Int J Med Rev 2022 September;9(3): 333-343
doi 10.30491/IJMR.2021.309798.1222

INTERNATIONAL JOURNAL OF
MEDICAL
REVIEWS
Narrative Review

An Overview of Antibacterial Materials: Plants, Polymers, and Nanoparticles

Milad Sheydaei [1*], Shabnam Shahbazi-Ganjgah [2], Ebrahim Alinia-Ahandani [3]

[1] Faculty of Polymer Engineering, Sahand University of Technology, Tabriz, Iran
[2] Department of Polymer Engineering, Payame Noor University, Tehran, Iran
[3] Department of Biochemistry, Payame Noor University, Tehran, Iran

*** Corresponding Author:** Milad Sheydaei, Faculty of Polymer Engineering, Sahand University of Technology, Tabriz, Iran. E-mail: mi_sheydaei@sut.ac.ir

Received October 10, 2021; **Accepted** November 27, 2021; **Online Published** September 6, 2022

Abstract

With the change in human lifestyle due to the expansion of industry, climate change, deforestation, and pollution of oceans and surface waters, humans are more exposed to danger than ever before. In many countries, humans are affected by bacterial and fungal infections and even mosquito-related diseases such as lymphatic filariasis, malaria, and cellulitis. Many drugs are found in nature, which is why humans have been using plants as a valuable resource for thousands of years. Humans are extremely interested in using natural antibacterial compounds such as plant extracts and spices because they have their own characteristic flavor. Herbs were the basis of medicine in the past and also are widely used in countries such as China, India, and the Middle East. Plants are useful for supporting human health and some parts of the plant (flowers, leaves, stems, and roots) have medicinal activities such as analgesics, antispasmodics, and antimicrobials. With recent advances, polymers and nanoparticles have come to the help of medical cures. Polymers can be designed to be used in a variety of fields such as prosthesis, antibacterial and antifungal surfaces, drug carrier, gene delivery etc. Also, the nanoparticles due to their unique properties, have many applications in medicine such as cancer diagnosis, colorimetric detection of cancer cells, cancer imaging, antibacterial surfaces, and drug carrier. In this study, researches which have been conducted on plants, polymers, and nanoparticles antibacterial are reviewed.

Keywords: Antimicrobial Properties, Plants, Polymers, Nanoparticles

Introduction

After the exploration of penicillin and its introduction into clinical use, it revolutionized the treatment of infections caused by bacteria. This is while, but over the time one of the biggest recent global public health challenges is considered to be bacterial and fungal infections.[1,2] The high resistance of many gram-positive and gram-negative bacteria as well as fungi is relatively worrying, which can be intrinsic, adaptive or acquired.[3-6] In general, bacteria have a social life and can communicate with each other through signaling molecules and adapt their behavior at the population level, which has been proven in both gram-positive and gram-negative bacteria.[7] Research have shown that more than a billion people worldwide suffer from fungal infections each year, and over 1.6 million related deaths are being reported each year.[8,9] Among these, one of the most common causes of deadly fungal infections is *Aspergillus*, which despite significant advances in diagnosis and treatment, severe fungal diseases continues to be reported with high mortality, especially in immunocompromised patients with invasive infections.[10] In recent years, some multidrug-resistant gram-positive bacteria, including *Staphylococcus aureus*, *Streptococcus pneumoniae*, and *Enterococci*, have raised public health concerns.[11,12] Also, infections caused by gram-negative bacteria become much harder due to high resistance to drugs.[13-15] Hence, research shows that approximately two-thirds of deaths due to antibiotic-resistant bacteria in Europe are due to gram-negative infections.[16] Concerns about infections are greater in environments with high population densities.[17] Hospital environments are a major candidate for the cyclical transmission of viruses, bacteria, and fungi through patient-healthcare worker-surface contact.[18-20] Also, transmission can occur through benchtops, telephones, toilets, food trays, and implanted medical equipment.[21-23] In addition to hospital environments, subway and bus stations are also at high risk of transmitting bacteria

Copyright © 2022 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

and fungi. Extensive efforts have always been made to prevent and treat fungal and bacterial infections, which are reflected by the continued development of antibiotics such as amphotericin B, azoles, hydrogels, silver particles, antimicrobial peptides, and plant-based antimicrobials.[24-32] Bacterial and fungal infections are always serious threats to health.[33] Over the years in the advancement of science has been one of the greatest achievements of antimicrobial materials because they can be used in various fields such as medical equipment, food packaging and storage, water treatment systems, and hospitals.[34] Among these, plants, polymers, and nanoparticles have some particular places.[35,36] This study is a review on the research conducted in these three areas.

Antibacterial Materials

Plants

Humans have been using plants as a source of medicine for thousands of years. Medicinal plants contain various biological compounds with anticancer, antibacterial, antifungal etc. activities that can be used as drugs (Figure 1). As the cost of producing synthetic drugs is extremely high; herbs can be a great alternative item, especially for developing countries and low-income countries. It is estimated that about 50,000 plant species have been studied and used for medical properties.[37] In the following, some studies on the antimicrobial and antifungal activity of plants have been reviewed.

Figure 1. Some Plants with Antibacterial Properties.

