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Study of various forms of propolis nanoparticles and their antibacterial effectiveness

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ABSTRACT

Most bacteria are beneficial to human health, but some have pathogenic properties. Pathogenic bacteria cause diseases in the host by directly damaging tissues or cells during replication via toxin production. Propolis nanoparticles is a method that has the potential to be an effective antibacterial. Advantages of using nanotechnology include boosting the drug delivery system and absorption of active herbal medicine substances, which have poor bioavailability owing to their high molecular weight, improved solubility, rapid penetration with low cytotoxicity, reduced drug dosage, and fewer side effects. This study reviews the literature on the effectiveness of propolis in various forms of nanoparticle technology as an antibacterial agent, which may help researchers to develop nanoparticle technology in the pharmaceutical industry. We conducted this research using search engines, including Scopus, PubMed, and ScienceDirect, with the keywords " Nanoparticles,"" Propolis,"and "Antibacterial," without limiting the year of publication. We conducted a search between April and June 2025. They related the reviewed articles to knowledge of nanoparticle use. Propolis is a natural resinous substance produced by honeybees in various forms. These parameters were used to extract 1699 articles, which were reviewed and examined. The study identified eight types of propolis nanoparticles with antibacterial properties: nanoemulsions, nanostructured lipid carriers (NLC), nanosheets, metal nanoparticles, chitosan nanoparticles, nanoencapsulation, solid lipid nanoparticles (SLN), and polymer nanoparticles. The effectiveness of antibacterial propolis nanoparticles varies agents. The metallic form of propolis nanoparticles is the most effective nanoparticles. Metallic propolis nanoparticles can inhibit 19 types of bacteria and can be applied in eight different forms.

1. Introduction

Bacteria are microorganisms that play an important role in human life [1]. Most bacteria have many benefits for human health, whereas others have pathogenic properties [2]. Pathogenic bacteria are microorganisms that cause diseases in the host and directly

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damage tissues or cells during replication or by producing toxins [3]. Propolis is a substance that can kill or inhibit bacterial growth [4].

Propolis is a herbal substance with potential antibacterial properties. Numerous in vivo and in vitro studies have shown that propolis exhibits excellent antibacterial properties. Propolis contains several compounds that are beneficial to human health, including polyphenols, flavonoids, cinnamates, amino acids, benzoic acid derivatives, vitamins, carotenoids, sterols, terpenes, phenolic compounds, coumarins, steroids, and aromatic acids [4–8]. The antibacterial mechanism of propolis involves the disruption of bacterial metabolism, inhibition of colony formation, and damage to the bacterial cells [9,10]. One of the latest technologies for utilizing active propolis is the formation of nanoparticles. The advantages of using nanotechnology include improved drug delivery systems and the absorption of active herbal drug substances, which have low bioavailability due to their high molecular weight, but better solubility, rapid penetration with low cytotoxicity, lower doses, and fewer side effects [11,12].

Propolis has varying chemical properties that influence the quality of its bioactivity. Some of these factors include geography, season, plant source, and extraction method [13]. The variability of these various factors is thought to influence the effectiveness of antibacterial properties. One way to increase the antibacterial effectiveness of propolis can be done by converting the preparation into nanoparticle form because it can improve drug efficiency, bioavailability, permeability, and have minimal side effects [14–16].

Propolis nanoparticles exist in various forms, including nanoemulsions, nanostructured lipid carriers (NLCs), nanosheets, metal nanoparticles, chitosan nanoparticles, nanoencapsulation, solid lipid nanoparticles (SLNs), and polymer nanoparticles. Various forms of nanoparticles are believed to affect their antibacterial properties. This review determined the effectiveness of various forms of propolis nanoparticles as antibacterial agents. This study also reveals the effectiveness of propolis nanoparticles in various dosage forms as an antibacterial agent. A brief overview of the study on 9 nanoparticle dosage forms is presented in the Graphical Abstract.

2. Method

This research is a Systematic Literature Review conducted by analyzing, identifying, and interpreting the results of previous research journal searches through journal portals, such as Scopus, PubMed, and ScienceDirect, followed by an assessment. The research stages are illustrated in Fig. 1. A flow diagram of the search strategy according to the PRISMA guidelines.

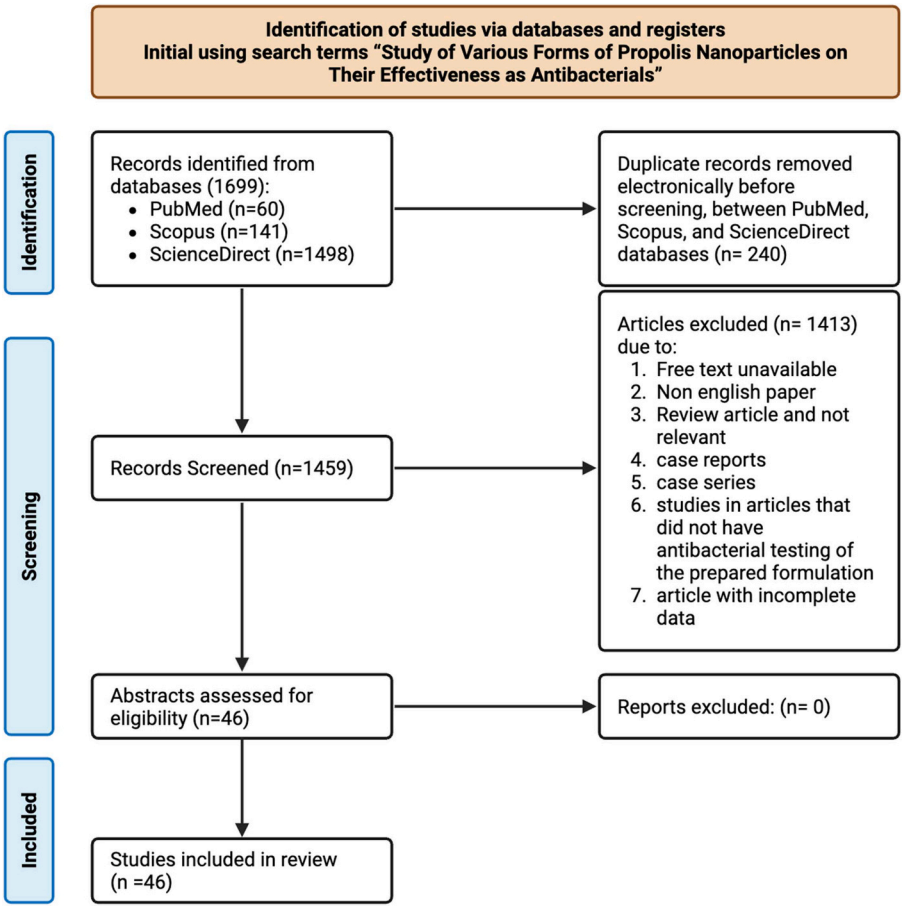

Fig. 1. A flow diagram of the search strategy according to PRISMA guidelines.

The review was conducted from April to June 2025. The initial stage involved a literature search using the keywords "Nanoparticles," "Propolis", and "Antibacterial" across Scopus, PubMed, and ScienceDirect databases. The collected articles were converted to PDF format to facilitate the selection process. The inclusion criteria were applied to screen articles for discussion in this review, including articles published in English, studies using propolis nanoparticle preparations, and the inclusion of pharmacologically active substances that were tested to ensure their antibacterial efficacy. Exclusion criteria in this article review included: articles with study designs such as case reports, case series, and review articles; studies in articles that did not have antibacterial testing of the prepared formulations; and articles with incomplete data, such as those lacking information about the active substances used and the bacterial species used in antibacterial efficacy testing.

3. Result

Propolis nanoparticles are nanosized propolis particles (diameter: 1–100 nm) that are bound together to make them more effective without changing their properties by altering the size of the propolis through various methods [88,89]. This differs from the opinion [17,18] that the size of nanoparticles is in the range of 10–1000 nm. Based on these opinions, propolis can be considered a nanoparticle if it is less than 1000 nm in size. The results of the literature analysis on the effectiveness of propolis nanoparticles as antibacterial agents from 46 journals that met the inclusion criteria are listed in Table 1.

3.1. Nanoemulsion

Nanoemulsions are complex and kinetically stable emulsions with an average droplet size of 50–100 nm and average droplet diameter of 50–1000 nm. Nanoemulsions adhere to lipid-coated bacteria through thermodynamic processes and electrostatic attractions. When a certain number of nanoparticles attach to pathogens, the active ingredients and trapped energy generated by the nanoemulsion degrade the lipid membrane of the pathogen, causing cell lysis and bacterial death [19–22]. The mechanism of the antibacterial effect of the nanoemulsions is shown in Fig. 2.

Based on the analysis results in Table 1, the nanoemulsion inhibited five types of bacteria (*P. aeruginosa, S. mutans, S. sanguinis, Lactobacillus acidophilus,* and *E. faecalis*) [10,23–25]. Propolis nanoemulsions can enhance the antibacterial effects, reduce bacterial viability, and inhibit the formation of MDR P. aeruginosa biofilms [10]. Nano-propolis significantly reduced the number of cariogenic bacterial colonies in a rat model [23]. Propolis nanoparticles have the same effectiveness as 6 % NaOCl and 2 % chlorhexidine in reducing the bacterial CFU of *E. faecalis* [24,25]. Nanoemulsions can be used directly [10,24] in the form of composite resins [23] and bioceramic sealers [25] for dental care.

Propolis in nanoemulsion form has effective antibacterial properties against several types of pathogenic bacteria (*P. aeruginosa, S. mutans, S. sanguinis,* L. *acidophilus,* and *E. faecalis*) [10,23–25]. Propolis in nanoemulsion form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in nanoemulsion form. Propolis nanoemulsions with MIC 15.6 to 125 μg/mL are more effective than non-nano propolis with MIC 31.2 to 500 μg/mL [24]. Propolis in nanoemulsion form does not have a Minimum Inhibitory Concentration (MIC) against bacteria that is higher than that of antibiotics. Propolis nanoemulsions with MICs of 3.2 to 15 mg/mL were not more effective than antibiotics with MIC 0.31 to 1.25 mg/mL [10]. The smaller of the Minimum Inhibitory Concentration (MIC) number, the better the effectiveness of a preparation, this shows that a very small dose can control pathogenic bacteria.

3.2. Nanostructure lipid carrier (NLC)

Nanostructured lipid carriers (NLC) are lipid-based nanoparticles [26,27]. Nanostructured lipid carriers (NLC) have a hybrid structure of polymer nanocapsules and liposomes, which serve as an alternative for encapsulating lipophilic drugs in a liquid core and protecting them from potential degradation. NLC can improve stability, controlled drug release, good tolerability, overcome multidrug resistance (MDR), enhance intracellular internalization, and increase the efficacy of transported drugs [27,28]. Nanostructured lipid carrier (NLC) propolis can inhibit bacteria in two stages. First, propolis directly affects the bacterial membrane and inhibits its motility, thereby damaging the immune system of bacterial cells [16,27]. The mechanism of the antibacterial effect of the Nanostructured lipid carrier (NLC) is illustrated in Fig. 3.

The analysis results in Table 1 show that the propolis nanostructure lipid carriers (NLC) are effective in inhibiting the two types of bacteria (*B. subtilis* and *S. aureus*), and one type of fungus (*C. albicans*) [29]. Propolis NLC is effective in inhibiting the growth of gram-positive bacteria (*Bacillus subtilis* and *Staphylococcus aureus*), gram-negative bacteria (*Salmonella spp.*), and fungi (*C. albicans*) twice as much as propolis extract [29]. NLC can be used directly as antibacterial agents [29].

Propolis in Nanostructured lipid carriers (NLC) form has effective antibacterial properties against several types of pathogenic bacteria (*B. subtilis* and *S. aureus*), and one type of fungus (*C. albicans*) [29]. Propolis in Nanostructured lipid carriers (NLC) form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in Nanostructured lipid carriers (NLC) form. NLC Propolis with MIC 31.25 to 500 μg/mL are more effective than non-NLC propolis with MIC 250 to 500 μg/mL [29].

4. Nanosheet

A nanosheet is a very thin two-dimensional nanomaterial with a thickness ranging from 1 nm to 100 nm and a large surface area-to-volume ratio. This structure possesses unique properties, such as high durability and excellent electrical and thermal conductivity, and

Table 1
Application of propolis nanoparticles for antibacterial pathogens.

