Multifunctional Polymer Nanocomposites Reinforced With Bio-Modified Gold and Laponite Nanoparticles: A Study on Structural and Antibacterial Performance

Hayjaa M. Sadeq[1, a)] and Tabarak A. Alwan [2, b)]

[1] *Middle Technical University, Technical Medical Institute -Baghdad Department of Radiology, Baghdad, Iraq*
[2] *Al-Karkh University for Science, College of Energy and Environmental Science, Department of Environmental Science Baghdad, Iraq*

[a)] *Corresponding author: hayjaa.mohammed@mtu.edu.iq*
[b)] *tabark.k.abdulla@kus.edu.iq*

Abstract. This study investigates the impact of bioengineered nanoparticles, specifically gold and laponite, on the thermal behavior, mechanical strength, and antimicrobial effectiveness of polymers. Gold and laponite nanoparticles were synthesized and incorporated into polymer matrices at a 1% concentration to evaluate their performance improvements. To study the interaction between nanoparticles and Escherichia coli, scanning electron microscopy and transmission electron microscopy were used, revealing significant adhesion, membrane damage, and bacterial structural deformation, particularly in the presence of gold nanoparticles. Mechanical testing demonstrated a significant increase in tensile strength from 35.3 MPa (pure polymer) to 42.7 MPa and 47.9 MPa with gold and laponite nanoparticles, respectively. Similarly, thermal decomposition temperatures improved from 265.2°C in the control group to 282.6°C and 294.4°C for the gold-Laponite-reinforced composites. Statistical analysis using analysis of variance (ANOVA) and Pearson's correlation coefficient confirmed that these improvements were significant and positively correlated with the incorporation of the nanoparticles. The results support the multifunctional role of gold and Laponite nanoparticles in improving polymer nanocomposites, indicating their promising applications in biomedical and industrial materials that require structural integrity and antibacterial function.

Keywords: Polymer Nanocomposites, Laponite, Antibacterial Activity, Mechanical Strength, Thermal Stability.

INTRODUCTION

Nanotechnology involves nanomaterials engineering (usually 1-100 nanometers) in which new polymers may be developed with stronger and novel properties. Nanocomposites are formed by adding nanoparticles to polymer structures, which enhance mechanical dispersion and provide multiple properties that a single polymer cannot, including improved antibacterial properties and electrical conductivity [1]. High surface area and peculiar physicochemical properties of the nanoparticles provide intensive interfacial interactions with polymer chains opening the way to better load transfer and the impediment of the motions of polymer chains leading to the better mechanical and thermal properties [2]. Metal oxides, noble metals (gold and silver), layered silicates (laponite) are some of the commonly used nanoparticles due to its demonstrated enhancement of polymer performance in biomedical applications down to packaging materials [3,4]. Moreover, nanotechnology enables the creation of polymers with antimicrobial properties, based on the ability of nanoparticles to disrupt bacterial membranes or generate reactive oxygen species, offering potential alternatives to commercial antibiotics [5]. When the size of the Gold Nanoparticles (AuNPs) becomes very small and the surface-to-volume ratio is large, then there are specific physical and chemical properties. The properties make them unusual in optical behavior especially in such phenomenon as the localized surface plasmon resonance (LSPR) [6]. Such features render the gold nanoparticles very useful in biomedicine, such as drug delivery, imaging, and diagnostics, because of their simple interaction with the biomolecules, which increases their biocompatibility and targeting capability [7]. Besides, gold nanoparticles promise to replace traditional antibiotics, as their antimicrobial properties are extraordinary: they interfere with the membranes of bacteria and produce reactive oxygen species (ROS) [8]. Laponite is an artificial multilayered silicate clay which is composed mostly of magnesium, lithium, and silicates. Laponite molecules are disc shaped nanoparticles sized around 25 to 30 nm in diameter and 1 nm thick. It possesses high surface charge density which makes the dispersion to be quite good in polymer matrices [9]. The platelet form leads to an effective form of mechanical interlocking and stress redistribution in the polymers considerably increasing the tensile strength and elastic modulus. Moreover, the polymer compounds are not so optimally applied to packaging and electronic equipment, but with Laponite nanoparticles, they provide better heat resistance and blocking capability [10]. The