Ili´c et al.[38] investigated the antioxidant and antimicrobial properties of goji berries cultivated in Serbia. The antibacterial activity properties of their methanol extracts were investigated against *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Enterococcus faecalis*, *Escherichia coli*, *Klebsiella pneumoniae*, *Salmonella enterica*, *Pseudomonas aeruginosa*, and *Candida albicans*. Based on the results, red goji berry had the highest content of fats, dietary fiber, iron, total carotenoids, and 2-*O*-β-ᴅ-glucopyranosyl-ʟ-ascorbic acid. This is while, the yellow goji berry extract showed the highest level of flavonoids and the best antimicrobial properties. Also, the highest total phenolic content and the most potent antioxidant activity were related to the extract of black goji berry. Bendjedid et al.[39] investigated the antioxidant, antimicrobial, photoprotective activities and cytotoxic effect of leave extracts and fractions of *Aloe vera*. The acetone extract, methanol extract and its four fractions: chloroform, ethyl acetate, n-butanol, aqueous were subjected to investigate their antibacterial activity against *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, *Pseudomonas aeruginosa*, and *Acinetobacter baumannii*. Results have shown that yields of methanol, chloroform, ethyl acetate, n-butanol, aqueous, and acetone extracts are respectively 20.56% ± 0.38, 3.4% ± 0.11, 1.58% ± 0.12, 14.16% ± 0.11, 13.56% ± 0.78, 0.68% ± 0.50. Also, the n-butanol fraction on acetone and methanol extracts has a positive effect against all the bacteria. The antioxidant activity showed that the chloroform fraction exhibited the highest activity in ($OH^{\bullet 2}$) scavenging assay and in galvinoxyl radical scavenging assay, the acetone extract exhibited the highest activity in phenanthroline assay. Moreover, all extracts and fractions showed high photo protective activity, and acetone, chloroform, and ethyl acetate fractions have displayed significant effect against the brine shrimp larvae. Furthermore, the highest toxicity was related to acetone extract and ethyl acetate fraction. Danish et al.[40] investigated the antimicrobial and antifungal properties of *Aloe vera*. Ethanolic extract of *Aloe vera* leaves and roots in different concentrations were used to investigate antibacterial activity against *Escherichia coli*, *Acinetobacter baumannii*, *Pseudomonas aerugenosa*, *Salmonella typhii*, *Agrobacterium tumefacins*, *Proteus mirabilis*, *Proteus vulgaris*, *bacillus cereus*, *bacillus subtitis*, *bacillus megaterium*, *streptococcus pyogenes*, *staphylococcus aureus*, *enterococcus faecalis*, *fuserium oxysporum*, *Candida albicans*, *Aspergillus fumigatus*, and *Aspergillus niger*. *Escherichia coli* and *Agrobacterium tumefacins* showed zone of inhibition around 18 mm, and *Bacillus subtitis* and *Bacillus megaterium* showed around 16 mm. In addition, Proteus mirabilis and *Pseudomonas aeruginosa* showed minimum zone of inhibition which is around 11 mm. Moreover, among all used fungal strains *fuserium oxysporum* and *Aspergillus niger* showed excellent results around 19 mm both against root extract and leaves extract. Alamholo[41] investigated the chemical composition, antibacterial and antioxidant activity of *Thymus daenensis* and *Thymus eriocalyx* essential oils. The antibacterial activity of the samples was investigated against *Bacillus subtilis*, *Bacillus cereus*, *Streptococcus pyogenes*, *Micrococcus luteus*, *Enterococcus faecalis*, *Staphylococcus aureus*, *Salmonella typhi*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Shigella boydii*, *Enterobacter aerogenes*, *Acinetobacter baumannii*, *Proteus mirabilis*, *Neisseria meningitidis*, and *Klebsiella pneumoniae*. The results showed that eleven (94.06%) and seven (90.76%) compounds were present in *Thymus eriocalyx* and *Thymus daenensis* essential oils, respectively. *Thymus eriocalyx* essential oil showed the highest activity against *Bacillus cereus*. Also, the most potent radical scavenging activity was obtained for *Thymus daenensis* essential oil. Moreover, *Pseudomonas aeruginosa* and *Staphylococcus aureus* showed the highest susceptibility against *Thymus eriocalyx* essential oil. Furthermore, gram-negative bacteria showed resistance to *Thymus daenensis* essential oil. Sadat et al.[42] investigated the antimicrobial activity of *Matricaria chamomilla*, *Malva sylvestris*, and *Capsella bursa-pastoris* against methicillin-resistant *Staphylococcus aureus*. For this purpose, the plants thoroughly dried in the shade and after grinding, extraction was performed by the maceration method and the extract was dried at 37 °C for 24 h. The results showed no inhibitory effects for the ethanolic extracts of *Malva sylvestris* and *Capsella bursa-pastoris* against the *Methicillin-resistant Staphylococcus aureus* isolates. This is while, the chamomile flower and leaves extract showed antibacterial activity. Rubab et al.[43] investigated the preservative effect of Chinese cabbage (*Brassica rapa subsp. pekinensis*) extract on their molecular docking, antioxidant and antimicrobial properties. Seven extracts by chloroform, toluene, dichloromethane, ethyl ether, ethanol, methanol, and distilled water were prepared to evaluate the antimicrobial activity. The results revealed that the ethanol, methanol, and distilled water extracts were not at all effective. Also, the chloroform extract was the most effective among all extracts in retarding microbial growth. Biochemical results revealed that total phenol and flavonoids were higher in the extracts of *Brassica rapa subsp. pekinensis*, which resulted in enhanced antioxidant activity in chloroform extracts. The results showed that mid-polar extracts of *Brassica rapa subsp. pekinensis* were a potential source of polyphenols with significant antimicrobial activity and also this extract could be considered as an eco-friendly and cost-efficient alternative as compared to the synthetic preservatives for food. Karthik et al.[44] investigated the larvicidal, super hydrophobic, and antibacterial properties of herbal nanoparticles from *Acalypha indica*. The herbal nanoparticles were prepared using the ball-milling technique. The nanoparticles possess an average particle size distribution of 54 ± 3 nm and are superhydrophobic in nature. The antibacterial activity of the nanoparticles was investigated against *Staphylococcus aureus* and *Escherichia coli*. The maximum zone of inhibition was observed against *Escherichia coli* (23.5 mm) and *Staphylococcus aureus* (22.7 mm) at a concentration of 100 mg/ml^{-1}, and also the magnitude of this inhibition zone is slightly higher in *Escherichia coli* than *Staphylococcus aureus*. Also, Mosquito repellent properties were investigated against three disease vectors, *Aedes aegypti*, *Anopheles stephensi* and *Culex quinquefasciatus*, and showed significant larvicidal activity. The acute toxicity of the herbal nanoparticles was tested with an in vivo animal model, zebrafish (*Danio rerio*), and it was determined that the particles of 200 mg/L^{-1} concentration were highly effective with no mortality of the zebrafish embryos and also a high concentration of nanoparticles does not affect the embryogenesis or hatching rate. Subramani et al.[45] investigated the antibacterial and textural properties of cotton fabrics using herbal nanoparticles from *Azadirachta indica* (neem). Nanoparticles were prepared from shade-dried *Azadirachta indica* plant leaves using ball milling without additives, and then nanoparticles-chitosan nanocomposites were prepared and coated on cotton fabrics employing the pad-dry cure method. The antibacterial activity of the nanoparticles was investigated against *Staphylococcus aureus* and *Escherichia coli*. The results showed that the average particle size diameters of the nanoparticles were around 30 nm, and also the topography of the fibers was coated by nanoparticles and chitosan polymer was observed to be rough. The antibacterial results showed that the agar loaded with nanoparticles had the maximum zone of inhibition against *Escherichia coli* and *Staphylococcus aureus* bacteria at a concentration of 100 mg/ml^{-1}.

Polymers

One of the greatest achievements of science has been antimicrobial materials because they can be used in a variety of fields. Among these, antimicrobial polymers are one of the suitable candidates because they have intrinsic properties such as high resistance to solvents, corrosion, and moisture (Figure 2).[46,47] Polymer materials with strong bactericidal properties through directly grafting quaternary ammonium group, nanoparticles, plant extracts, etc. are used because of their excellent mechanical properties, low cost, and popularity.[46] The surface of the antibacterial polymer must have self-cleaning properties that can maintain its antibacterial properties for a long term.[46,47] In the following, studies on the antimicrobial activity of polymers have been reviewed.