No	Type of Nanoparticle	Type of Preparation	Bacterial Species	MIC or effectiveness of killing bacteria	Antibacterial properties/ activity	Reference
1	Nanoemulsion	Nanoemulsion	*P. Aeruginosa*	Iranian Propolis MIC 3.2–15 mg/ mL NP MIC 0.31–1.25 mg/ mL AB	Propolis nanoemulsion can enhance antimicrobial effects, reduce bacterial viability, and affect the formation of MDR *P. aeruginosa* biofilms.	[10]
		Transbond XT orthodontic primer (Orthodontic Composite)	*S. mutans, S. sanguinis*, dan L. *acidophilus*	Iranian Propolis Dose 1 %, 5 %, and 10 % of nano-propolis	Orthodontic primer containing nano-propolis significantly reduced the number of cariogenic bacterial colonies in a rat model.	[23]
		Nanoemulsion	*E. faecalis*	Malaysian Propolis MIC 15.6 to 125 μg/ mL Propolis MIC 31.2 to 500 μg/ mL NP	Propolis nanoparticles had the same effectiveness as 6 % NaOCl and 2 % CHX in reducing CFU of *E. faecalis* bacteria	[86]
		Nanoemulsion (bioceramic sealers)	*E. faecalis*	Indonesian Propolis MIC 0.9664 g/ml NP MIC 0.9513 g/ml comercil MIC 0.9528 g/ml NP MIC 0.9492 g/ml comercil	The addition of 5 % propolis nanoparticles to commercial bioceramic sealers and epoxy resins can eliminate *E. faecalis* bacteria	[25]
2	NLC	Nanostructure Lipid Carrier	Gram-positif (*B. subtilis* and *S. aureus*), bakteri Gram-negatif, dan mikroba jamur (*C. albicans*)	South east Asia Propolis MIC 31.25 to 500 μg/mL NP MIC 250 to 500 μg/ mL Propolis	Propolis-NLC showed antibacterial effect on Gram-positive bacteria (*B. subtilis* and *S. aureus*), Gram-negative bacteria, and fungal microbes (*C. albicans*) ($p < 0.0001$)	[29]
3	Nanosheet	Hydrogel bio nanocomposite propolis	*C. albicans, S. aureus*, and *E. coli*	Iranian Propolis MIC 25 μg/mL NP MIC 0.5–32 μg/mL AB	Antimicrobial efficacy increased with the concentration of nanosheets showing effectiveness against *C. albicans* (0 CFU), S. *aureus* (1×10^3 CFU), and *E. coli* (22 $\times 10^3$ CFU).	[8]
4	Metallic nanoparticle	Zinc nanoparticle (Nanocomposite)	*E. coli, S. typhi, P. aeruginosa, B. cereus*, and *S. aureus*	Egypt Propolis MIC 100 – 500 μg/ mL P MIC 100 – 400 μg/ mL NP MIC 50 – 400 μg/ mL PE MIC 50 – 75 μg/mL ZnO-P MIC 30 – 50 ZnO—NPs	The synthesized ZnO-propolis composite, incorporating propolis, was verified to enhance its antimicrobial efficacy, including *E. coli, S. typhi, P. aeruginosa, B. cereus, and S. aureus.*	[7]
		Silver nanoparticle	Biofilm *P. gingivalis*	Dose 0.1 %, 0.3 %, and 0.5 % of AgNPs	AgNPs exhibited an inhibitory effect on P. *gingivalis* biofilm formation.	[38]
		Zinc oxide nanoparticle (Gel)	*E. coli*	Egypt Propolis Dose 5 – 10 % of ZnO–NPs	The antimicrobial activity of the nanocomposite gel loaded with 10 % PP1/ZnO–NPs (G6) revealed the highest inhibition zone against *E. coli* (26 ± 2.31 mm).	[37]
		Silver nanoparticle	Gram negative bacteria *P. aeruginosa, E. coli, K. pneumoniae, A. baumannii* and gram positive bacteria: *S. aureus and E. faecalis*	MIC 20 and 30 μg/ mL NP	AgNPs propolis showed greater inhibitory effect against the growth of gram-negative bacteria *P. aeruginosa, E. coli, K. pneumoniae, A. baumannii* and gram-positive bacteria: *S. aureus and E. faecalis*	[39]

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Table 1 (*continued*)

No	Type of Nanoparticle	Type of Preparation	Bacterial Species	MIC or effectiveness of killing bacteria	Antibacterial properties/ activity	Reference
		Iron oxide nanoparticle propolis	Gram-positive (B. subtilis and S. pyogenes) and gram-negative (P. aeruginosa, and *E. coli*) / Gram-negative and gram-positive bacteria, including *E. coli*, P. aeruginosa, S. aureus, and B. subtilis.	Egypt Propolis / For particle sections 23.5 ± 0.7 mm NP 21.0 ± 0.4 mm Rifampicin / Cyprus (North West, North East, Central Cyprus and South West) (1:1) BEP-IONPs and (1:2) BEP-IONPs MIC 0.46, 0.39, and 0.19 mg/mL	The Fe2O3 NP based on the effective threat to eliminate pathogenic bacteria at lower doses, with an inhibition zone of 23.5 mm for gram-negative bacteria Pseudomonas aeruginosa. / The results showed that the synthesized BEP-IONPs had strong antibacterial activity, either Gram-negative or Gram-positive.	[39] [40]
		Silver and gold ZnONPs	Gram-positive S. sciuri and Gram-negative P. aeruginosa and S. enterica	Egypt Propolis MIC 0.15, 0.113, and 0.098 mg/mL 75 µg/ml AgNPs@ZnO 75 µg/ml AuNPs@ZnO 155 µg/ml ZnO—NPs	Promising medical applications for biosynthesized ZnNPs in combination with other metals, such as ZnO-AgNPs, as safe antibacterial and anticancer drugs.	[41]
		ZnO nanoparticle propolis	Gram-positive bacteria (B. Subtilis and S. Aureus), Gram negative bacteria (*E. coli* and P. Aeruginosa), and fungal microorganisms (C. Albicans and Mucor).	Egypt Propolis 10 mg/mL ZnO—NPs	The antimicrobial activity of the optimally prepared ZnO nanoparticles was studied using various types of microbes, Gram-positive bacteria (Bacillus Subtilis and Staph. Aureus), Gram-negative bacteria (*E. coli* and Pseudomonas Aeruginosa), and fungal microorganisms (Candida Albicans and Mucor).	[42]
		Copper nanoparticle	*E. coli*	Iranian Propolis 8.4 ± 0.192 1 mg/ mL	Significant biofilm inhibition (84 %) and reduction in motility (92 %) when compared to the positive control (Ampicillin)	[43]
		Au-Ag nanoparticle	S. sciuri, P. aeruginosa, and S. enterica Typhimurium	Egypt Propolis Au@AgNPs (1.6 µg/mL) Au@AgNPs (5 µg/ mL)	Biosynthesis of Au–Ag nanoparticles using propolis has activity as a natural reducing agent and has effective antibacterial activity against antibiotic-resistant S. sciuri, P. aeruginosa, and S. enterica Typhimurium and shows anticancer activity in cancer cell lines.	[44]
		Silver nanoparticle propolis	S. aureus dan E coli	State of Sonora 25 – 100 µg/mL	Silver nanoparticle propolis demonstrated remarkable antibacterial and antibiofilm activity against multidrug-resistant clinical isolates, with S. Aureus and *E. coli*	[45]
		ZnO nanoparticle propolis	Gram-positive (bacteria S. Aureus) and gram-negative bacteria (*E. coli* and P. Aeruginosa)	Iraqi Propolis 164.31 µg/ml for ZnONPs 111.43 µg/ml for ascorbic acid	The results showed effective antibacterial activity on both Gram-negative and Gram-positive bacteria at different concentrations.	[46]
		Silver-platinum (Ag-Pt) nanoparticle propolis	*E. coli*, S. aureus, B. subtilis, K. pneumoniae, S. epidermidis, and S. marcescens	100 µg/ml of Ag–Pt bimetallic NPs	The antimicrobial activity of silver-platinum (Ag–Pt) bimetallic nanoparticles showed effective results against *E. coli*, S. aureus, B. subtilis, K. pneumoniae, S. epidermidis, and S. marcescens.	[47]
		Pullulan ZnONP nanoparticle (Meat packaging)	Gram-positive L. monocytogenes and Gram-negative *E. coli* bacteria	Korea	In addition, the pullulan/ chitosan based biocomposite films showed good antioxidant activity due to propolis and excellent antibacterial activity against foodborne pathogens due to ZnONPs.	[48]

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Table 1 (*continued*)

No	Type of Nanoparticle	Type of Preparation	Bacterial Species	MIC or effectiveness of killing bacteria	Antibacterial properties/ activity	Reference
		Silver (Ag) nanoparticle	Salmonella, *S. enteritidis*	MIC 92 μg/mL to 5.25 μg/mL AgNPs	This combination of AgNPs and phages offers the prospect of nanoparticles with significantly enhanced antibacterial properties and therapeutic performance.	[49]
		Ag nanoparticle propolis	(L. monocytogenes, S. typhimurium,and *E. coli*) and three fungal strains (A. solani, Helminthosporium sp., and F. oxysporum).	Saudi Propolis	These compounds did not enhance the antiradical activity in the aqueous extract of Pro-AgNP but enhanced its antibacterial activity.	[50]
		Silver nanoparticle (Wound sewing thread)	pathogenic gram-negative and gram-positive bacteria, *E. coli* and S. aureus	Turkey Propolis 40 μg/cm	The fabrication of bioAgNP-propolis coated sutures showed strong antibacterial activity against pathogenic gram-negative and gram-positive bacteria, *E. coli* and Staphylococcus aureus	[51]
		Silver nanoparticle propolis	S. Aureus, S. Epidermidis, *E. coli*, P. Aeruginosa	Brazilian Red Propolis 4.162 to 16.650 μg/mL Propolis 4.162 to 16.650 μg/mL AgNp-C 8 to 2081μg/mL AgNP-P	Our product showed significant antimicrobial activity indicating synergism between propolis and silver nanoparticles as expected and shows promise as an effective antimicrobial product for use in infections.	[52]
		Magnetite nanoparticle propolis (combination Chloramphenicol)	S. Aureus	Morocco Propolis MIC 0.025 to 0.36 mg/ml	Synthesis of novel antibacterial nanocomposites, for possible applications as prospective nanoantibacterial agents or drug carriers.	[53]
		Silver nanoparticle	Pathogen Bacteria (*E. coli*, S. Aureus, C. Albicans	Bulgaria Propolis	Propolis containing silica-silver showed significantly better antibacterial and antifungal activities than poplar propolis and the carrier modified with silver itself.	[54]
		Silver nanoparticle propolis	S. aureus, S. epidermidis, E. faecalis, *E. coli*, P. aeruginosa, P. vulgaris, B. subtilis, B. cereus, and C. albicans	UAB Medicata Filia, Lithuania 0.347 μg/*mL*	Antimicrobial activity testing confirmed the ability of AgNPs containing PLA electrospun materials to inhibit the growth of microorganisms.	[55]
		Silver nanoparticle (wound dressing)	S. aureus, S. epidermidis, E. faecalis, *E. coli*, P. aeruginosa, P. vulgaris, B. subtilis, B. cereus, dan C. albicans	UAB Medicata Filia, Lithuania 750 or 1500 μg/*mL*	Evaluation of antimicrobial activity on S. aureus, S. epidermidis, E. faecalis, *E. coli*, P. aeruginosa, P. vulgaris, B. subtilis, B. cereus, dan C. albicans strains confirmed the ability of the electrospun mats to inhibit the growth of the tested microorganisms.	[56]
		Silver nanoparticle (wound healing)	S. Aureus	Indian Propolis 06.3 ± 0.6 ppm AgNp 03.7 ± 0.57 ppm PSLN 08.0 ± 1.00 ppm PMSN 10.00±1.00 ppm Propolis	The combination of propolis with AgNP significantly reduced the minimum inhibitory concentration of AgNP alone when tested against S. aureus.	[57]
5	Chitosan Nanoparticle	Chitosan nanoparticle	*E. coli*, S. aureus, dan S. epidermidis	Iran Propolis 2 to 230 μg/ml	Statistically significant and greater reduction in the number of *E. coli*, S. aureus, and S. epidermidis strains in biofilms, pre-formed biofilms, and planktonic phases.	[5]