study of nanoparticle demonstrated a remarkable antimicrobial effect through various ways, comprising destroying the membranes of bacteria and generating reactive oxygen species (ROS) as well as disturbing the cellular metabolic functions [11]. The mechanisms damage the integrity of the membrane, and leakage of its contents occurs, and eventually killing of the bacteria takes place [12]. It has been demonstrated that nanoparticles of gold, silver, and different metal oxides can adhere to the surfaces of bacteria, enter cells and result in oxidative stress. They are especially bottom supported on drug-resistant ones [13]. Development of antibiotic-resistant bacteria represents a significant threat to the health of majorities requiring alternative measures to fight infections [14]. The application of nanomaterials suggests interesting solutions because of properties not covered by conventional antibiotics, unique physicochemical characteristics, and antibacterial multifactorial mechanisms of action that can reduce the resistance by usage of nanomaterials [15]. Also, nanomaterial composites in polymer matrices also increase the durability and functionality of antimicrobial coatings, which can broadly be applied in medical devices, food packaging, and water treatment [16]. It has well been established that high levels of mechanical properties are well enhanced by addition of nanoparticles in polymer matrices which include tensile strength, stiffness and toughness. The nano-sized surface area of nanoparticles is seen to have contributed to this improvement to a large extent as nanoparticles provide a large area to bond with the polymer chains strongly to allow transfer of stress conveniently and to prevent the movement of polymer chains [17]. As an example, the tensile strength is shown to increase by 40 percent as well as more depending on the level of dispersion and load as importantly metal oxide and layered silicate nanoparticles have demonstrated this [18]. Moreover, nanoparticles enhance thermal stability of polymers through physical barriers to heat and mass transfer, and thus thermal degradation reaction and potential industrial products based on them, including automotive and packaging industries, are slowed down [19]. The augmented thermal conductivity can also be connected with the fact that nanoparticles can enhance developing char and inhibition of releasing volatiles in the process of decomposition [20]. Equal distribution of nanoparticles with the polymer matrix is particularly crucial toward the achievement of these improvements. The concentrations of stress through agglomeration may lead to a weakened composite and they decrease the performances of the composite [21]. Some of the typical fabrication methods involve solution casting, melt blending, and in situ polymerization, among others which are best to exfoliate nanoparticles and attain homogeneous nanoparticles [22]. In order to enhance the quality of the distribution and in case of interface compatibility one can improve it through ultrasonication and nanoparticle surfaces functionalization [23]. In combination, these advancements recommend the significance of nanoscale organization strategies to get the most out of the multifunctional utility of polymer nanocomposites. Certainly, the examination of interactions between nanoparticles and bacterial cells have to be based on sophisticated imaging processes able to reveal slight morphological and structural alterations. This is often done with the use of scanning electron microscopy (SEM) and transmission electron microscopy (TEM). (SEM) gives high-resolution images of its surface, where a physical adhesion of the nanoparticles to the bacterial membranes, surface roughness, and signs of the cell wall damage or rupture are observed [24]. Unlike transmission electron microscopy (TEM), which and visualizes internal cellular structures at nanometer scale, allowing one to observe nanoparticle entrapment, disruption of the cytoplasm, and damage of organelles or DNA [25]. Examples of this include the work done in transmission electron microscopy (TEM), which have demonstrated that metals (nanoparticle metallic) such as gold or silver can concentrate in the periplasm or the cytoplasmic zone of Escherichia coli bacteria causing thinning of the membrane, extracellular content in the cellular vicinity and hence the death of the cell [26]. Thus, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) play a crucial role in relating antimicrobial activity with appreciable morphological indices of a traumatic stress attributed to nanoparticle in the context of a nano bio interface [27]. The methods have also become common in the field of nanotoxicology and the development of antimicrobial materials allowing nanoscale visualization of interactions between materials and microbes. The current study aims to explore the potential of bioengineered nanoparticles, specifically gold and laponite, in enhancing the functional properties of polymeric materials. While previous research has demonstrated the individual benefits of these nanomaterials, there remains a significant gap in understanding their combined effects on mechanical and thermal performance, as well as their antimicrobial capacity against harmful bacterial strains such as Escherichia coli. This study addresses this lack of integrated analysis by assessing how the incorporation of these nanoparticles affects polymer strength, degradation resistance, and microbial inhibition. The primary objectives include assessing the tensile strength and thermal stability of polymer nanocomposites reinforced with gold and laponite nanoparticles, and studying their interaction with bacterial cells using imaging techniques such as (SEM) and (TEM). The materials used in this study included a commercial thermoplastic polymer (e.g., polyethylene) as a matrix, biosynthesized gold nanoparticles (AuNPs) prepared via green synthesis using microbial extracts, and commercially synthesized Laponite nanoparticles (with platelet sizes of approximately 25–30 nm). Escherichia coli (ATCC strain) was used to evaluate their antimicrobial properties. Gold nanoparticles were synthesized by reducing $HAuCl_4$ using an active biofiltration system under controlled pH and temperature, then