Sun et al.[48] prepared the polypyridinium salt coated silica nanoparticles and investigated antibacterial properties. For this purpose, bare silica particle carriers with different particle sizes (SiO_2-1 (15 ± 5 nm), SiO_2-2 (30 ± 5 nm), and SiO_2-3 (2 mm)) and functional organic-inorganic silica particles (SiO_2-2/P4VP-psl) "grafted" by P4VP-psl (4-vinyl pyridine-polypyridinium salt) and then, antibacterial ability was evaluated against *Escherichia coli*. The average size of SiO_2-2/P4VP-psl was 161.3 nm. Also, the results showed that silica particle sizes had no effects on its antibacterial and antifouling activities, but SiO_2-2/P4VP-psl possessed more excellent antibacterial and antifouling ability than other bare silica particle carriers. Moreover, the main role in killing bacterial cells and renewing the antibacterial ability of positive and negative charges in pyridinium salts outside SiO_2-2/P4VP-psl. Li et al.[49] prepared Polyvinyl alcohol/ Polyacrylamide interpenetrating networks (PVA/PAAm IPN) hydrogel and investigated antibacterial and mechanical properties. Hydrogel was prepared by a one-pot free radical polymerization method and the antibacterial activity of the hydrogel was investigated

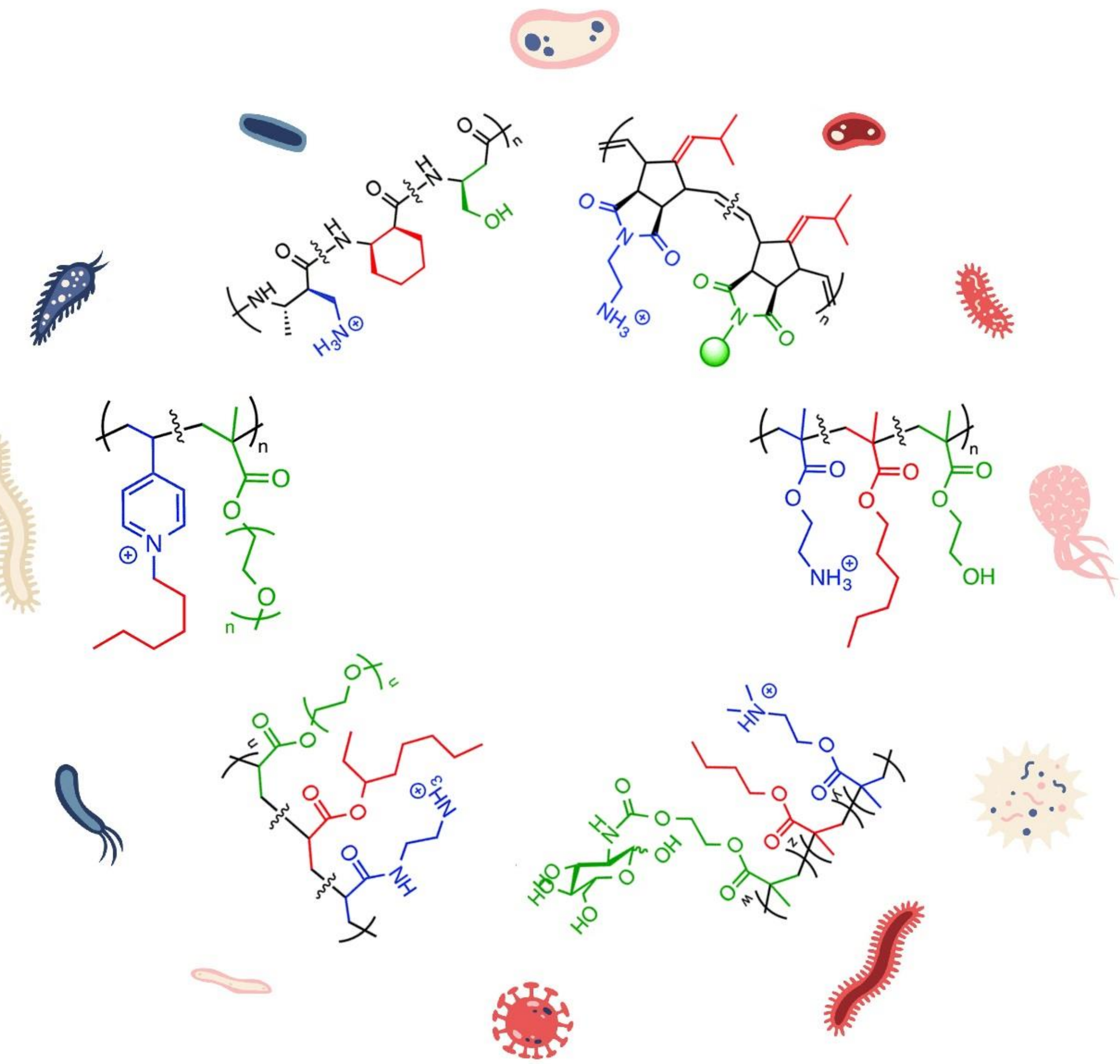

Figure 2. Some Polymers with Antibacterial Properties.