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Table 1 (*continued*)

No	Type of Nanoparticle	Type of Preparation	Bacterial Species	MIC or effectiveness of killing bacteria	Antibacterial properties/ activity	Reference
		Chitosan nanoparticle	S. sciuri, *S. typhimurium*, dan P. aeruginosa	31.2 and 62.2 μg/ mL Ag-CS NPs	Ag-CS-NPs with phages showed potential bactericidal and inhibitory effects against S. sciuri, *S. typhimurium*, and P. aeruginosa bacteria, as well as against biofilm production.	[64]
		Chitosan nanoparticle propolis (Edible coating)	*E. coli*, S. aureus dan *S. typhimurium*, S aureus	Egypt Propolis 50 to 57.5 μg/mL bee chitosan nanoparticles 35 to 45 μg/mL Propolis 30 to 37.5 μg/mL Pro/SeNPs 25 to 30 μg/mL BCht/Pro/SeNPs 37.5 to 47.5 μg/mL Ampicillin	Chitosan nanoparticle propolis showed strong antibacterial action against *E. coli*, S. aureus and *S. typhimurium*.	[65]
		Chitosan nanoparticle (intracanal medicament)	Biofilm Enterococcus faecalis	Malaysian Propolis 100 μg/ml propolis 250 μg/ml propolis 100 μg/ml CPN 250 μg/ml CPN250 2 % chlorhexidine	CPN250 was the most effective in reducing E. faecalis colonies on day 1, day 3 at both depths, and day 7. CPN250 was equally effective as CPN100 and 2 % CHX.	[66]
		Chitosan nanoparticle	K. pneumonia	Egypt Propolis MIC 6.25 μg/ml	The developed nanoformulation can be considered as a potential antibacterial agent in the treatment of K. pneumonia.	[67]
		nanoparticle chitosan propolis (edible film)	*E. coli* dan L. monocytogenes	Mexico Propolis	The use of chitosan nanoparticles and propolis ethanol extract in edible films is a promising alternative for active packaging with antibacterial properties considering its application for strawberry preservation against foodborne bacteria.	[68]
		Chitosan propolis nanoparticle (combination with antibiotics)	S. Epidermidis	Malaysian Propolis 100 μg/mL CPNP	CPNP has a direct inhibitory effect on the survival of S. epidermidis.	[69]
		Chitosan nanoparticle propolis (Pasta)	Bacterial biofilm, E. Faecalis	Uruguay Propolis	Incorporating CNP into Ca (OH)2 paste has the potential to be beneficial when using intracanal treatment between appointments due to its ability to kill bacteria in both short-term and long-term exposure.	[70]
		Chitosan nanoparticle propolis (varnishes)	S. Mutans	Egypt Propolis	Incorporating natural products with fluoride into dental varnish can be an effective approach to caries prevention, especially miswak and propolis when financial resources are limited.	[87]
		Chitosan nanoparticle propolis	E. faecalis	Malaysian Propolis Kill 90 % at 200 μg/ mL Kill 40 % and ~75 % at 200 and 300 μg/ml	The results of this study indicate that chitosan-propolis nano formulation can be considered as a potential anti-biofilm agent in fighting infections involving biofilm formation such as chronic wounds and surgical site infections.	[72]
6	Nanoencapsulation	Nanoencapsulation	*E. coli* and S. Aureus	Turkey Propolis 2 % of the PVA-NPs	Antibacterial efficacy was evaluated by Broth dilution	[16]

(*continued on next page*)

Table 1 (*continued*)

No	Type of Nanoparticle	Type of Preparation	Bacterial Species	MIC or effectiveness of killing bacteria	Antibacterial properties/ activity	Reference
					method and PVA-NP showed good inhibitory activity against S. aureus at low concentration ratio, while it had no inhibitory activity against *E. coli*.	
		Propolis encapsulated with mesoporous silica	S. aureus	Red Propolis MIC 150 to 375 μg/ml	The analysis showed that the integrity of the red propolis constituents was maintained after the embedding process, and the antioxidant and antibacterial activities were maintained.	[76]
		Propolis encapsulated alginate nanoparticle	S. Aureus, *E. coli*, P. vulgaris, C. diversus and S. enterica	Egypt Propolis	Propolis-ALg NP samples showed the highest antimicrobial activity against all pathogens examined compared to pure propolis and/or antibiotics (clindamycin)	[77]
		Collagen film (nanoencapsulation) (wound healing)	*E. coli* dan S. aureus.	Sigma-Aldrich MIC 100 to 200 μg/ml	The antibacterial effect depends on the concentration of nanoparticles in the collagen film, the effect is more pronounced against *E. coli* than S. aureus.	[78]
7	Solid Lipid Nanoparticle	Solid Lipid Nanoparticle	Gram positive bacteria	Propolis PSLN 1 ± 0.034 0.5 ± 0.010 0.5 ± 0.021 0.25 ± 0.019 0.125 ± 0.029 0.125 ± 0.008 2 ± 0.031 1 ± 0.011	Optimized SLN propolis can be used as an antioxidant and antibacterial additive and has the potential to be used as a drug or drug carrier for the treatment of lung cancer.	[80]
8	Polymer nanoparticle	Polymer nanoparticle (wound healing)	S. aureus, K. pneumonia, *E. coli*, P. aeruginosa, and A. baumannii	MIC 750 μg/ml Sericin MIC 1250 μg/ml Propolis MIC 250 μg/ml nSE/P MIC 1 μg/ml nSE/P Amoxicilin	Significant reduction in bacterial growth was seen after 2 h of incubation with sericin/propolis/Amoxicillin (nSE/P/AMX) nanoparticles, and complete eradication of the growth of S. aureus, K. pneumonia, *E. coli*, P. aeruginosa, and A. baumannii bacteria was seen after 4 h of incubation.	[85]
		Polymer (Root canal sealer)	E. faecalis and S. mutans bacterial strains and antifungal activity against C. albicans	Egypt Propolis 154.1, 95.97, 85.55 and 100.2 μg/mL	ProE loaded NPs can be incorporated into and represented as root canal sealers with extended release and enhanced cytocompatibility as well as antimicrobial activity.	[84]

is used in semiconductor technologies such as nanosheet transistors [30]. Propolis nanosheets inhibit bacterial growth by attaching to the bacterial cell wall and coating the entire bacterial cell, thus damaging the bacterial cell wall and ultimately causing cell contents to leak, leading to bacterial cell death[31]. The mechanism of the antibacterial effect of the nanosheets is illustrated in Fig. 4.

Based on the analysis results in Table 1, propolis nanosheets are effective in inhibiting two types of bacteria (*S. aureus* and *Escherichia coli*) and one type of fungus (*C. albicans*) [8]. Nanosheet propolis has good antibacterial activity, as evidenced by its antibacterial activity, which increases with the concentration of nanosheets. Nanosheets were effective in inhibiting the growth *of C. albicans* (0 CFU), *S. aureus* (1×10^3 CFU), and *E. coli* (22×10^3 CFU) to prevent infection [8]. Nanosheets used in this study were used directly, as in the study conducted by [8].

Propolis in nanosheet form has effective antibacterial properties against several types of pathogenic bacteria (*S. aureus* and *E. coli*) and one type of fungus (*C. albicans*) [8]. Propolis in nanosheet form has a higher Minimum Inhibitory Concentration (MIC) against

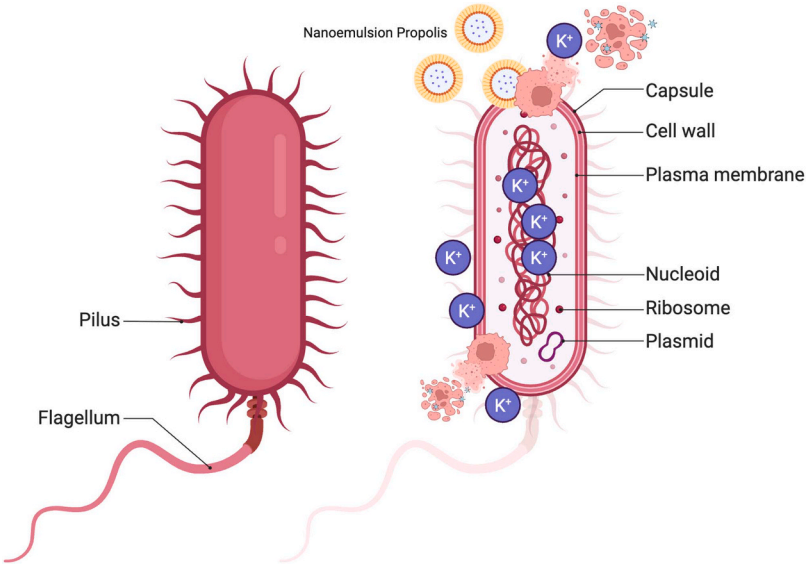

Fig. 2. Antibacterial mechanism of Nanoemulsion.

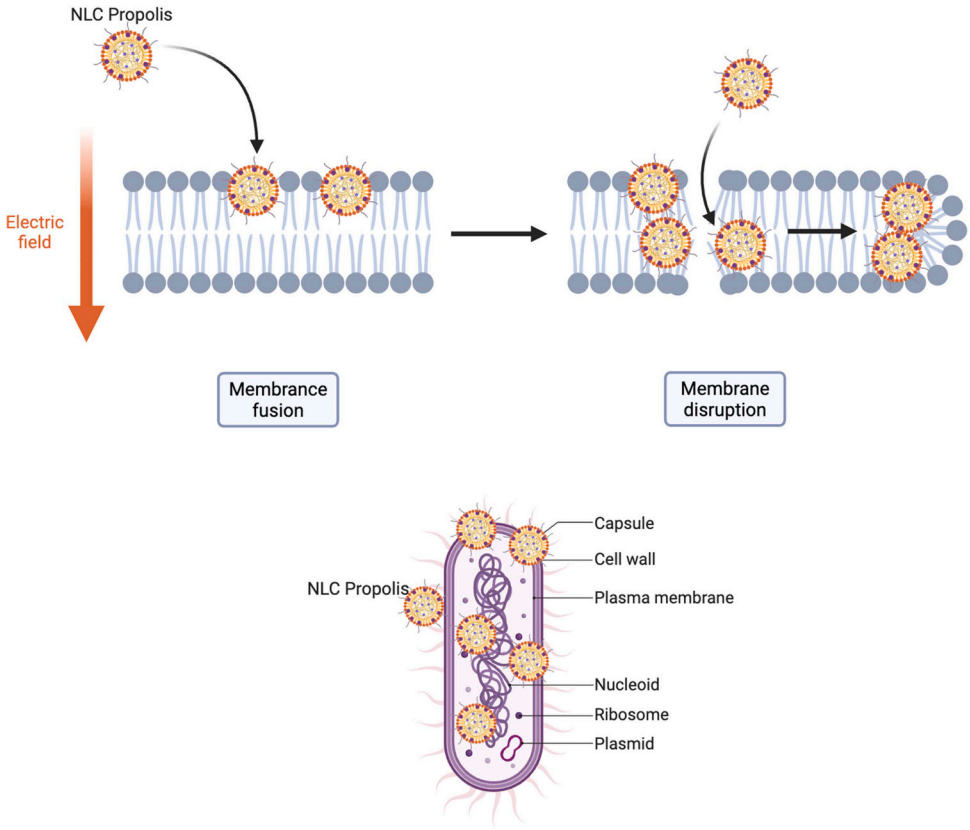

Fig. 3. Antibacterial mechanism of Nanostructured Lipid Carrier (NLC).