purified by centrifugation and rinsing with deionized water. Polymer nanocomposites were manufactured by mixing the melt in a twin-screw extruder, adding 1 wt% of gold or Laponite nanoparticles to the melt, and then compression-casting them into standard tensile rods. Three sets of samples were prepared: pure polymer (control), polymer + gold nanoparticles, and nanoparticles of polymer + Laponite. The interaction between the nanomaterials and E. coli bacteria was evaluated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). SEM imaging was performed after fixing the bacteria with 2.5% glutaraldehyde, dehydrating in an ethanol series, and sputter-coating them with gold, while TEM imaging involved cutting the embedded samples into ultra-thin slices and staining them with uranyl acetate and lead citrate. Mechanical strength was determined using an Instron universal testing machine according to ASTM D638 standard, while thermal degradation behavior was evaluated using thermogravimetric analysis (TGA) in a nitrogen atmosphere at a heating rate of 10 °C/min. Antibacterial activity was assessed visually by membrane rupture and loss of cell integrity in SEM and TEM images. The statistical procedure was done with the help of one-way analysis of variance (ANOVA), utilizing IBM SPSS Statistics version 29 to compare the means of mechanical strength and temperature at which the sample undergoes thermal decomposition, as per the group. When statistical significance was realized, Tukey HSD test of post hoc analysis was conducted. The relationship between nanoparticle concentration and material property improvement was analysed by means of Pearson correlation coefficient. The analysis was two-tailed with $p < 0.05$ being the criterion of significance.

RESULTS AND DISCUSSION

The interaction of the bioengineered nanomaterials with E. coli bacteria and the morphology of the nanomaterials prior to their inclusion into the polymer matrices were analysed using microscopic investigation in scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The images captured by SEM and TEM show that the biosynthesized nanomaterials interact with E. coli cells successfully. SEM images showed clear accumulation of gold and Laponite nanoparticles around the bacterial cells, with noticeable attachment to the cell membranes. The TEM images also showed that there was direct contact between the nanoparticles and E. coli and evident damage to the membrane and affecting the structure of the cells most especially when using the gold nanoparticle. These findings argue the high affinity of nanomaterials to the bacterium surface and validate their possible antimicrobial activity.