against *Escherichia coli* and *Staphylococcus aureus*. Also, Polyhexamethylene Guanidine (PHMG) was used as an antibacterial agent. The PVA/PAAm IPN hydrogel without PHMG had a weak inhibitory effect on gram-positive and gram-negative bacteria. However, as the concentration of PHMG increased, the inhibition zone also increased. The results of cytotoxicity of PVA/PAAm IPN hydrogel showed that approximately 90% of cell viability can be observed at concentrations less than 5 mg/ml^{-1}. Moreover, hydrogels have excellent adhesion to substrates such as rubber, wood, leather, plastic, stone, Teflon, glass, copper, ceramics and other materials. Zhu et al.[50] prepared an antibacterial ultrafiltration membrane with silver (Ag) nanoparticle impregnation. This membrane was prepared by using the interfacial polymerization method and the membrane surface was made of commercial polyethersulfone (PES), and also the antibacterial activity of the membrane was investigated against *Escherichia coli*, *Vibrio coralliilyticus*, *Exiguobacterium aestuarii*, and *Staphylococcus aureus*. By using sodium borohydride in the presence of Polyethyleneimine (PEI), Ag nano-particles were prepared from the reduction of silver nitrate ($AgNO_3$). The results showed that the membrane needed more time to completely kill gram-positive bacteria than gram-negative bacteria, and also the membrane prepared with 50 mmol/L of $AgNO_3$ and 20 mmol/L of PEI had the best antibacterial effect against *Escherichia coli*, and at $AgNO_3$ concentration of 50 mmol/L, the sizes of the Ag nanoparticles were in the range of 8 to 75 nm. Moreover, this membrane was 100% effective in killing various types of marine bacteria and bacteria in the seawater Sentosa Island in Singapore. Tekin et al.[51] prepared a bionanocomposites of organo-sepiolite/chitosan/silver. The samples with different content of Ag were prepared via synthesis of Ag nanoparticles using the wet chemical reduction method in the lamellar space layer of the organo-sepiolite/chitosan (O-SEP/CS), and sodium borohydride was used as the chemical reduction agent. The Scanning Electron Microscope (SEM) images of the SEP and O-SEP showed fibrous structures, but the O-SEP had more individual fibrous particles after the modification, and also the CS showed homogenous, dense, and smooth surface structures, while the O-SEP /CS composite showed a rough morphology with many protruding bulk-like agglomerates. The antibacterial activity of the samples were investigated against *Pseudomonas aeruginosa*, *Escherichia coli*, *Enterococcus faecalis*, and *Staphylococcus aureus*. The results showed that the bionanocomposites were sensitive to bacteria and for all tested bacteria had high antibacterial activity, but the antimicrobial activity against gram-negative bacteria is higher than against gram-positive bacteria. It actually increased when the amount of Ag nanoparticles in synthesized composites grew. Solak et al.[52] prepared mupirocin-loaded microspheres were embedded in the ethyl cellulose films, and release controlling of the mupirocin against *Staphylococcus aureus* was investigated. For this purpose, polyvinyl alcohol and sodium alginate were used and the microspheres were prepared by the emulsion cross-linking method and cross-linked with calcium chloride and finally, the microspheres were covered with ethyl cellulose. The SEM images showed that the microspheres have maintained a spherical form. The results showed that increasing the amount of polyvinyl alcohol will increase the % encapsulation efficiency and % drug loading. Also, microspheres showed antibacterial activity similar to mupirocin and the amount of active substance released in a controlled manner. Tekin et al.[53] investigated the thermal, photocatalytic, and antibacterial properties of calcinated nano-titanium dioxide (TiO_2)/ polymer composites. Polyethylene Glycol (PEG) and Polyvinyl Alcohol (PVA) were used for the matrix, and also TiO_2 nanoparticles, PEG/TiO_2, and PVA/TiO_2 were synthesized using the sol-gel method. The photocatalytic and antibacterial activities of samples were investigated using Acid Black I dye and *Escherichia coli*, respectively. The SEM images showed that TiO_2 nanoparticles had a spherical shape and a porous structure and their average diameter was approximately 15 nm. Also, due to the dispersion of TiO_2 particles on the PVA matrix, the surface morphology of the PVA/TiO_2 composite is uniform. However, the surface morphology of the PEG/TiO_2 composite had pores, which is due to the molecular weight of PEG. In addition, due to the compatibility of TiO_2 particles with PEG, the structure of the PEG/TiO_2 composite showed a homogeneous distribution. Anti-bacterial results showed that TiO_2 particles, PVA/TiO_2, and PEG/TiO_2 removal 19.9%, 24.4%, and 26.2% of bacteria, respectively. Also, the investigation of photocatalytic showed that PEG/TiO_2 composite had a better activity compared to the other samples and the dye decomposition of the PEG/TiO_2 composite was 62.82%. Khona et al.[54] prepared a Hyperbranched polymer nanofibrous membrane grafted with silver nanoparticles for dual antifouling and antibacterial properties against *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*. For this purpose, Ag-loaded hyperbranched polyethyleneimine/poly-ethersulfone nanofibrous membranes were prepared via electrospinning. The SEM images revealed smooth, dense, and uniform nanofibres with average diameters ranging from 107.8 ± 46.2 to 145.9 ± 49.9 nm. Also, Ag nanoparticles were observed in a spherical shape with an average diameter of 6.3 ± 2.3 nm. The antibacterial results showed that the membranes displayed excellent antibacterial properties against *Escherichia coli*, *Staphylococcus aureus* and *Pseudomonas aeruginosa* achieving an inhibition of growth rate (IR) $\geq$ 99%, and also prevented the attachment and colonization of the three bacterial species which this is probably due to the production of reactive oxygen species by Ag nanoparticles. This actually causes oxidative stress and leads to the death of bacterial cells. Khaki et al.[55] prepared new thermostable polyamides containing xanthene units with modified graphene oxide nano-particles. For this purpose, the first two series of new diamine monomers containing ether linkages, polar trifluoromethyl, and xanthene segments were prepared, and polymers synthesized through condensation polymerization. *Staphylococcus aureus* and *Pseudomonas aeruginosa* were used to investigate the antibacterial properties and *Aspergillus oryzae* and *Aspergillus Niger* were used to evaluate the antifungal activity. The results of thermogravimetric analysis showed that polyamides have high thermal stability. In addition, their glass transition temperatures are within the range of 187-244 ºC, and also 10% weight loss temperatures are within the range of 395-497 ºC. The antibacterial results that due to the presence of xanthene segments in the structure as well as the presence of graphene oxide, the samples have good antibacterial activity.

Nanoparticles

In recent years, ongoing research has focused on the use of nanoparticles as effective as antimicrobial therapies. Nanoparticles, due to their unique properties, have many applications in medical imaging, drug delivery, and nanocomposites.[56-62] Also, particles can be used as carriers due to their unique structures such as tubular, plate etc. (Figure 3). In the following, some studies on the antimicrobial activity of nanoparticles will be reviewed.

Edraki et al.[24] introduced ginger particles into the structure of sodium montmorillonite nano clay. The results showed that ginger particles could be placed between the layers as well as slightly on the surface. Also, the results of the antibacterial test showed that this hybrid inhibits *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella paratyphi-A serotype*, *Shigella dysenteriae*, *Bacillus subtilis*, *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Streptococcus pyogenes*, and *Candida Albicans*. This is while it had no effects on the *Aspergillus niger*. Moreover, the results showed that this hybrid had more effect on gram-negative bacteria, which can be because of the dual nature, due to the hydrophilicity of sodium montmorillonite and the hydrophobicity of ginger. This hybrid can penetrate the hydrophilic cell wall containing lipopolysaccharide and inhibit gram-negative bacteria. Suleiman et al.[63] investigated the antibacterial properties of sulfur nanoparticles prepared used sodium thiosulphate and tetraoctylammonium bromide surfactants in conc by precipitation method. The results showed that the nanoparticles had antimicrobial activity (Minimum Inhibitory Concentration = 5.47 µg/ml) against *Staphylococcus aureus* but there was no antimicrobial activity against *Escherichia coli* and *Pseudomonas aeruginosa* at 0.68 to 800 µg/ml. Sulfur exerts its effects through contact action, respiratory inhibition, and the formation of chelating complexes with cellular lipid moieties. In fact, after taking up sulfur by pathogens, it forms hydrogen sulfide and disrupts important intermediary metabolites in the mitochondria.[64] Priyadarshi et al.[65] investigated the enhanced functionality of green synthesized sulfur nanoparticles using kiwifruit peel polyphenols. They used kiwifruit peel polyphenols as natural capping agents to cap sulfur nanoparticles. This was done to address the hydrophobicity of sulfur nanoparticles and the low stability of aqueous suspensions, and the antimicrobial activity of both kinds of nanoparticles was studied against *Listeria monocytogenes* and *Escherichia coli*. The results showed that the capped and uncapped particles were 90 and 130 nm, respectively. This is while the capped particles had better dispersion and stability in aqueous suspension. Also, the antimicrobial activity of sulfur nanoparticles increased by two times, indicating that the function of sulfur nanoparticles had improved through capping. Both sulfur nanoparticles were not effective against *Escherichia coli* and no inhibition zones were observed. However, inhibition zones were observed against *Listeria monocytogenes* which is probably due to the difference in the cell wall structure of the two types of bacteria. In fact, sulfur nanoparticles can penetrate more easily inside the gram-positive bacterial cell, compared to gram-negative, and exert antimicrobial