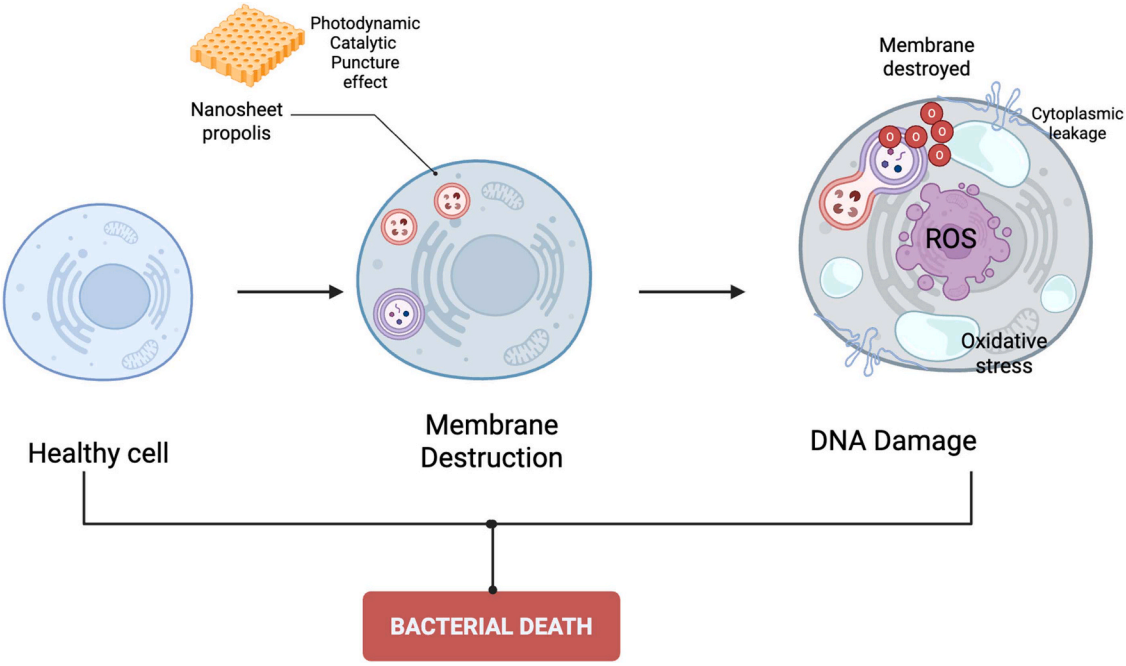

Fig. 4. Antibacterial mechanism of Nanosheet.

bacteria compared to propolis not in nanosheet form. Nanosheet propolis with MIC 25 μg/mL were not more effective than antibiotics with MIC 0.5 to 32 μg/mL [8]

4.1. *Metallic nanoparticle*

Metallic nanoparticles are nanoparticles with sizes between 10 and 500 nm [32]. Metallic nanoparticles can be applied in the medical field, including drug delivery, cancer treatment, antibacterial applications, and targeted therapy [33]. The most commonly used metals for nanoparticle synthesis are gold (Au), silver (Ag), iron (Fe), aluminum (Al), cadmium (Cd), cobalt (Co), copper (Cu), and zinc (Zn) [34,35]. Metal-based nanoparticles are known to have non-specific antibacterial toxicity mechanisms (not binding to specific receptors in bacterial cells), which makes it difficult for bacteria to develop resistance and broaden the spectrum of antibacterial

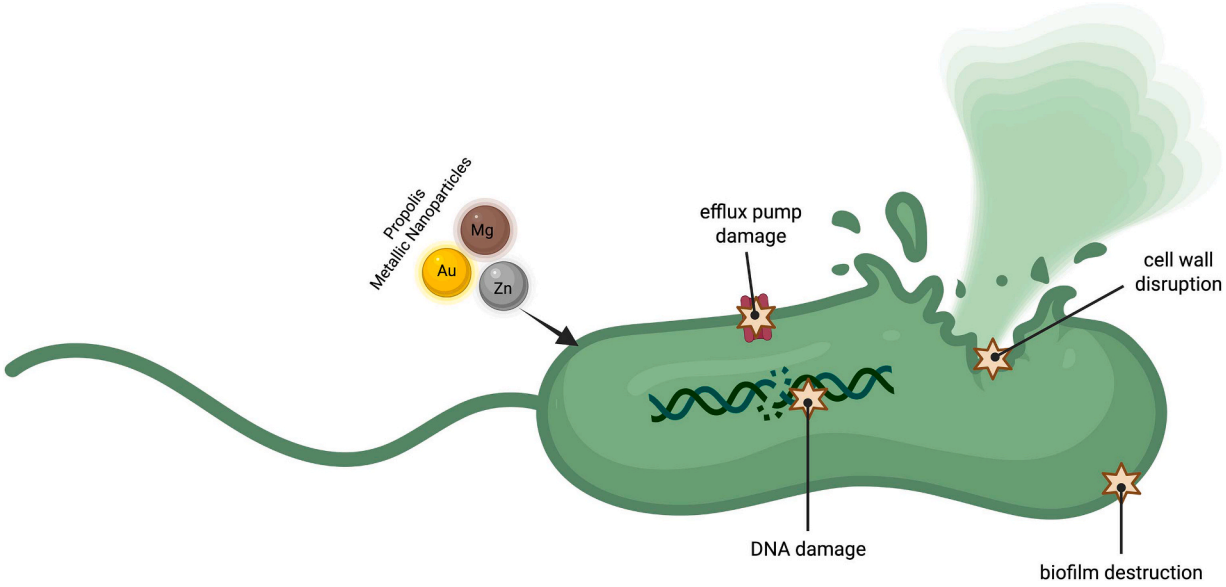

Fig. 5. Antibacterial mechanism of Metallic Nanoparticle.

activity [36]. The antibacterial mechanism of metallic nanoparticles is related to increasing the permeability of metal compounds into microbes and increasing cell wall damage due to electrostatic interactions, which also causes protein denaturation, membrane lipid oxidation, and oxidative DNA damage in microbes [37]. The mechanism of the antibacterial effect of metallic nanoparticles is illustrated in Fig. 5.

Based on the analysis results in Table 1, metallic nanoparticles effectively inhibited 19 types of bacteria (*E. coli, Salmonella typhi, P. aeruginosa, B. cereus, S. aureus, biofilm P. gingivalis, K. pneumoniae, A. baumannii, E. faecalis, B. subtilitis, S. pyogenes, S. enterica, S. sciuri, S. enterica typhimurium, S. epidermidis, S. marcesens,* L. *monocytogenes, Salmonella enteritidis,* and *P. vulgaris*), and 4 type of fungus (*C. albicans, A. solani, Helminthosporium* sp., and *F. oxysporum*) [7,33,37–57].

Propolis zinc oxide nanoparticles (ZnO—NPs) exhibited the highest activity against all the tested bacteria. ZnO—NPs had a higher antibacterial effect than the propolis extract, followed by nanopropolis and propolis. The combination of ZnO—NPs with nanopropolis in a nanocomposite has a synergistic effect and high antibacterial activity [7,37,48]. According to Osman et al. 2023 of propolis ZnO nanoparticles has stronger antibacterial activity than antibiotics (gentamicin) in inhibiting bacterial activity. Antibacterial activity increased with increasing concentrations. Propolis ZnO nanoparticles disrupt cell wall and membrane permeability, endangering biomolecules such as DNA and proteins by inhibiting key activities such as DNA replication and protein synthesis and by cutting off energy access to bacteria [46].

Silver nanoparticle propolis has potential as an effective option for improving periodontal treatment outcomes as it has shown good inhibitory effects against various types of bacteria and biofilm formation [38,45,50,52,54–56]. AgNP-propolis showed a greater inhibitory effect against several bacteria and did not cause any toxic effects [39]. The combination of AgNPs and propolis exhibits significant antibacterial properties against various types of bacteria and can prevent multidrug resistance [49]. However, coating silk surgical threads with propolis and biogenic silver nanoparticles provides effective antibacterial capacity against surgical threads [51, 56,57].

The iron oxide nanoparticle propolis showed a more effective antibacterial effect than iron oxide nanoparticles without propolis [33,40].

The combination of silver and gold zinc oxide nanoparticles and propolis is effective as an antibacterial agent against both Gram-positive and Gram-negative bacteria [41,44]. The combination of silver-platinum nanoparticle propolis shows that the antibacterial activity of silver-platinum nanoparticles is directly proportional to the nanoparticle concentration [47,48].

Copper nanoparticle propolis (CuNPs) has good antibacterial activity [43].

Metallic nanoparticles are used directly [33,38,39–47,49,50,52,54,55], in composite form [7], in gel form [37], in meat packaging form [48], in wound sewing form [51], in combination with chloramphenicol [53], wound dressing, and wound healing [56,57] for wound treatment.

Propolis in metallic nanoparticle form has effective antibacterial properties against several types of pathogenic bacteria. Propolis in metallic nanoparticle (Zinc) form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in metallic nanoparticle (Zinc) form. ZnO—NP Propolis nanoemulsions with MIC 10 to 164.31 μg/mL are more effective than non-nano

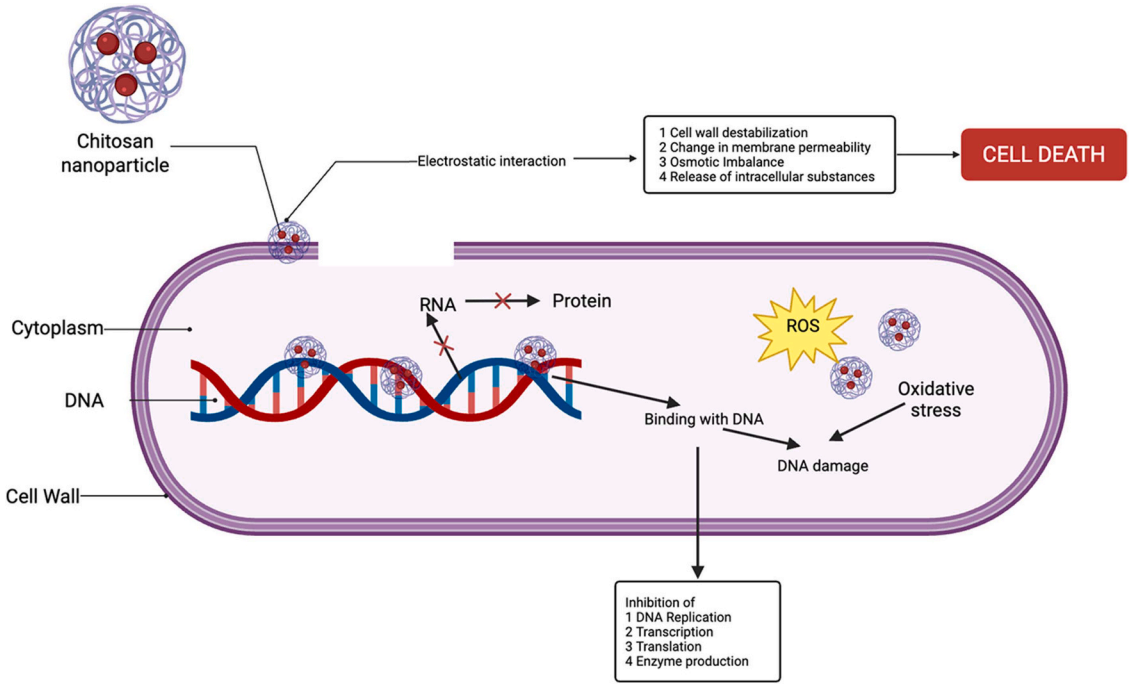

Fig. 6. Antibacterial mechanism of Chitosan Nanoparticle.

propolis with MIC 100 to 500 μg/mL [7,42,46]. Propolis in metallic nanoparticle (Silver) has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in metallic nanoparticle (Silver) form. Propolis nanoemulsions with MIC of 1.6 to 100 μg/mL are more effective than non-nano propolis with 155 μg/mL [39,41,45,47,49,52,55].

4.2. Chitosan nanoparticle

Chitosan is a natural carbohydrate polymer obtained by deacetylating chitin, the main compound found in crabs, lobsters, and shrimp shells [58]. Chitosan nanoparticles are drug delivery systems that can be combined with propolis [59]. The studies of chitosan nanoparticles have shown that chitosan nanoparticles (CNPs) have a more potent antibacterial action against gram-positive, gram--negative bacteria, and biofilms that are difficult to destroy [60]. The antibacterial activity of chitosan nanoparticles is attributed to their interactions with bacterial cell walls or cell membranes [58]. Its antibacterial mechanism can cause electrostatic interactions between positively charged chitosan nanoparticles and negatively charged bacterial cell membranes, this disrupts the integrity of the membrane, which causes leakage of intracellular components and bacterial cell death [60]. This interaction triggers common variations on the cell surface, leading to modifications in membrane permeability that sequentially trigger osmotic imbalance and release of intracellular substances, resulting in cell death [61,62]. Chitosan nanoparticles also have better antioxidant effects compared to those derived from herbal extracts, antioxidants from chitosan nanoparticles work by increasing the transition metal ion catalyst, breaking down peroxides, then inhibiting chain reactions, and blocking continuous hydrogen abstraction [60,63]. The mechanism of the antibacterial effect of chitosan nanoparticles propolis is illustrated in Fig. 6.