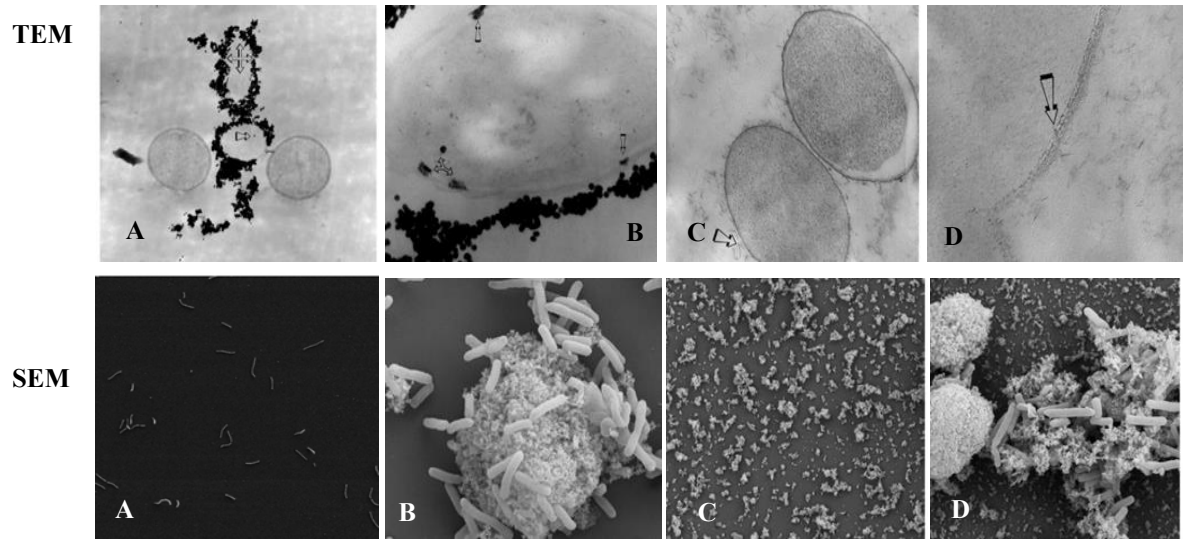

FIGURE 1. TEM images showing the interaction between bioengineered nanoparticles and E. coli cells: (a, b) Gold nanoparticles clustering around and adhering to E. coli cell surfaces, with evidence of membrane damage; (c, d) Laponite nanoparticles in direct contact with E. coli, causing structural changes and membrane rupture. While SEM showing the interaction between bioengineered nanoparticles and E. coli cells: (a) untreated E. coli cells as a control, (b) gold nanoparticles assembling around E. coli cells, (c) uniform distribution of Laponite nanoparticles, and (d) Laponite nanoparticles surrounding and interacting with E. coli cells.

The antibacterial activity was evaluated using inhibition zone measurements and colony-forming unit (CFU) counts for *Escherichia coli*. The results showed that gold nanoparticles achieved a larger inhibition zone

compared to Laponite nanoparticles, highlighting their superior antibacterial efficacy. Additionally, a significant reduction in CFU counts was observed after exposure to the nanoparticles, reinforcing the antimicrobial effectiveness of these nanocomposites. Mechanical strength and thermal decomposition temperatures of pure polymer and polymer composites reinforced with bioengineered nanoparticles was shown in Table 1. The results indicate a significant improvement in both properties due to the addition of nanoparticles. The addition of gold nanoparticles increased the mechanical strength from 35.3 MPa to 42.7 MPa, while the addition of Laponite nanoparticles improved the mechanical strength to 47.9 MPa. Similarly, the thermal decomposition temperature increased from 265.2 °C in the pure polymer to 282.6 °C and 294.4 °C with gold and Laponite nanoparticles, respectively. These results confirm that bioengineered nanomaterials, especially Laponite, effectively improve the mechanical and thermal performance of polymer matrices. Gold and Laponite nanoparticles were found to be effective in combating bacteria by disrupting bacterial membranes and generating reactive oxygen species (ROS), leading to bacterial cell death. The SEM and TEM images provide strong evidence for this interaction, showing significant adhesion and membrane damage, particularly with gold nanoparticles. These findings suggest that nanoparticle-based antimicrobial materials could be a promising alternative to traditional antibiotics.

TABLE 1. Mechanical and Thermal Properties of Polymer Samples.

Sample No.	Sample Type	Nanomaterials Present	Nanomaterial Type	Concentration (%)	Mechanical Strength (MPa)	Thermal Degradation Temp (°C)
1	Pure Polymer	No	-	0	35.3	265.2
2	Polymer + Gold Nanoparticles	Yes	Gold	1	42.7	282.6
3	Polymer + Laponite Nanoparticles	Yes	Laponite	1	47.9	294.4

The results of the one-way analysis of variance (ANOVA) in Table 2 show that the differences in mechanical strength among the three groups are statistically significant. The F value of 56.12 and the p value of 0.002 ($p < 0.05$) indicate that the improvement in mechanical strength observed in the polymer composites reinforced with bioengineered nanoparticles is not due to random variation. The low within-group variability also supports the consistency of these results, confirming that both the gold and Laponite nanoparticles significantly contribute to the mechanical improvement of the polymer. The performance of gold and Laponite nanoparticles was compared in terms of mechanical and thermal properties. The results indicated that Laponite nanoparticles contributed more significantly to thermal stability, whereas gold nanoparticles showed greater enhancement in mechanical strength. These findings suggest that combining both nanoparticles could result in a multifaceted improvement of polymer nanocomposites, offering enhanced mechanical and thermal properties.

TABLE 2. One-way analysis of variance for mechanical strength.

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	790.4	2	395.2	56.12	0.002
Within Groups	84.2	12	7.02	-	-
Total	874.6	14	-	-	-

Table 3 shows the analysis of variance (ANOVA) for the thermal decomposition temperatures. A significant difference was observed between the two groups, with an F value of 78.44 and a P value of 0.004. These results confirm that the addition of bioengineered nanoparticles significantly enhances the thermal stability of the polymer. The increase in decomposition temperature observed in the composites is statistically significant, especially with the use of Laponite nanoparticles, which provided the highest thermal resistance among the tested groups.

TABLE 3. One-way analysis of variance for thermal decomposition temperature.