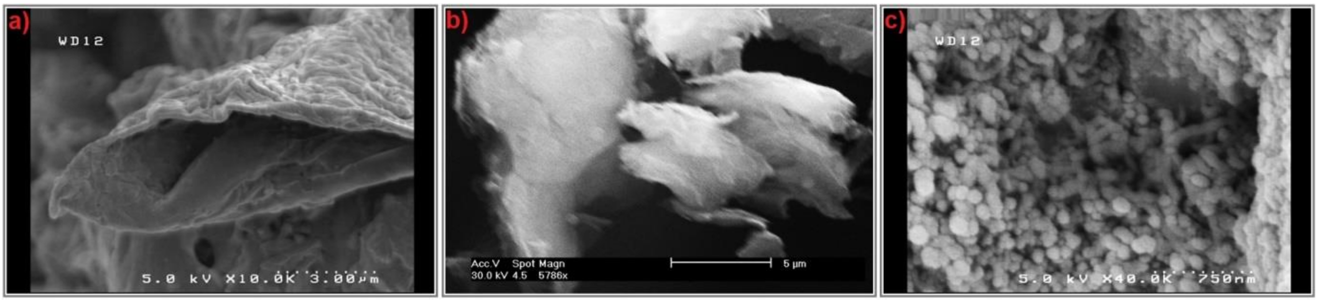

Figure 3. SEM Images of (a) Nano Clay, (b) Graphite, (c) Carbon Nanotube.

effect more proficiently. Moreover, thermal analysis results showed degradation of capped particles at a much lower temperature than uncapped particles, which is due to the decomposition of organic kiwi fruit peel polyphenols before sulfur nanoparticles. Abed et al.[66] synthesized iron oxide nanoparticles by mixing chilli with rust iron extract and investigated the antibacterial activity. Iron oxide nanoparticles were synthesized via a chemical reaction by mixing hot red pepper with waste rust iron extract at 300 °C for 1.5 h and the antibacterial activity of the nanoparticles was investigated against *Staphylococcus aureus*, *Bacillus subtilis*, *Escherichia Coli*, and *Klebsiella pneumonia* bacteria. The results showed particle sizes ranged from 27.59 to 29.29 nm with cubic structures. The nanoparticles yielded a high level of inhibition against bacterial activity, which is mainly due to the iron releasing most of the metal ions inside of it, which all attach to the bacterial cell wall due to electrostatic attraction. Also, metal ions both interact with the surface of the membrane and can penetrate inside bacteria. Moreover, the effect of nanoparticles was more for gram-positive bacteria than gram-negative bacteria. Garibo et al.[67] synthesized Ag nanoparticles using *Lysiloma acapulcensis* and investigated antibacterial activity. The presence of alkyl halides and other reducing agents in the extract of *Lysiloma acapulcensis* can reduce Ag to Ag nanoparticles and enhance its antimicrobial activity. The size of nanoparticles ranged from 1.2 to 62 nm with an average size of 5 nm with spherical and quasi-spherical structures. The nanoparticles showed a significant antimicrobial effect against *Candida albicans*, *Escherichia Coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, that the antimicrobial potency obtained was as follows: *Escherichia Coli* ≥ *Staphylococcus aureus* ≥ *Pseudomonas aeruginosa* > *Candida albicans*. Also, the results showed that these Ag nanoparticles have higher antimicrobial potency than chemically produced Ag nanoparticles and also low-cytotoxicity than the Ag nanoparticles produced chemically. Azizi-Lalabadi et al.[68] investigated the antimicrobial activity of titanium dioxide and zinc oxide nanoparticles which were supported in 4A zeolite. The presence of titanium dioxide and zinc oxide nanoparticles in 4A zeolite caused to control the release of them, and enhance their antimicrobial properties. The size of 4A zeolite particles were around 400 to 600 nm and the average crystallite size of nanoparticles was approximately 50 nm. The results revealed that the numbers of viable bacterial cells of *Staphylococcus aureus*, *Pseudomonas fluorescens*, *Listeria monocytogenes*, and *Escherichia coli* decreased significantly. In fact, the most sensitive bacteria were *Pseudomonas fluorescens* and then *Escherichia coli*. Kaushik et al.[69] investigated the antimicrobial activity and wound healing potential of ZnO nanoparticles. The antibacterial activity of the nanoparticles was investigated against *Escherichia coli*, *Staphylococcus aureus*, *Salmonella enterica Typhimurium*, *Aspergillus flavus*, *Aspergillus fumigatus*, and *Candida albicans*. The nanoparticles were synthesized by wet chemical method and annealed at 300, 500, 700, and 900 °C for 3 h. The results showed that the average particle size increases due to annealing. Accordingly, for ZnO nanoparticles annealed at 300, 500, 700, and 900 °C, particle sizes 82 ± 10 nm, 150 ± 12 nm, 230 ± 15 nm, and 420 nm ± 10 nm, respectively. Also, nanoparticles are spherical and mono dispersive in nature. Moreover, the growth of fibroblast cell is higher with nanoparticles of larger particle size, and also antimicrobial activity is higher for nanoparticles of lower particle size. The nanoparticles inhibit both gram-positive, gram-negative bacteria, and fungus. The antimicrobial activity of nanoparticles is due to the release of Zn^{2+} ions. Then, ions will penetrate the cell wall of bacteria and kill the microorganism. On the other hand, nanoparticles can get attached to the bacterial cell by electrostatic interaction. This leads to the generation of reactive oxygen species on the surface of the particles, and cause membrane dysfunction and destroys the bacterial cell. Liu et al.[70] investigated the antimicrobial activity of graphite, graphite oxide, graphene oxide, and reduced graphene oxide. The antibacterial activity of the nanoparticles was investigated against *Escherichia coli*. The results showed that graphene oxide has the highest antibacterial activities, followed by reduced graphene oxide, graphite, and graphite oxide. Direct contacts with graphene nanosheets disrupt cell membrane. In fact, there is a three-step antimicrobial mechanism for graphene-based materials that includes initial cell deposition on graphene-based materials, membrane stress caused by direct contact with sharp nanosheets, and the ensuing superoxide anion-independent oxidation. Oxidative stress may come from two paths, one is Reactive Oxygen Species (ROS) mediated oxidative stress, and the other is ROS-independent oxidative stress. In the first possibility, oxidative stress is induced by

ROS generated by graphene oxide, and in the second probability, graphene oxide may disrupt a specific microbial process by disturbing or oxidizing a vital cellular structure or component without the production of ROS.