Based on the results in Table 1, propolis nanoparticles with chitosan nanoparticles were effective in inhibiting 10 types of bacteria (*E. coli, S. aureus, S. epidermidis, S. sciuri, Salmonella typhimurium, P. aeruginosa, biofilm E. faecalis, K. pneumonia,* L. *monocytogenes,* and *S. mutans*) [5,64–72].

The propolis chitosan nanoparticles exhibited a strong antibacterial effect against several bacteria with the highest resistance [64–66,72]. Propolis extracted using ethanol combined with chitosan showed statistically significant and greater antibacterial inhibition than propolis extracted without chitosan [5,65]. Chitosan nanoparticles combined with ethanol propolis extract and colistin showed potential antibacterial activity. This effect occurs because of the interaction between polycationic chitosan nanoparticles and the negative charges on the surface of bacterial cells, which disrupts the cell membrane, leading to leakage of intracellular compounds and cell death [67]. Chitosan-propolis nanoparticles not only directly inhibit the survival of bacteria but also show synergy with several synthetic antibiotics, namely ciprofloxacin, vancomycin, doxycycline, and rifampicin, indicating an effective treatment regimen. This will provide opportunities to overcome bacterial antibiotic resistance by reducing antibiotic treatment doses by at least four-fold in combination therapy [69].

Propolis chitosan nanoparticles are known to be directly usable [5,64,67,72], in edible coating form [65], in intracanal medicament form [66], in edible film form [68], can be combined with antibiotics [69], in pasta form [70], and in varnish form [71] for dental

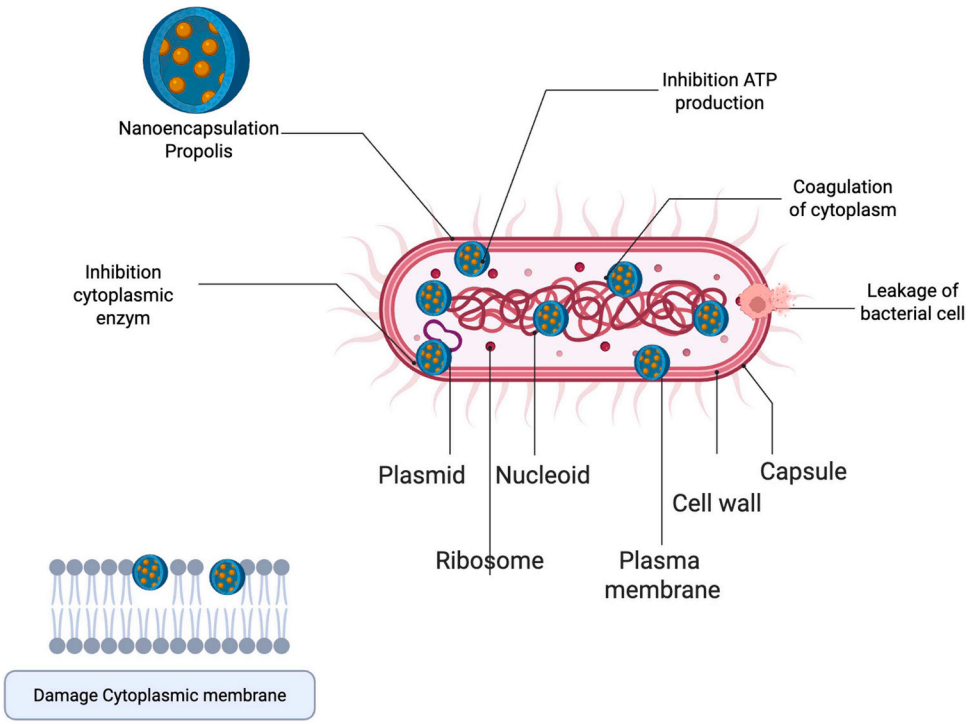

Fig. 7. Antibacterial mechanism of Nanoencapsulation.

care.

Propolis in chitosan nanoparticle form has effective antibacterial properties against several types of pathogenic bacteria (*E. coli, S. aureus, S. epidermidis, S. sciuri, S. typhimurium, P. aeruginosa, biofilm E. faecalis, K. pneumonia,* L. *monocytogenes,* and *S. mutans*) [5,64–72]. Propolis in chitosan nanoparticle form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in chitosan nanoparticle form. Chitosan nanoparticle propolis with MIC 2 to 230 μg/mL are more effective than non-chitosan nanoparticle propolis with MIC 250 μg/mL [5,66,67]. Chitosan nanoparticle propolis form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to antibiotics. Chitosan nanoparticle propolis with MIC of 25 to 30 mg/mL are more effective than antibiotics with MIC 37.5 to 47.5 mg/mL [65].

4.3. Nanoencapsulation

Nanoparticles with encapsulation result in a small size, large surface area, and protection, with high bioavailability compared to large-sized particles [73]. Nanoencapsulation can be achieved by emulsification, high-pressure homogenization, evaporation, spray drying, sonication, high-speed stirring, microemulsion, and ball milling [74]. The mechanism of action of nanoencapsulated propolis against its antibacterial activity begins with its entry into microbial cells, followed by the inhibition of DNA synthesis and bacterial ribosomal activity, and ultimately inhibiting protein metabolism [75]. The mechanism of the antibacterial effect of the nanoencapsulation is illustrated in Fig. 7.

Based on the results in Table 1, it is known that nanoencapsulation of propolis is effective in inhibiting five types of bacteria (*E. coli, S. aureus, P. vulgaris, C. diversus,* and *S. enterica*) [16,76–78].

Propolis nanoencapsulation exhibits good inhibitory activity against several pathogenic bacteria at low concentration ratios [16]. The antioxidant and antibacterial activities of red propolis encapsulated in nanoparticles showed good performance in inhibiting various types of bacteria as well as increasing the surface area of dispersion [76]. Propolis processed by nanoencapsulation showed the highest antibacterial activity against several pathogenic bacteria compared to pure propolis [77,78]. The nanoencapsulation of propolis in this study was directly applicable [16,76,77] and the wound healing form [78] for wound care.

Propolis in nanoencapsulation form has effective antibacterial properties against several types of pathogenic bacteria (*E. coli, S. aureus, P. vulgaris, C. diversus,* and *S. enterica*) [16,76–78]. Propolis in nanoencapsulation form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in nanoencapsulation form. Nanoencapsulation propolis with MIC 100 to 375 μg/mL are more effective than non nanoencapsulation form [76,78].

4.4. Solid lipid nanoparticle (SLN)

Solid Lipid Nanoparticles (SLNs) are stable colloidal carriers composed of solid lipids with a size range of 10–1000 nm, consisting of lipids dispersed in an aqueous phase. These nanoparticles are formed from a solid lipid core stabilized by surfactants and contain dissolved or dispersed drugs [79–81]. The rigidity of the lipid core is an important parameter that determines the drug release rate. These nanoparticles have low toxicity [79]. The mechanism of action of Solid Lipid Nanoparticles (SLN) of propolis against its antibacterial activity involves the prevention of biofilm formation, inhibition of ATPase activity, damage of bacterial membranes, and disruption of bacterial division, ultimately leading to membrane damage [80]. In addition, Propolis SLN (PSLN) has an antioxidant effect that is not as good as propolis ethanolic extract (PEE), because the structure of PSLN resembles lipid particles. The antioxidant

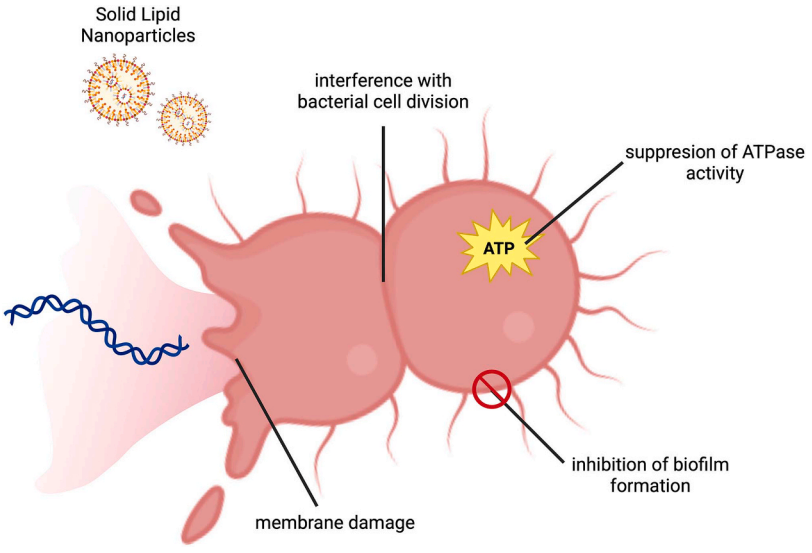

Fig. 8. Antibacterial mechanism of Solid Lipid Nanoparticle (SLN).

performance of PSLN in the ABTS test is weaker compared to PEE. ABTS is soluble in water and organic solvents, while DPPH is only soluble in organic solvents. Therefore, PEE shows better results due to the presence of more hydrophilic and lipophilic compounds compared to PSLN [80]. The mechanism of the antibacterial effect of solid lipid nanoparticles (SLN) is illustrated in Fig. 8.

Based on the analysis results in Table 1, propolis nanoparticles of the Solid Lipid Nanoparticle (SLN) type were effective in inhibiting four types of bacteria (*E. coli, S. aureus, B. subtilis,* and *P. aeruginosa*) [80]. Ethanol propolis extract and propolis Solid Lipid Nanoparticles (PSLN) were effective against the inhibition of various types of bacteria [80]. Solid lipid nanoparticles (SLN) are used directly [80].

Propolis in Solid Lipid Nanoparticles (SLN) form has effective antibacterial properties against several types of pathogenic bacteria (*E. coli, S. aureus, B. subtilis,* and *P. aeruginosa*) [80]. Propolis in Solid Lipid Nanoparticles (SLN) form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in Solid Lipid Nanoparticles (SLN) form. Propolis SLN with 0.125 ± 0.008 to 1 mg/mL are more effective than non SLN form with MIC 0.125 ± 0.029 to 2 mg/mL [80].

4.5. Polymer nanoparticle

Polymer nanoparticles are particles with a size range of 1–1000 nm and can be loaded with active compounds that are either trapped inside or adsorbed onto the surface of the polymer core [82]. Polymer nanoparticles have great potential for targeted drug delivery in the treatment of several diseases [82]. Polymer nanoparticles can penetrate and disrupt microbial cell membranes through abrasiveness that damages bacterial cell membranes, induces intracellular antibacterial effects such as the production of reactive oxygen species (ROS), interacts with DNA/RNA and proteins, inactivates enzymes, enhances efflux by overexpressing efflux pumps, decreases cell permeability, releases metal ions, and inhibits biofilm formation[83,84]. The mechanism underlying the antibacterial effect of the polymer is illustrated in Fig. 9.

Based on the analysis results in Table 1, propolis nanoparticles of the polymer nanoparticle type are effective in inhibiting seven types of bacteria (*S. aureus, K. pneumonia, E. coli, P. aeruginosa, A. baumannii, E. faecalis,* and *S. mutans*) and 1 type of fungi (C. Albicans) [84,85].

Polymer nanoparticle propolis has a significant inhibitory effect on the growth of several types of bacteria [85]. Propolis polymer nanoparticles can be used as root canal sealers. Sealers containing propolis polymer nanoparticles have shown antibacterial activity against several types of bacteria [84]. Polymer nanoparticle propolis is used for wound healing [85] and root canal sealer forms [84] for dental and oral care.

