of silver nanoparticles (AgNPs), structural characterization, and their antibacterial potential. Dose Response. 2022;20(1):15593258221088709. Available from: http://dx.doi.org/10.1177/15593258221088709.
99. Giri AK, Jena B, Biswal B, Pradhan AK, Arakha M, Acharya S, et al. Green synthesis and characterization of silver nanoparticles using Eugenia roxburghii DC. extract and activity against biofilm-producing bacteria. Sci Rep. 2022;12(1):8383. Available from: http://dx.doi.org/10.1038/s41598-022-12484-y.
100. Hemlata, Meena PR, Singh AP, Tejavath KK. Biosynthesis of silver nanoparticles using Cucumis prophetarum aqueous leaf extract and their antibacterial and antiproliferative activity against cancer cell lines. ACS Omega. 2020;5(10):5520–8. Available from: http://dx.doi.org/10.1021/acsomega.0c00155.
101. Rautela A, Rani J, Debnath (Das) M. Green synthesis of silver nanoparticles from Tectona grandis seeds extract: Characterization and mechanism of antimicrobial action on different microorganisms. J Anal Sci Technol. 2019;10(1). Available from: http://dx.doi.org/10.1186/s40543-018-0163-z.
102. Alsamhary KI. Eco-friendly synthesis of silver nanoparticles by Bacillus subtilis and their antibacterial activity. Saudi J Biol Sci. 2020;27(8):2185–91. Available from: http://dx.doi.org/10.1016/j.sjbs.2020.04.026.
103. Divya K, Kurian LC, Vijayan S, Shaikmoideen JM. Green synthesis of silver nanoparticles by Escherichia coli : Analysis of antibacterial activity. J Water Environ Nanotechnol. 2016 [cited 2025 Dec 19];1(1):63–74. Available from: https://www.jwent.net/article_20480.html.

104. Naseer QA, Xue X, Wang X, Dang S, Din SU, Kalsoom, et al. Synthesis of silver nanoparticles using Lactobacillus bulgaricus and assessment of their antibacterial potential. Braz J Biol. 2021;82:e232434. Available from: http://dx.doi.org/10.1590/1519-6984.232434.
105. Syame SM, Mansour AS, Khalaf DD, Ibrahim ES, Gaber ES. Green synthesis of silver nanoparticles using lactic acid bacteria: Assessment of antimicrobial activity. World S Vet J. 2020;10(4):625–33. Available from: http://dx.doi.org/10.54203/scil.2020.wvj75.
106. Van Tan L, Tran T, Thi VD. Biosynthesis of silver nanoparticles from Bacillus licheniformis TT01 isolated from quail manure collected in Vietnam. Processes (Basel). 2021;9(4):584. Available from: http://dx.doi.org/10.3390/pr9040584.
107. Wang D, Xue B, Wang L, Zhang Y, Liu L, Zhou Y. Fungus-mediated green synthesis of nano-silver using Aspergillus sydowii and its antifungal/antiproliferative activities. Sci Rep. 2021;11(1):10356. Available from: http://dx.doi.org/10.1038/s41598-021-89854-5.
108. Ahluwalia V, Kumar J, Sisodia R, Shakil NA, Walia S. Green synthesis of silver nanoparticles by Trichoderma harzianum and their bio-efficacy evaluation against Staphylococcus aureus and Klebsiella pneumonia. Ind Crops Prod. 2014;55:202–6. Available from: http://dx.doi.org/10.1016/j.indcrop.2014.01.026.
109. Ahmad A, Mukherjee P, Senapati S, Mandal D, Khan MI, Kumar R, et al. Extracellular biosynthesis of silver nanoparticles using the fungus Fusarium oxysporum. Colloids Surf B Biointerfaces. 2003;28(4):313–8. Available from: http://dx.doi.org/10.1016/s0927-7765(02)00174-1.
110. AbdelRahim K, Mahmoud SY, Ali AM, Almaary KS, Mustafa AE-ZMA, Husseiny SM. Extracellular biosynthesis of silver nanoparticles using Rhizopus stolonifer. Saudi J Biol Sci. 2017;24(1):208–16. Available from: http://dx.doi.org/10.1016/j.sjbs.2016.02.025.
111. Basavaraja S, Balaji SD, Lagashetty A, Rajasab AH, Venkataraman A. Extracellular biosynthesis of silver nanoparticles using the fungus Fusarium semitectum. Mater Res Bull. 2008;43(5):1164–70. Available from: http://dx.doi.org/10.1016/j.materresbull.2007.06.020.
112. Gopu M, Kumar P, Selvankumar T, Senthilkumar B, Sudhakar C, Govarthanan M, et al. Green biomimetic silver nanoparticles utilizing the red algae Amphiroa rigida and its potent antibacterial, cytotoxicity and larvicidal efficiency. Bioprocess Biosyst Eng. 2021;44(2):217–23. Available from: http://dx.doi.org/10.1007/s00449-020-02426-1.
113. Venkatesan J, Kim S-K, Shim MS. Antimicrobial, antioxidant, and anticancer activities of biosynthesized silver nanoparticles using marine algae Ecklonia cava. Nanomaterials (Basel). 2016;6(12):235. Available from: http://dx.doi.org/10.3390/nano6120235.
114. Choudhary S, Kumawat G, Khandelwal M, Khangarot RK, Saharan V, Nigam S, et al. Phyco-synthesis of silver nanoparticles by environmentally safe approach and their applications. Sci Rep. 2024;14(1):9568. Available from: http://dx.doi.org/10.1038/s41598-024-60195-3.
115. Do J-M, Hong JW, Yoon H-S. Microalgae-mediated green synthesis of silver nanoparticles: a sustainable approach using extracellular polymeric substances from Graesiella emersonii KNUA204. Front Microbiol. 2025;16:1589285. Available from: http://dx.doi.org/10.3389/fmicb.2025.1589285.
116. Abdel-Raouf N, Al-Enazi NM, Ibraheem IBM, Alharbi RM, Alkhulaifi MM. Biosynthesis of silver nanoparticles by using of the marine brown alga Padina pavonia and their characterization. Saudi J Biol Sci. 2019;26(6):1207–15. Available from: http://dx.doi.org/10.1016/j.sjbs.2018.01.007.
117. Silva SS, et al. Polysaccharide-based nanogels for biomedical applications. Carbohydrate Polymers. 2020;237:116109.
118. Necas J, Bartosikova L. Carrageenan: A review. Veterinarni Medicina. 2013;58:187–205.
119. Langer R, Vacanti JP. Tissue engineering. Science. 1993;260:920–926.
120. Hoare TR, Kohane DS. Hydrogels in drug delivery and tissue engineering. Polymer. 2008;49:1993–2007.

121. Silva SS, et al. Polysaccharide-based nanogels in tissue engineering and regenerative medicine. Carbohydrate Polymers. 2020;237:116109.
122. Campoccia D, Montanaro L, Arciola CR. A review of the biomaterials technologies for infection-resistant surfaces. Biomaterials. 2013;34:8533–8554.
123. Aslam Khan MU, Raza MA, Mehboob H, Abdul Kadir MR, Abd Razak SI, Shah SA, et al. Development and in vitro evaluation of κ-carrageenan based polymeric hybrid nanocomposite scaffolds for bone tissue engineering. RSC Adv. 2020;10(66):40529–42. Available from: http://dx.doi.org/10.1039/d0ra07446b.