Conclusion

To sum up, we reviewed recent research on antibacterial materials. The antibacterial plants are very diverse and contain various biologically active compounds. Accordingly, there is an urgent need to continue research to find important medicinal plants for the world and to investigate their potential for the discovery of antimicrobial drugs. On the other hand, amazing advances have been made in the field of antimicrobial polymers and nanoparticles which can be used in the main cyclical transmission environments of bacteria and fungi. They can actually be used as wall flooring, benches etc.

Conflict of Interest

The authors declare that they have no conflicts interest.

References

1. Woodford N, Livermore DM. Infections caused by Gram-positive bacteria: a review of the global challenge. J Infect. 2009;59:S4-16. doi:10.1016/S0163-4453(09)60003-7
2. Irwansyah I, Li YQ, Shi W, Qi D, Leow WR, Tang MB, et al. Gram-positive antimicrobial activity of amino acid-based hydrogels. Adv Mater. 2015;27(4):648-54. doi:10.1002/adma.201403339
3. Brown L, Wolf JM, Prados-Rosales R, Casadevall A. Through the wall: extracellular vesicles in Gram-positive bacteria, mycobacteria and fungi. Nat Rev Microbiol 2015;13(10):620-30. doi:10.1038/nrmicro3480
4. Ramachandran G. Gram-positive and gram-negative bacterial toxins in sepsis: a brief review. Virulence. 2014;5(1):213-8. doi:10.4161/viru.27024
5. Tischler BY, Hohl TM. Menacing mold: recent advances in *Aspergillus* pathogenesis and host defense. J Mol Biol. 2019; 431(21):4229-46. doi:10.1016/j.jmb.2019.03.027
6. Schuster E, Dunn-Coleman N, Frisvad JC, Van Dijck PW. On the safety of *Aspergillus niger* – a review. Appl Microbiol Biotechnol. 2002;59(4):426-35. doi:10.1007/s00253-002-1032-6
7. Monnet V, Juillard V, Gardan R. Peptide conversations in Gram-positive bacteria. Crit Rev Microbiol. 2016;42(3):339-51. doi:10.3109/1040841X.2014.948804
8. Zakaria A, Osman M, Dabboussi F, Rafei R, Mallat H, Papon N, et al. Recent trends in the epidemiology, diagnosis, treatment, and mechanisms of resistance in clinical *Aspergillus* species: a general review with a special focus on the Middle Eastern and North African region. J Infect Public Health. 2020;13(1):1-0. doi:10.1016/j.jiph.2019.08.007
9. Cole DC, Govender NP, Chakrabarti A, Sacarlal J, Denning DW. Improvement of fungal disease identification and management: combined health systems and public health approaches. Lancet Infect Dis. 2017;17(12):e412-9. doi:10.1016/S1473-3099(17)30308-0
10. Chowdhary A, Sharma C, Meis JF. Azole-resistant aspergillosis: epidemiology, molecular mechanisms, and treatment. J Infect Dis. 2017;216(suppl_3):S436-44. doi:10.1093/infdis/jix210
11. Jubeh B, Breijyeh Z, Karaman R. Resistance of gram-positive bacteria to current antibacterial agents and overcoming approaches. Molecules. 2020;25(12):2888. doi:10.3390/molecules25122888
12. Mai-Prochnow A, Clauson M, Hong J, Murphy AB. Gram positive and Gram negative bacteria differ in their sensitivity to cold plasma. Sci Rep. 2016;6(1):38610. doi:10.1038/srep38610
13. Hammoudi Halat D, Ayoub Moubareck C. The current burden of carbapenemases: Review of significant properties and dissemination among gram-negative bacteria. Antibiotics. 2020;9(4):186. doi:10.3390/antibiotics9040186
14. Karakonstantis S, Kritsotakis EI, Gikas A. Pandrug-resistant Gram-negative bacteria: a systematic review of current epidemiology, prognosis and treatment options. J Antimicrob Chemother. 2020;75(2):271-82. doi:10.1093/jac/dkz401
15. Mazzariol A, Bazaj A, Cornaglia G. Multi-drug-resistant Gram-negative bacteria causing urinary tract infections: a review. J Chemother. 2017;29(sup1):2-9. doi:10.1080/1120009X.2017.1380395
16. Arzanlou M, Chai WC, Venter H. Intrinsic, adaptive and acquired antimicrobial resistance in Gram-negative bacteria. Essays Biochem. 2017;61(1):49-59. doi:10.1042/EBC20160063
17. Mehrad B, Clark NM, Zhanel GG, Lynch III JP. Antimicrobial resistance in hospital-acquired gram-negative bacterial infections. Chest. 2015;147(5):1413-21. doi:10.1378/chest.14-2171
18. Cepas V, Lypez Y, Mucoz E, Rolo D, Ardanuy C, Martí S, et al. Relationship between biofilm formation and antimicrobial resistance in gram-negative bacteria. Microb Drug Resist. 2019;25(1):72-9. doi:10.1089/mdr.2018.0027
19. Macdonald TJ, Wu K, Sehmi SK, Noimark S, Peveler WJ, Du Toit H, et al. Thiol-capped gold nanoparticles swell-encapsulated into polyurethane as powerful antibacterial surfaces under dark and light conditions. Sci Rep. 2016;6(1):39272. doi:10.1038/srep39272
20. Alinia-Ahandani E, Sheydaei M. Overview of the introduction to the new coronavirus (Covid19): A Review. J Med Biol Sci Res. 2020;6(2):14-20. doi:10.36630/jmbsr_20005
21. Boix-Amorys A, Martinez-Costa C, Querol A, Collado MC, Mira A. Multiple approaches detect the presence of fungi in human breastmilk samples from healthy mothers. Sci Rep. 2017;7(1):13016. doi:10.1038/s41598-017-13270-x
22. Fujiyoshi S, Tanaka D, Maruyama F. Transmission of airborne bacteria across built environments and its measurement standards: a review. Front Microbiol. 2017;8:2336. doi:10.3389/fmicb.2017.02336
23. Taylor LH, Latham SM, Woolhouse ME. Risk factors for human disease emergence. Philos Trans R Soc Lond B Biol Sci. 2001;356(1411):983-9. doi:10.1098/rstb.2001.0888
24. Edraki M, Moghaddampour IM, Alinia-Ahandani E, Banimahd Keivani M, Sheydaei M. Ginger intercalated sodium montmorillonite nano clay: assembly, characterization, and investigation antimicrobial properties. Chem Rev Lett. 2021;4:120-9. doi:10.22034/crl.2021.273340.1103
25. Al-Fregi AA, Al-Salami BK, Al-Khazragie ZK, Al-Rubaie AZ. Synthesis, characterization and antibacterial studies of some new tellurated azo compounds. Phosphorus Sulfur Silicon Relat Elem. 2019;194(1-2):33-8. doi:10.1080/10426507.2018.1470179
26. Rajkoomar N, Murugesan A, Prabu S, Gengan RM. Synthesis of methyl piperazinyl-quinolinyl α-aminophosphonates derivatives under microwave irradiation with Pd-$SrTiO_3$ catalyst and their antibacterial and antioxidant activities. Phosphorus Sulfur Silicon Relat Elem. 2020;195(12):1031-8. doi:10.1080/10426507.2020.1799366
27. Narayana B, Ashalatha BV, Vijaya Raj KK, Kumari NS. Synthesis of Some New 4-{2-[(Aryl) amino]-1, 3-thiazol4-yl} benzene-1, 2-diols as Possible Antibacterial and Antifungal Agents. Phosphorus Sulfur Silicon Relat Elem. 2006;181(6):1381-9. doi:10.1080/10426500500327071
28. Ngaini Z, Rasin F, Wan Zullkiplee WS, Abd Halim AN. Synthesis and molecular design of mono aspirinate thiourea-azo hybrid molecules as potential antibacterial agents. Phosphorus Sulfur Silicon Relat Elem. 2020;196(3):275-82. doi:10.1080/10426507.2020.1828885
29. Owonubi SJ, Ateba CN, Revaprasadu N. Co-assembled ZnO-Fe_2O_{3x}-CuO_x nano-oxide materials for antibacterial protection. Phosphorus Sulfur Silicon Relat Elem. 2020;195(12):981-7.