Propolis in polymer form has effective antibacterial properties against several types of pathogenic bacteria (*S. aureus, K. pneumonia, E. coli, P. aeruginosa, A. baumannii, E. faecalis,* and *S. mutans*) and 1 type of fungi (C. Albicans) [84,85]. Propolis in polymer form has a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to propolis not in polymer form. Nanoparticle polymer propolis with 100 to 250 μg/mL are more effective than non nanoencapsulation form with MIC 1250 μg/mL [84,85]. Propolis in polymer form has not a higher Minimum Inhibitory Concentration (MIC) against bacteria compared to antibiotic. Nanoparticle polymer propolis with 100 to 250 μg/mL were not more effective than antibioticm with MIC 1 μg/mL [84,85].

5. Discussion

In this study, the effectiveness of propolis nanoparticles was evaluated based on the frequency of technology use and the number of

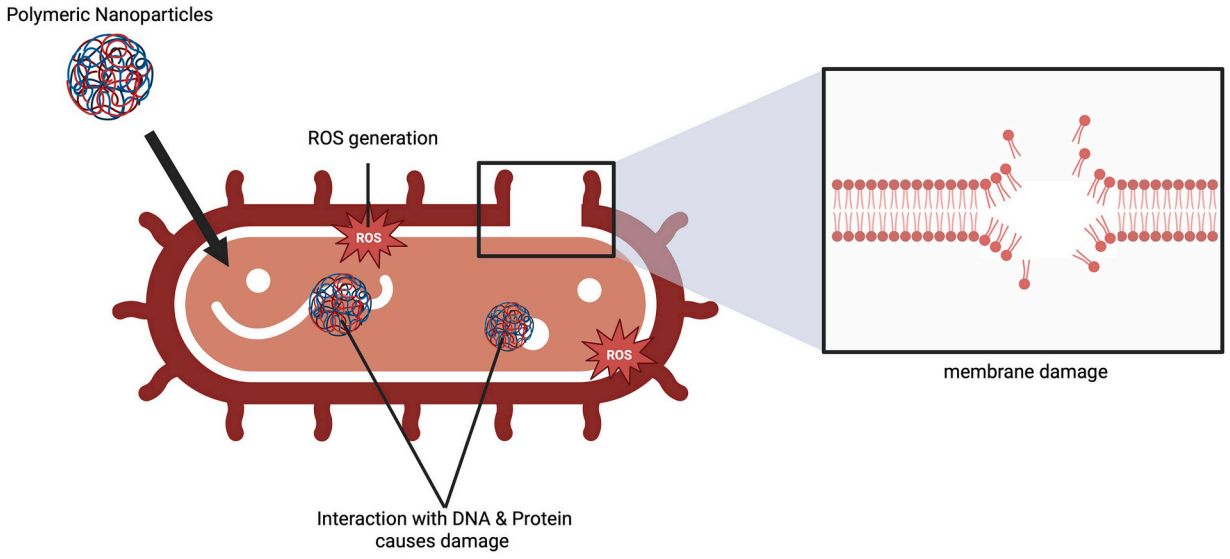

Fig. 9. Antibacterial mechanism of Polymer Nanoparticle.

bacterial species inhibited. Based on the number of technologies used, nanoparticles in the form of nanoemulsions are more applicable than nanoparticles in the form of NLC, nanosheets, nanoencapsulation, Solid Lipid Nanoparticles (SLN), and polymer nanoparticles. Nanoemulsions can be applied in three forms: directly, made into resin composites, and as bioceramic sealers (in dental treatment). Propolis nanoparticles in the form of NLC, nanosheets, and SLN can only be directly applied.

The application of propolis nanoparticles in the form of metallic nanoparticles is more widespread than in all other forms of propolis nanoparticles. Metallic propolis nanoparticles can be applied in eight ways: directly made into composites, gels, meat packaging, wound sewing, wound dressings, wound healing, and combined with chloramphenicol to enhance antibacterial activity.

Chitosan nanoparticle propolis can be applied in seven forms: directly used, made into edible coatings, edible films, intracanal medicaments, combined with antibiotics, and made into pastes and varnishes for dental and oral care. Chitosan nanoparticle propolis has more applications than nanoemulsions, Nanostructured Lipid Carriers, nanosheets, nanoencapsulation, Solid Lipid Nanoparticles (SLN), and polymer nanoparticles.

Nanoencapsulation of propolis can be applied in two ways: directly or in the form of wound healing. The application of nanoencapsulated propolis is more extensive than the application of Nanostructured Lipid Carriers, nanosheets, and Solid Lipid Nanoparticles (SLN), where SLN can only be applied in their own SLN form.

Polymer nanoparticle propolis can be applied in two ways: for wound healing and as a root canal sealer, which is more effective than Nanostructured Lipid Carriers, nanosheets, and Solid Lipid Nanoparticles (SLN).

The effectiveness of propolis nanoparticles, as reviewed by the number of bacterial species they can inhibit, showed that nanoemulsions can inhibit up to five types of bacteria (*P. aeruginosa, S. mutans, S. sanguinis, L. acidophilus,* and *E. faecalis*). The antibacterial properties of nanoemulsions are more effective than those of NLC, which can inhibit two types of bacteria (*B. subtilis* and *S. aureus*), and nanosheets that can only inhibit two types of bacteria (*S. aureus, E. coli*).

The antibacterial properties of propolis in the form of metallic nanoparticles have the highest inhibitory effect compared to all other nanoparticle forms, being able to inhibit 19 types of bacteria (*E. coli, S. typhi, P. aeruginosa, B. cereus, S. aureus, biofilm P. gingivalis, K. pneumoniae, A. baumannii, E. faecalis, B. subtilitis, S. pyogenes, S. enterica, S. sciuri, S. enterica typhimurium, S. epidermidis, S. marcesens, L. monocytogenes, S. enteritidis,* and *P. vulgaris*).

The antibacterial properties of propolis chitosan nanoparticles can inhibit 10 types of bacteria (*E. coli, S. aureus, S. epidermidis, S. sciuri, S. typhimurium, P. aeruginosa, biofilm E. faecalis, K. pneumonia, L. monocytogenes,* and *S. mutans*). Chitosan nanoparticle propolis has more effective antibacterial properties than nanoemulsions, nanosheets, Nanostructured Lipid Carriers (NLCs), nanoencapsulation, Solid Lipid Nanoparticles (SLNs), and polymer nanoparticles.

Nanoencapsulation was effective as an antibacterial agent against five types of bacteria (*E. coli, S. aureus, P. vulgaris, C. diversus,* and *S. enterica*). Nanoencapsulation is more effective than some types of nanoparticles, such as Nanostructured Lipid Carriers (NLCs), nanosheets, and Solid Lipid Nanoparticles (SLNs), and has the same bacterial inhibitory effectiveness as nanoemulsions.

Solid Lipid Nanoparticles (SLNs) are effective at inhibiting four types of bacteria (*E. coli, S. aureus, B. subtilis,* and *P. aeruginosa*). SLN are more effective than some types of nanoparticles, such as Nanostructured Lipid Carriers (NLC) and nanosheets.

Polymer nanoparticle propolis has effective antibacterial activity against seven types of bacteria (*S. aureus, K. pneumonia, E. coli, P. aeruginosa, A. baumannii, E. faecalis,* and *S. mutans*). Polymer nanoparticle propolis has good antibacterial effectiveness compared with nanoemulsions, Nanostructured Lipid Carriers (NLCs), nanosheets, and Solid Lipid Nanoparticles (SLNs).

Propolis treatment made into nanoparticle preparations in various forms can increase the Minimum Inhibitory Concentration (MIC) of bacteria higher than those without nanoparticle form. However, propolis treatment into nanoparticles has a lower effectiveness in inhibiting bacteria compared to antibiotics, except for the chitosan nanoparticle form of propolis. Chitosan nanoparticle propolis showed better MIC data compared to antibiotics.

6. Challenges and future perspectives

Based on the results of this study, it is known that there are already quite a few applications of nanoparticles available, but their effectiveness as antibacterial agents in each form has not been widely reported. The wide variety of technologies and lack of information about their effectiveness make the application of nanoparticles, especially as antibacterial agents, less practical.

To overcome this, it is necessary to study and create effective, safe, and easy-to-use nanoparticle products. In the field of health, nanoparticle products are expected to be combined with other treatments to make them more effective in treating diseases. Besides being used in the pharmaceutical and health fields, the use of propolis nanoparticles is also expected to be developed for other areas of human well-being, such as antiviral, antifungal, and anticancer properties of propolis nanoparticles.

7. Conclusion

Based on the analysis conducted, it was found that metallic nanoparticle propolis had the most applications compared with other nanoparticles. The number of applications for propolis nanoparticles, in order, are as follows: 1) metallic nanoparticles, 2) chitosan nanoparticles, 3) nanoemulsions, 4) polymer nanoparticles, 5) nanoencapsulation, 6) NLC, nanosheets, and SLN. In terms of the number of bacteria inhibited by nanoparticles, propolis in the form of metallic nanoparticles had the highest ability to inhibit most types of bacteria. The nanoparticles that inhibited most bacteria, in order, were as follows: 1) metallic nanoparticles, 2) chitosan nanoparticles, 3) polymer nanoparticles, 4) nanoemulsions, 5) nanoencapsulation, 6) SLN, 7) nanosheets, and NLC. Propolis treatment made into nanoparticle preparations in various forms can increase the Minimum Inhibitory Concentration (MIC) of bacteria higher than those without nanoparticle form. However, propolis treatment into nanoparticles has a lower effectiveness in inhibiting bacteria

compared to antibiotics, except for the chitosan nanoparticle form of propolis. Chitosan nanoparticle propolis showed better MIC data compared to antibiotics.

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CRediT authorship contribution statement