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2200.6	2	1100.3	78.44	0.004
Within Groups	168.4	12	14.03		
Total	2369	14			

The Pearson's correlation coefficient results shown in Table 4 indicate a strong and statistically significant positive correlation between the concentration of bioengineered nanoparticles and the improvement of both the mechanical and thermal properties of the polymer. Specifically, the Pearson's correlation coefficient value of 0.921 for mechanical strength and 0.879 for thermal decomposition temperature, with corresponding p-values of 0.003 and 0.009, respectively, indicate that higher nanoparticle concentrations lead to greater improvements in these properties. These results highlight the direct and measurable impact of bioengineered nanomaterials on the improvement of polymer performance.

TABLE 4. Pearson correlation analysis between nanomaterial concentration and material properties.

Property	Pearson's r	Sig.(2-tailed)	Interpretation
Nanomaterial Concentration × Mechanical Strength	0.921	0.003	Very strong positive correlation, statistically significant
Nanomaterial Concentration × Thermal Degradation Temp	0.879	0.009	Strong positive correlation, statistically significant

SEM and TEM analyses revealed that gold nanoparticles aggregate around E. coli surfaces, adhere to membranes, and cause structural damage a finding consistent with the findings of Cui et al. (2012), who reported that gold nanoparticles disrupt membrane potential, inhibit ATPase activity, collapse energy metabolism, and inhibit ribosome functions, leading to bacterial death [28]. Furthermore, Bin Niu and Zhang (2023) studies using a similar microscope confirmed that gold and Laponite nanoparticles aggregate on the surfaces of E. coli bacteria, distorting the membranes and ultimately compromising cell integrity [29]. Also, Laponite's high surface charge and large surface area highlighted in Gita Kiaee et al. (2022) review on drug delivery using Laponite facilitate strong interactions with bacterial surfaces [30].The increase in tensile strength from 35.3 MPa (pure polymer) to 42.7 MPa (with gold) and 47.9 MPa (with Laponite) reflects findings reported in Hussain et al. (2006) and Paul and Robison (2008) that showed nanofillers limit polymer chain movement and enhance load transfer, increasing mechanical strength. More specifically, the platelet structure of Laponite promotes greater stiffness compared to spherical nanoparticles a well-known effect in materials science [31,32].The thermal decomposition temperatures increased significantly, reaching 282.6 °C for gold and 294.4 °C for laponite. Previous studies support this effect: layered silicate nanocomposites (such as laponite) impede polymer chain movement and act as thermal barriers, as reported by Ghadiri et al, (2014) [33]. Analyses of variance (ANOVA) for both mechanical strength ($F = 56.12$, $p = 0.002$) and thermal decomposition temperature ($F = 78.44$, $p = 0.004$) indicate that these improvements are statistically significant. Pearson correlation coefficients ($r = 0.921$ for mechanical strength; $r = 0.879$ for thermal stability) with $p < 0.01$ confirm strong, positive, and significant associations between nanoparticle concentration and performance increases, which is consistent with studies demonstrating concentration-dependent enhancing effects in polymer nanocomposites.

CONCLUSION

The conclusions drawn from this research demonstrate the significant impact of bioengineered gold and laponite nanoparticles on the mechanical, thermal, and antimicrobial properties of polymer nanocomposites. The study found that the incorporation of both gold and laponite nanoparticles into the polymer matrix significantly enhanced its mechanical strength and thermal stability. The tensile strength of the polymer was notably increased from 35.3 MPa to 42.7 MPa with gold nanoparticles and to 47.9 MPa with laponite nanoparticles. Similarly, the

thermal decomposition temperature improved from 265.2°C in the pure polymer to 282.6°C and 294.4°C with gold and laponite, respectively. These improvements were supported by statistical analyses, which confirmed their significance. Furthermore, the antimicrobial activity of the nanocomposites was evident, with both nanoparticles causing notable adhesion to and damage of Escherichia coli membranes, leading to bacterial structural deformation. The combined application of gold and laponite nanoparticles presents promising opportunities for developing multifunctional polymer nanocomposites with enhanced mechanical, thermal, and antibacterial properties, making them highly suitable for biomedical and industrial applications. The findings of this study confirm the significant enhancement of both the mechanical and thermal properties of the polymer nanocomposites with gold and Laponite nanoparticles. However, further studies are recommended to explore cytotoxicity assessments for these nanocomposites. Additionally, future work could investigate varied nanoparticle loadings to optimize the balance between mechanical, thermal, and biological properties.