doi:10.1080/10426507.2020.1764955
30. Alinia-Ahandani E, Alizadeh-Terepoei Z, Sheydaei M. An overview to some effective herbs to treat tick-borne disease in the world. Herb Med J. 2021;6(2):1-7. doi:10.22087/hmj.v6i2.793
31. Alinia-Ahandani E, Alizadeh-Terepoei Z, Sheydaei M. Some pointed medicinal plants to treat the tick-borne disease. Op Acc J Bio Sci & Res. 2020;1(5):1-3. doi:10.46718/JBGSR.2020.01.000028
32. Alinia-Ahandani E, Sheydaei M, Shirani-Bidabadi B, Alizadeh-Terepoei Z. Some effective medicinal plants on cardiovascular diseaaes in Iran-a review. J Glob Trends Pharm Sci. 2020;11(3):8021-33.
33. Namivandi-Zangeneh R, Wong EH, Boyer C. Synthetic Antimicrobial Polymers in Combination Therapy: Tackling Antibiotic Resistance. ACS Infect Dis. 2021;7(2):215-53. doi:10.1021/acsinfecdis.0c00635
34. Ahamed MI, Prasad R. Advanced antimicrobial materials and applications. Springer, Singapore; 2021.
35. Jain A, Duvvuri LS, Farah S, Beyth N, Domb AJ, Khan W. Antimicrobial polymers. Adv Healthcare Mater. 2014;3(12):1969-85. doi:10.1002/adhm.201400418
36. Timofeeva L, Kleshcheva N. Antimicrobial polymers: mechanism of action, factors of activity, and applications. Appl Microbiol Biotechnol. 2011;89(3):475-92. doi:10.1007/s00253-010-2920-9
37. Egamberdieva D, Jabborova D, Babich S, Xalmirzaeva S, Salakhiddinov K, Madazimov M. Antimicrobial activities of herbal plants from Uzbekistan against human pathogenic microbes. Environ Sustain. 2021;4(1):87-94. doi:10.1007/s42398-020-00147-5
38. Ilić T, Dodevska M, Marčetić M, Božić D, Kodranov I, Vidović B. Chemical characterization, antioxidant and antimicrobial properties of goji berries cultivated in Serbia. Foods. 2020;9(11):1614. doi:10.3390/foods9111614
39. Bendjedid S, Lekmine S, Tadjine A, Djelloul R, Bensouici C. Analysis of phytochemical constituents, antibacterial, antioxidant, photoprotective activities and cytotoxic effect of leaves extracts and fractions of *Aloe vera*. Biocatal Agric Biotechnol. 2021;33:101991. doi:10.1016/j.bcab.2021.101991
40. Danish P, Ali Q, Hafeez MM, Malik A. Antifungal and antibacterial activity of aloe vera plant extract. Biol Clin Sci Res J. 2020;2020(1):1-8. doi:10.54112/bcsrj.v2020i1.4
41. Alamholo M. Investigation of chemical composition, antibacterial and antioxidant activity of *Thymus daenensis* and *Thymus eriocalyx* essential oils against human pathogenic bacteria. J Med Microbiol Infect Dis. 2020;8(4):148-54. doi:10.29252/JoMMID.8.4.148
42. Sadat SS, Ahani Azari A, Mazandarani M. Evaluation of antibacterial activity of ethanolic extract of *Matricaria chamomilla*, *Malva sylvestris* and *Capsella bursa-pastoris* against *Methicillin-Resistant Staphylococcus aureus*. J Med Microbiol Infect Dis. 2020;8(4):127-31. doi:10.29252/JoMMID.8.4.127
43. Rubab M, Chellia R, Saravanakumar K, Mandava S, Khan I, Tango CN, et al. Preservative effect of Chinese cabbage (*Brassica rapa subsp. pekinensis*) extract on their molecular docking, antioxidant and antimicrobial properties. PloS One. 2018;13(10):e0203306. doi:10.1371/journal.pone.0203306
44. Karthik S, Suriyaprabha R, Vinoth M, Srither SR, Manivasakan P, Rajendran V, et al. Larvicidal, super hydrophobic and antibacterial properties of herbal nanoparticles from *Acalypha indica* for biomedical applications. RSC Adv. 2017;7(66):41763-70. doi:10.1039/C7RA05697D
45. Subramani K, Murugan V, Shanmugam BK, Rangaraj S, Palanisamy M, Venkatachalam R, et al. An ecofriendly route to enhance the antibacterial and textural properties of cotton fabrics using herbal nanoparticles from *Azadirachta indica* (neem). J Alloys Compd. 2017;723:698-707. doi:10.1016/j.jallcom.2017.06.242
46. Xu X, Wang Y, Zhang D, Wang J, Yang Z. In situ growth of photocatalytic Ag-decorated β-Bi_2O_3/$Bi_2O_{2.7}$ heterostructure film on PVC polymer matrices with self-cleaning and antibacterial properties. Chem Eng J. 2021:131058. doi:10.1016/j.cej.2021.131058
47. Edraki M, Sheydaei M, Alinia-Ahandani E, Nezhadghaffar-Borhani E. Polyvinyl chloride: chemical modification and investigation of structural and thermal properties. J Sulfur Chem. 2021;42(4):397-409. doi:10.1080/17415993.2021.1895996
48. Sun Y, Lei K, Lang M. Synthesis, structural characterization, antifouling and antibacterial properties of polypyridinium salt coated silica nanoparticles. J Macromol Sci A. 2021;58(11):769-77. doi:10.1080/10601325.2021.1936549
49. Li Z, Xu W, Wang X, Jiang W, Ma X, Wang F, et al. Fabrication of PVA/PAAm IPN hydrogel with high adhesion and enhanced mechanical properties for body sensors and antibacterial activity. Eur Polym J. 2021;146:110253. doi:10.1016/j.eurpolymj.2020.110253
50. Zhu J, Lua AC. Antibacterial ultrafiltration membrane with silver nanoparticle impregnation by interfacial polymerization for ballast water. J Polym Sci. 2021;1-14. doi:10.1002/pol.20210365
51. Tekin N, Şafaklı A, Budak F, Kara A. Preparation, characterization, and antibacterial activity of organo-sepiolite/chitosan/silver bionanocomposites. J Macromol Sci A. 2019;56(5):403-10. doi:10.1080/10601325.2019.1578620
52. Kondolot Solak E, Kaya S, Asman G. Preparation, characterization, and antibacterial properties of biocompatible material for wound healing. J Macromol Sci A. 2021;58(10):709-16. doi:10.1080/10601325.2021.1929315
53. Tekin D, Birhan D, Kiziltas H. Thermal, photocatalytic, and antibacterial properties of calcinated nano-TiO_2/polymer composites. Mater Chem Phys. 2020;251:123067. doi:10.1016/j.matchemphys.2020.123067
54. Maziya K, Dlamini BC, Malinga SP. Hyperbranched polymer nanofibrous membrane grafted with silver nanoparticles for dual antifouling and antibacterial properties against *Escherichia coli*, *Staphylococcus aureus* and *Pseudomonas aeruginosa*. React Funct Polym. 2020;148:104494. doi:10.1016/j.reactfunctpolym.2020.104494
55. Khaki D, Namazi H, Amininasab SM. Synthesis and identification of new thermostable polyamides containing xanthene units with antibacterial properties and relevant composite grafted with modified GO nanoparticles. React Funct Polym. 2021;158:104780. doi:10.1016/j.reactfunctpolym.2020.104780
56. Sheydaei M, Alinia-Ahandani E. Cancer and the role of polymeric-carriers in diagnosis and treatment. J Fasa Univ Med Sci. 2020;10(3):2408-21. doi:20.1001.1.22285105.2020.10.3.22.6
57. Sheydaei M, Alinia-Ahandani E. Cancer and Polymeric-Carriers. Biomed J Sci & Tech Res. 2020;31:24107-10. doi:10.26717/BJSTR.2020.31.005084
58. Sheydaei M, Alinia-Ahandani E, Ghiasvandnia P. Cancer and The Role of Polymer-Carriers in Drug Delivery. J Genet Cell Biol. 2020;4(1):217-20.
59. Sheydaei M, Alinia-Ahandani E. Breast cancer and the role of polymer-carriers in treatment. Biomed J Sci & Tech Res. 2021;34(5):27057-61. doi:10.26717/BJSTR.2021.34.005601
60. Bagherinia MA, Sheydaei M, Giahi M. Graphene oxide as a compatibilizer for polyvinyl chloride/rice straw composites. J Polym Eng. 2017;37(7):661-70. doi:10.1515/polyeng-2016-0249
61. Sheydaei M, Talebi S, Salami-Kalajahi M. Synthesis, characterization, curing, thermophysical and mechanical properties of ethylene dichloride-based polysulfide polymers. J Macromol Sci A. 2021;58(5):344-52. doi:10.1080/10601325.2020.1857267
62. Sheydaei M, Edraki M, Javanbakht S, Alinia-Ahandani E, Soleimani M, Zerafatkhah A. Poly (butylene disulfide) and poly (butylene tetrasulfide): Synthesis, cure and investigation of polymerization yield and effect of sulfur content on mechanical and thermophysical properties. Phosphorus Sulfur Silicon Relat Elem. 2021;196(6):578-84. doi:10.1080/10426507.2021.1872076
63. Suleiman M, Al-Masri M, Al Ali A, Aref D, Hussein A, Saadeddin I, et al. Synthesis of nano-sized sulfur nanoparticles and their antibacterial activities. J Mater Environ Sci. 2015;6(2):513-8.
64. Choudhury SR, Ghosh M, Goswami A. Inhibitory effects of sulfur nanoparticles on membrane lipids of *Aspergillus niger*: a novel route of fungistasis. Curr Microbiol. 2012;65(1):91-7. doi:10.1007/s00284-012-0130-7
65. Priyadarshi R, Roy S, Rhim JW. Enhanced functionality of green synthesized sulfur nanoparticles using kiwifruit