Ammar Fadhil: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sriwidodo:** Writing – review & editing, Validation, Supervision. **Khaled M. Elamin:** Writing – review & editing, Validation. **Ahmed Fouad Abdelwahab Mohammed:** Writing – review & editing, Validation, Supervision. **Safwat A Mahmoud:** Writing – review & editing, Supervision. **Nasrul Wathoni:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M.A. Malla, A. Dubey, A. Kumar, S. Yadav, A. Hashem, E.F.A. Allah, Exploring the human microbiome: the potential future role of next-generation sequencing in disease diagnosis and treatment, Front. Media S.A (2019), https://doi.org/10.3389/fimmu.2018.02868.
[2] J. Soni, S. Sinha, R. Pandey, Understanding bacterial pathogenicity: a closer look at the journey of harmful microbes, Front. Media SA (2024), https://doi.org/10.3389/fmicb.2024.1370818.
[3] A. Aulia Putri, Y. Ahda, D. Hilda Putri, and A. Achyar, "Optimization of pathogenic bacterial DNA isolation in PCR-based river water samples optimasi isolasi DNA bakteri patogen pada sampel air sungai berbasis PCR," 2023.
[4] N. Zullkiflee, H. Taha, A. Usman, Propolis: Its Role and Efficacy in Human Health and Diseases, MDPI, Sep. 01, 2022, https://doi.org/10.3390/molecules27186120.
[5] A. Vaseghi, R.A. Parchin, K.R. Chamanie, M. Herb, H. Maleki, M. Sadeghizadeh, Encapsulation of propolis extracted with methylal in the chitosan nanoparticles and its antibacterial and cell cytotoxicity studies, BMC Complement Med. Ther. 24 (1) (Dec. 2024), https://doi.org/10.1186/s12906-024-04472-8.
[6] S.I. Anjum, et al., Composition and Functional Properties of Propolis (bee glue): A review, Elsevier B.V, Nov. 01, 2019, https://doi.org/10.1016/j.sjbs.2018.08.013.
[7] S.A. Salama, et al., Novel composite of nano zinc oxide and nano propolis as antibiotic for antibiotic-resistant bacteria: a promising approach, Sci. Rep. 14 (1) (Dec. 2024), https://doi.org/10.1038/s41598-024-70490-8.
[8] S. Zaki-Germi, D. Afshar, A. Akbari, N. Nikfarjam, Multifunctional bionanocomposite hydrogels based on gelatin methacrylate and polyphenolic 2D nanoparticles Decorated with antimicrobial Bis(imidazolium)-based ionic liquids, Compos. Sci. Technol. 262 (Mar. 2025), https://doi.org/10.1016/j.compscitech.2025.111059.
[9] S. Suryono, et al., Potential of 10% propolis-based toothpaste on the inhibition of biofilm-forming bacteria growth in vitro, Pharmacia 71 (2024) 1–7, https://doi.org/10.3897/pharmacia.71.e118072.
[10] S. Kazemi, et al., Propolis Nanoemulsion Enhance the Antimicrobial Effect on Multidrug-Resistant Strains of Pseudomonas aeruginosa in Combination with Ciprofloxacin, Nat. Prod. Commun. 19 (9) (Sep. 2024), https://doi.org/10.1177/1934578X241284006.
[11] P.M. Kustiawan, P.H. Syaifie, K.A.A.K. Siregar, D. Ibadillah, E. Mardliyati, New Insights of Propolis Nanoformulation and Its Therapeutic Potential in Human Diseases, International Association of Physical Chemists, 2024, https://doi.org/10.5599/admet.2128.
[12] U. Subbiah, S. Elango, R. Jayesh, Herbals and green synthesized nanoparticles in dentistry. Nanobiomaterials in Clinical Dentistry, Elsevier, 2019, pp. 617–646, https://doi.org/10.1016/B978-0-12-815886-9.00025-5.
[13] S. Martinotti, G. Bonsignore, E. Ranzato, Propolis: A Natural Substance with Multifaceted Properties and Activities, Multidisciplinary Digital Publishing Institute (MDPI), Feb. 01, 2025, https://doi.org/10.3390/ijms26041519.
[14] O. Afzal, et al., Nanoparticles in Drug Delivery: From History to Therapeutic Applications, MDPI, Dec. 01, 2022, https://doi.org/10.3390/nano12244494.
[15] N.A.E. Hagras, et al., The powerful synergistic effect of spiramycin/propolis loaded chitosan/alginate nanoparticles on acute murine toxoplasmosis, PLoS Negl. Trop. Dis. 16 (3) (2022), https://doi.org/10.1371/journal.pntd.0010268.
[16] B. Subaşı-Zarbaliyev, G. Kutlu, and F. Tornuk, "Polyvinyl alcohol nanoparticles loaded with propolis extract: fabrication, characterization and antimicrobial activity," 2023, doi: 10.5599/adme.
[17] N.R. Amalia, et al., Propolis nanoemulsion extract from celebes stingless bee (Tetragonula biroi) phytochemistry and antibacterial analysis to periodontopathogen bacteria, J. Oral Biol. Craniofac. Res. 15 (3) (May 2025) 576–584, https://doi.org/10.1016/j.jobcr.2025.03.013.
[18] K. Gurpreet, S.K. Singh, Review of nanoemulsion formulation and characterization techniques [Online]. Available: www.ijpsonline.com, 2018.
[19] S. Begum JP, et al., Antimicrobial Nanoemulsion: A futuristic Approach in Antibacterial Drug Delivery System, Elsevier B.V., Jul. 01, 2024, https://doi.org/10.1016/j.jscs.2024.101896.
[20] F. Kazemi, A. Divsalar, A.A. Saboury, Structural analysis of the interaction between free, glycated and fructated hemoglobin with propolis nanoparticles: a spectroscopic study, Int. J. Biol. Macromol. 109 (Apr. 2018) 1329–1337, https://doi.org/10.1016/j.ijbiomac.2017.11.143.
[21] C. Oliveira, C. Coelho, J.A. Teixeira, P. Ferreira-Santos, C.M. Botelho, Nanocarriers As Active Ingredients Enhancers in the Cosmetic Industry—The European and North America Regulation Challenges, MDPI, Mar. 01, 2022, https://doi.org/10.3390/molecules27051669.
[22] H.M. Tran, C.Y. Yang, T.H. Wu, F.L. Yen, Liposomes encapsulating morin: investigation of physicochemical properties, dermal absorption improvement and anti-aging activity in PM-Induced Keratinocytes, Antioxidants 11 (6) (Jun. 2022), https://doi.org/10.3390/antiox11061183.

[23] Z. Imani, A. Sodagar, M. Pourhajibagher, A.H. Nader, A. Bahador, Evaluation of antibacterial effect of the orthodontic composite containing propolis nanoparticles in rat as an animal model, Folia Med. (Plovdiv) 65 (1) (2023) 131–139, https://doi.org/10.3897/folmed.65.e67782.

[24] A. Parolia, et al., Effect of propolis nanoparticles against enterococcus faecalis biofilm in the root canal, Molecules 26 (3) (Feb. 2021), https://doi.org/10.3390/molecules26030715.

[25] N. Wahyuni, N. Yanti, T. Abidin, W. Prasetia, D. Suryanto, The effect of addition 5% propolis nanoparticles in epoxy resin and bioceramic sealers on the growth of enterococcus faecalis atcc 29212 and the dentinal tubular penetration: in vitro, Int. J. Appl. Pharm. 15 (4) (Jul. 2023) 99–105, https://doi.org/10.22159/ijap.2023v15i4.47486.

[26] A. Chinsriwongkul, et al., Nanostructured lipid carriers (NLC) for parenteral delivery of an anticancer drug, AAPS PharmSciTech 13 (1) (Mar. 2012) 150–158, https://doi.org/10.1208/s12249-011-9733-8.

[27] M. Rohmah, S. Raharjo, C. Hidayat, R. Martien, Formulasi dan Stabilitas Nanostructured Lipid Carrier dari Campuran Fraksi Stearin dan Olein Minyak Kelapa Sawit, J. Apl. Teknol. Pangan 8 (1) (Feb. 2019), https://doi.org/10.17728/jatp.3722.

[28] R. Rabima and A. Oktamauri, "Karakterisasi & aktivitas antibakteri dari kurkumin-nanostructured lipid carrier characterization & antibacterial activity of curcumin-nanostructured lipid carrier," 2018.

[29] O.M. Elkhateeb, M.E.I. Badawy, A.E. Noreldin, H.M. Abou-Ahmed, M.H. El-Kammar, H.A. Elkhenany, Comparative evaluation of propolis nanostructured lipid carriers and its crude extract for antioxidants, antimicrobial activity, and skin regeneration potential, BMC Complement Med. Ther. 22 (1) (Dec. 2022), https://doi.org/10.1186/s12906-022-03737-4.

[30] S. Zaki-Germi, R. Taghizadeh-Tabarsi, S. Akbari-Birgani, H. Aghahosseini, N. Nikfarjam, Propolis polyphenol nanosheet for synergistic cancer chemo-photothermal therapy, Colloids Surf. Physicochem. Eng. Asp. 695 (Aug. 2024), https://doi.org/10.1016/j.colsurfa.2024.134262.

[31] T. Du, et al., Antibacterial activity of manganese dioxide nanosheets by ros-mediated pathways and destroying membrane integrity, Nanomaterials 10 (8) (Aug. 2020) 1–14, https://doi.org/10.3390/nano10081545.

[32] V. Mody, R. Siwale, A. Singh, H. Mody, Introduction to metallic nanoparticles, J. Pharm. Bioallied Sci. 2 (4) (2010) 282, https://doi.org/10.4103/0975-7406.72127.

[33] G.H. Matar, M. Andac, Green synthesis of iron oxide nanoparticles using brown Egyptian propolis extract for evaluation of their antibacterial activity and degradation of dyes, Inorg. Chem. Commun. 153 (Jul. 2023), https://doi.org/10.1016/j.inoche.2023.110889.

[34] A.M. Ealias, M.P. Saravanakumar, A review on the classification, characterisation, synthesis of nanoparticles and their application, in: IOP Conference Series: Materials Science and Engineering, Institute of Physics Publishing, Dec. 2017, https://doi.org/10.1088/1757-899X/263/3/032019.

[35] M. Salavati-Niasari, F. Davar, N. Mir, Synthesis and characterization of metallic copper nanoparticles via thermal decomposition, Polyhedron 27 (17) (Nov. 2008) 3514–3518, https://doi.org/10.1016/j.poly.2008.08.020.

[36] E. Sánchez-López, et al., Metal-based Nanoparticles As Antimicrobial agents: An overview, MDPI AG, Feb. 01, 2020, https://doi.org/10.3390/nano10020292.

[37] H.S. Zayed, S. Saleh, A.E. Omar, A.K. Saleh, A. Salama, E. Tolba, Development of collagen–chitosan dressing gel functionalized with propolis–zinc oxide nanoarchitectonics to accelerate wound healing, Int. J. Biol. Macromol. 261 (Mar. 2024), https://doi.org/10.1016/j.ijbiomac.2024.129665.

[38] M. Hedayatipanah, L. Gholami, A. Farmany, M.Y. Alikhani, A. Hooshyarfard, F.S. Hashemiyan, Green synthesis of silver nanoparticles and evaluation of their effects on the Porphyromonas gingivalis bacterial biofilm formation, Clin. Exp. Dent. Res. 10 (3) (Jun. 2024), https://doi.org/10.1002/cre2.887.

[39] Z. Karimitabar, A. Farmani, M. Azimzadeh, M.S. Alikhani, M.Moghadam Shakib, M.Y. Alikhani, The antimicrobial activity of propolis ethanolic extract and silver nanoparticles synthesized by green method on gram-positive and negative bacteria, Avicenna J. Clin. Microbiol. Infect. 10 (4) (Dec. 2023) 131–136, https://doi.org/10.34172/ajcmi.3514.

[40] S.O. Ukanwa, E. Özgör, Synthesis of iron oxide nanoparticle using propolis from northern cyprus and evaluation of its antibacterial, anticancer potential on MDA-MB 231 cells, J. Chem. Soc. Pak. 45 (4) (Aug. 2023) 336–344, https://doi.org/10.52568/001288/JCSP/45.04.2023.

[41] A.S. Abdelsattar, et al., The promising antibacterial and anticancer activity of green synthesized zinc nanoparticles in combination with silver and gold nanoparticles, J. Inorg. Organomet. Polym. Mater. 33 (7) (Jul. 2023) 1868–1881, https://doi.org/10.1007/s10904-023-02614-y.

[42] M.S. Osman, et al., Effective inhibition of waterborne and fungal pathogens using ZnO nanoparticles prepared from an aqueous extract of propolis: optimum biosynthesis, characterization, and antimicrobial activity, Appl. Nanosci. (Switz.) 13 (6) (Jun. 2023) 4515–4526, https://doi.org/10.1007/s13204-022-02726-w.

[43] A. Al-Shammari, Q.A. Ismael, M.S. Ali, O.A. Imran, Green synthesis and characterization of copper nano-particles with propolis and their potential inhibitory effect on uropathogenic E.coli, Rev. Latinoam. Hipertens. 18 (8) (2023) 383–393, https://doi.org/10.5281/zenodo.10027867.

[44] N. Rezk, A.S. Abdelsattar, S. Makky, A.H. Hussein, A.G. Kamel, A. El-Shibiny, New formula of the green synthesised Au@Ag core@shell nanoparticles using propolis extract presented high antibacterial and anticancer activity, AMB Express 12 (1) (Dec. 2022), https://doi.org/10.1186/s13568-022-01450-6.

[45] P. Mendez-Pfeiffer, et al., Biosynthesis of silver nanoparticles using seasonal samples of sonoran desert propolis: evaluation of its antibacterial activity against clinical isolates of multi-drug resistant bacteria, Pharmaceutics 14 (9) (Sep. 2022), https://doi.org/10.3390/pharmaceutics14091853.

[46] A.A. Obaid, S.S. Al-Ghabban, R. Al-Hussain, Appraising antioxidant and antibacterial activities of zinc oxide nanoparticles synthesized biologically by Iraqi propolis, Chem. Methodol. 6 (5) (May 2022) 366–371, https://doi.org/10.22034/chemm.2022.332390.1448.

[47] R.N.E. Tiri, F. Gulbagca, A. Aygun, A. Cherif, F. Sen, Biosynthesis of Ag–Pt bimetallic nanoparticles using propolis extract: antibacterial effects and catalytic activity on NaBH4 hydrolysis, Environ. Res. 206 (Apr. 2022), https://doi.org/10.1016/j.envres.2021.112622.

[48] S. Roy, R. Priyadarshi, J.W. Rhim, Development of multifunctional pullulan/chitosan-based composite films reinforced with ZnO nanoparticles and propolis for meat packaging applications, Foods 10 (11) (Nov. 2021), https://doi.org/10.3390/foods10112789.