(*Actinidia deliciosa*) peel polyphenols as capping agents. J Nanostructure Chem. 2022;12(3):389-99. doi:10.1007/s40097-021-00422-9

66. Abid MA, Kadhim DA. Synthesis of iron oxide nanoparticles by mixing chilli with rust iron extract to examine antibacterial activity. Mater Technol. 2022;37(10):1494-503. doi:10.1080/10667857.2021.1959189
67. Garibo D, Borbyn-Nucez HA, de Leyn JN, García Mendoza E, Estrada I, Toledano-Magaca Y, et al. Green synthesis of silver nanoparticles using Lysiloma acapulcensis exhibit high-antimicrobial activity. Sci Rep. 2020;10(1):12805. doi:10.1038/s41598-020-69606-7
68. Azizi-Lalabadi M, Ehsani A, Divband B, Alizadeh-Sani M. Antimicrobial activity of Titanium dioxide and Zinc oxide nanoparticles supported in 4A zeolite and evaluation the morphological characteristic. Sci Rep. 2019;9(1):17439. doi:10.1038/s41598-019-54025-0
69. Kaushik M, Niranjan R, Thangam R, Madhan B, Pandiyarasan V, Ramachandran C, et al. Investigations on the antimicrobial activity and wound healing potential of ZnO nanoparticles. Appl Surf Sci. 2019;479:1169-77. doi:10.1016/j.apsusc.2019.02.189
70. Liu S, Zeng TH, Hofmann M, Burcombe E, Wei J, Jiang R, et al. Antibacterial activity of graphite, graphite oxide, graphene oxide, and reduced graphene oxide: membrane and oxidative stress. ACS Nano. 2011;5(9):6971-80. doi:10.1021/nn202451x