[49] A.S. Abdelsattar et al., "antibiotics the synergistic effect of biosynthesized silver nanoparticles and phage ZCSE2 as a novel approach to combat multidrug-resistant salmonella enterica," 2021, doi: 10.3390/antibiotics.

[50] M.S. Al-Fakeh, M. Gassoumi, M. Rabhi, S. Othman, M. Omer, Biosynthesis and characterization of Saudi propolis-mediated silver nanoparticles and their biological properties, Open Phys. 19 (1) (Jan. 2021) 753–757, https://doi.org/10.1515/phys-2021-0091.

[51] T. Baygar, Characterization of silk sutures coated with propolis and biogenic silver nanoparticles (AgNPs); an eco-friendly solution with wound healing potential against surgical site infections (SSIs), Turk. J. Med. Sci. 50 (1) (2020) 258–266, https://doi.org/10.3906/sag-1906-48.

[52] V.T. Barbosa, et al., Biogenic synthesis of silver nanoparticles using Brazilian propolis, Biotechnol. Prog. 35 (6) (Nov. 2019), https://doi.org/10.1002/btpr.2888.

[53] S. El-Guendouz, et al., Magnetite nanoparticles functionalized with propolis against methicillin resistant strains of Staphylococcus aureus, J. Taiwan Inst. Chem. Eng. 102 (Sep. 2019) 25–33, https://doi.org/10.1016/j.jtice.2019.05.018.

[54] M. Popova, et al., Nanostructured silver silica materials as potential propolis carriers, Microporous Mesoporous Mater. 263 (Jun. 2018) 28–33, https://doi.org/10.1016/j.micromeso.2017.11.043.

[55] E. Adomavičiute, et al., Formation and investigation of electrospun PLA materials with propolis extracts and silver nanoparticles for biomedical applications, J. Nanomater. 2017 (2017), https://doi.org/10.1155/2017/8612819.

[56] E. Adomavičiute, S. Stanys, M. Žilius, V. Juškaite, A. Pavilonis, V. Briedis, Formation and biopharmaceutical characterization of electrospun PVP mats with propolis and silver nanoparticles for fast releasing wound dressing, Biomed. Res. Int. 2016 (2016), https://doi.org/10.1155/2016/4648287.

[57] S. Patil, N. Desai, K. Mahadik, A. Paradkar, Can green synthesized propolis loaded silver nanoparticulate gel enhance wound healing caused by burns? Eur. J. Integr. Med. 7 (3) (2015) 243–250, https://doi.org/10.1016/j.eujim.2015.03.002.

[58] M. Chandrasekaran, K.D. Kim, S.C. Chun, Antibacterial Activity of Chitosan nanoparticles: A review, MDPI AG, Sep. 01, 2020, https://doi.org/10.3390/PR8091173.

[59] Y. Dang, J. Guan, Nanoparticle-based Drug Delivery Systems For Cancer Therapy, KeAi Communications Co, Jan. 01, 2020, https://doi.org/10.1016/j.smaim.2020.04.001.

[60] M. Imath, C. Ragavendran, C. Kamaraj, R.K. Raja, G. abdi, Eco-friendly synthesis of chitosan NPs from Fioria vitifolia (L.) L: potential to antibacterial, antioxidant, cytotoxicity properties of HepG2 cells and their evaluation of safety on Zebrafish embryo, Results Eng. 25 (Mar. 2025), https://doi.org/10.1016/j.rineng.2025.104076.
[61] F. Shahidi, J.K.V. Arachchi, Y.J. Jeon, Food Applications of Chitin and Chitosans, Elsevier Ltd, 1999, https://doi.org/10.1016/S0924-2244(99)00017-5.
[62] D. Raafat, K. Von Bargen, A. Haas, H.G. Sahl, Insights into the mode of action of chitosan as an antibacterial compound, Appl. Environ. Microbiol. 74 (12) (Jun. 2008) 3764–3773, https://doi.org/10.1128/AEM.00453-08.
[63] M.J. Moreno-Vásquez, et al., Characterization of epigallocatechin-gallate-grafted chitosan nanoparticles and evaluation of their antibacterial and antioxidant potential, Polym. (Basel) 13 (9) (May 2021), https://doi.org/10.3390/polym13091375.
[64] A.S. Abdelsattar, A.Y. Yakoup, Y. khaled, A. Safwat, A. El-Shibiny, The synergistic effect of using bacteriophages and chitosan nanoparticles against pathogenic bacteria as a novel therapeutic approach, Int. J. Biol. Macromol. 228 (Feb. 2023) 374–384, https://doi.org/10.1016/j.ijbiomac.2022.12.246.
[65] D.M. Youssef, F.A. Alshubaily, A.A. Tayel, M.A. Alghuthaymi, M.A. Al-Saman, Application of nanocomposites from bees products and nano-selenium in edible coating for catfish fillets biopreservation, Polym. (Basel) 14 (12) (Jun. 2022), https://doi.org/10.3390/polym14122378.
[66] A. Parolia, H. Kumar, S. Ramamurthy, F. Davamani, A. Pau, Effectiveness of chitosan-propolis nanoparticle against Enterococcus faecalis biofilms in the root canal, BMC Oral Health 20 (1) (Dec. 2020), https://doi.org/10.1186/s12903-020-01330-0.
[67] Y.S.R. Elnaggar, B.H. Elwakil, S.S. Elshewemi, M.Y. El-Naggar, A.A. Bekhit, Z.A. Olama, Novel Siwa propolis and colistin-integrated chitosan nanoparticles: elaboration; in vitro and in vivo appraisal, Nanomedicine 15 (13) (Jun. 2020) 1269–1284, https://doi.org/10.2217/nnm-2019-0467.
[68] Z.N. Correa-Pacheco, S. Bautista-Baños, M. de L. Ramos-García, M. del C. Martínez-González, J. Hernández-Romano, Physicochemical characterization and antimicrobial activity of edible propolis-chitosan nanoparticle films, Prog. Org. Coat. 137 (Dec. 2019), https://doi.org/10.1016/j.porgcoat.2019.105326.
[69] T.H. Ong, E. Chitra, S. Ramamurthy, C.C.S. Ling, S.P. Ambu, F. Davamani, Cationic chitosan-propolis nanoparticles alter the zeta potential of S. Epidermidis, inhibit biofilm formation by modulating gene expression and exhibit synergism with antibiotics, PLoS One 14 (2) (Feb. 2019), https://doi.org/10.1371/journal.pone.0213079.
[70] A. del Carpio-Perochena, et al., Antibacterial properties of chitosan nanoparticles and propolis associated with calcium hydroxide against single- and multispecies biofilms: an in vitro and in situ study, J. Endod. 43 (8) (Aug. 2017) 1332–1336, https://doi.org/10.1016/j.joen.2017.03.017.
[71] M.O. Wassel, M.A. Khattab, Antibacterial activity against Streptococcus mutans and inhibition of bacterial induced enamel demineralization of propolis, miswak, and chitosan nanoparticles based dental varnishes, J. Adv. Res. 8 (4) (Jul. 2017) 387–392, https://doi.org/10.1016/j.jare.2017.05.006.
[72] T.H. Ong, et al., Chitosan-propolis nanoparticle formulation demonstrates anti-bacterial activity against Enterococcus faecalis biofilms, PLoS One 12 (3) (Mar. 2017), https://doi.org/10.1371/journal.pone.0174888.
[73] R. Vaidyanathan, K. Kalishwaralal, S. Gopalram, and S. Gurunathan, "Nanosilver-The burgeoning therapeutic molecule and its green synthesis," Nov. 2009. doi: 10.1016/j.biotechadv.2009.08.001.
[74] S.Mullick Chowdhury, G. Lalwani, K. Zhang, J.Y. Yang, K. Neville, B. Sitharaman, Cell specific cytotoxicity and uptake of graphene nanoribbons, Biomaterials 34 (1) (Jan. 2013) 283–293, https://doi.org/10.1016/j.biomaterials.2012.09.057.
[75] S. Yousefi, W. Weisany, S.E. Hosseini, M. Ghasemlou, Mechanisms of Nanoencapsulation to Boost the Antimicrobial Efficacy of Essential oils: A review, Elsevier B.V., May 01, 2024, https://doi.org/10.1016/j.foodhyd.2023.109655.
[76] L.F. Laís, et al., Antioxidant and antimicrobial activity of red propolis embedded mesoporous silica nanoparticles, Drug Dev. Ind. Pharm. 46 (7) (Jul. 2020) 1199–1208, https://doi.org/10.1080/03639045.2020.1782423.
[77] A.G. Hegazi, A.S. El-Houssiny, E.A. Fouad, Egyptian propolis 14: potential antibacterial activity of propolis-encapsulated alginate nanoparticles against different pathogenic bacteria strains, Adv. Nat. Sci.: Nanosci. Nanotechnol. 10 (4) (2019), https://doi.org/10.1088/2043-6254/ab52f4.
[78] S. Cavalu, P.M. Pasca, M. Brocks, Natural polymeric film encapsulating propolis nano-formulation for cutaneous wound healing [Online]. Available: http://www.revmaterialeplastice.ro, 2019.
[79] C. Loira-Pastoriza, J. Todoroff, R. Vanbever, Delivery Strategies For Sustained Drug Release in the Lungs, Elsevier B.V., Aug. 30, 2014, https://doi.org/10.1016/j.addr.2014.05.017.
[80] F. Shahab-Navaei, A. Asoodeh, Synthesis of optimized propolis solid lipid nanoparticles with desirable antimicrobial, antioxidant, and anti-cancer properties, Sci Rep 13 (1) (Dec. 2023), https://doi.org/10.1038/s41598-023-45768-y.
[81] M.R. Arabestani, et al., Solid Lipid Nanoparticles and Their Application in the Treatment of Bacterial Infectious Diseases, Elsevier Masson s.r.l, May 01, 2024, https://doi.org/10.1016/j.biopha.2024.116433.
[82] A. Zielinska, et al., Polymeric Nanoparticles: Production, Characterization, Toxicology and Ecotoxicology, MDPI AG, Aug. 01, 2020, https://doi.org/10.3390/molecules25163731.
[83] V.A. Spirescu, C. Chircov, A.M. Grumezescu, E. Andronescu, Polymeric Nanoparticles For Antimicrobial therapies: An up-To-Date Overview, MDPI AG, Mar. 01, 2021, https://doi.org/10.3390/polym13050724.
[84] I.A.A. Raheem, A.A. Razek, A.A. Elgendy, N.M. Saleh, M.I. Shaaban, F.K.A. El-Hady, Design, evaluation and antimicrobial activity of egyptian propolis-loaded nanoparticles: intrinsic role as a novel and naturally based root canal nanosealer, Int. J. Nanomed. 14 (2019) 8379–8398, https://doi.org/10.2147/IJN.S219577.
[85] S.E. Diab, N.A. Tayea, B.H. Elwakil, A.A.E.M. Gad, D.A. Ghareeb, Z.A. Olama, Novel amoxicillin-loaded sericin biopolymeric nanoparticles: synthesis, optimization, antibacterial and wound healing activities, Int. J. Mol. Sci. 23 (19) (Oct. 2022), https://doi.org/10.3390/ijms231911654.
[86] A. Parolia, et al., Effect of propolis nanoparticles against enterococcus faecalis biofilm in the root canal, Molecules 26 (3) (Feb. 2022), https://doi.org/10.3390/molecules26030715.
[87] M.O. Wassel, M.A. Khattab, Antibacterial activity against Streptococcus mutans and inhibition of bacterial induced enamel demineralization of propolis, miswak, and chitosan nanoparticles based dental varnishes, J. Adv. Res. 8 (4) (Jul. 2017) 387–392, https://doi.org/10.1016/j.jare.2017.05.006.
[88] N. Joudeh, D. Linke, Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists, BioMed Central Ltd (2022), https://doi.org/10.1186/s12951-022-01477-8.
[89] P. Tatli Seven, I. Seven, B. Gul Baykalir, S. Iflazoglu Mutlu, A.Z.M. Salem. Nanotechnology and nano-propolis in animal production and health: An overview, Taylor and Francis Ltd., 2018, https://doi.org/10.1080/1828051X.2018.1448726.