ACKNOWLEDGMENT

The authors would like to thank the technical staff and colleagues who provided support during the experimental phase of this work. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

REFERENCES

1. A. Kumar, S. Sharma, and N. Dilbaghi, "Nanomaterials for antibacterial applications: An overview," *Nanomaterials*, vol. 9, no. 10, p. 1384, 2019, doi: 10.3390/nano9101384.
2. J. Jeevanandam, et al., "Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations," *Beilstein J. Nanotechnol.*, vol. 9, pp. 1050–1074, 2018, doi: 10.3762/bjnano.9.104.
3. P. M. Ajayan, L. S. Schadler, and P. V. Braun, *Nanocomposite Science and Technology*, John Wiley & Sons, 2020.
4. Y. Liao, Y. Li, J. Liu, and Y. Wang, "Polymer nanocomposites reinforced with inorganic nanoparticles: Mechanical and thermal properties," *Prog. Polym. Sci.*, vol. 100, p. 101183, 2020, doi: 10.1016/j.progpolymsci.2019.101183.
5. N. Durán, et al., "Silver nanoparticles: A new view on mechanistic aspects on antimicrobial activity," *Nanomed. Nanotechnol. Biol. Med.*, vol. 12, no. 3, pp. 789–799, 2016, doi: 10.1016/j.nano.2015.10.013.
6. R. J. Gilkes, and N. Prakongkep, "How the unique properties of soil kaolin affect the fertility of tropical soils," *Appl. Clay Sci.*, vol. 131, pp. 100–106, 2016, doi: 10.1016/j.clay.2016.06.012.
7. E. C. Dreaden, et al., "The golden age: gold nanoparticles for biomedicine," *Chem. Soc. Rev.*, vol. 41, no. 7, pp. 2740–2779, 2012, doi: 10.1039/C1CS15209J.
8. G. Franci, A. Falanga, S. Galdiero, L. Palomba, M. Rai, G. Morelli, and M. Galdiero, "Silver Nanoparticles as Potential Antibacterial Agents," *Molecules*, vol. 20, no. 7, pp. 8856–8874, 2015, doi: 10.3390/molecules20078856.
9. P. K. Jain, et al., "Noble metals on the nanoscale: optical and photothermal properties and some applications in imaging, sensing, biology, and medicine," *Acc. Chem. Res.*, vol. 41, no. 12, pp. 1578–1586, 2008, doi: 10.1021/ar8000584.
10. N. Gorshkov, et al., "Polytetrafluorethylene-based high-k composites with low dielectric loss filled with priderite ($K_{1.46}Ti_{7.2}Fe_{0.8}O_{16}$)," *J. Appl. Polym. Sci.*, vol. 137, no. 22, p. 48762, 2020, doi: 10.1002/app.48762.
11. I. M. Adjei, B. Sharma, and V. Labhasetwar, "Nanoparticles: cellular uptake and cytotoxicity," *Nanomaterials: Impacts on Cell Biology and Medicine*, pp. 73–91, 2014, doi: 10.1007/978-1-4614-8120-9_5.
12. K. R. Raghupathi, R. T. Koodali, and A. C. Manna, "Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles," *Langmuir*, vol. 27, no. 7, pp. 4020–4028, 2011, doi: 10.1021/la200738k.
13. J. T. Seil, and T. J. Webster, "Antimicrobial applications of nanotechnology: methods and literature," *Int. J. Nanomedicine*, pp. 2767–2781, 2012, doi: 10.2147/IJN.S30267.
14. C. L. Ventola, "The antibiotic resistance crisis: part 1: causes and threats," *P & T: A Peer-Reviewed J. Formulary Manag.*, vol. 40, no. 4, pp. 277–283, 2015.
15. U. Philipose, Y. Jiang, G. Farmer, C. Howard, M. Harcrow, C. Littler, V. Lopes, A. J. Syllaios, A. Sood, and J. W. Zeller, "Using a novel approach to estimate packing density and related electrical resistance in multiwall carbon nanotube networks," *Nanomaterials*, vol. 10, no. 7, p. 2350, 2020, doi: 10.3390/nano10072350.

16. A. Haeri, et al., "A novel combined approach of short-chain sphingolipids and thermosensitive liposomes for improved drug delivery to tumor cells," *J. Biomed. Nanotechnol.*, vol. 12, no. 4, pp. 630–644, 2016, doi: 10.1166/jbn.2016.2190.
17. A. Haleem, J.-Y. Wang, H.-J. Li, C.-S. Hu, X.-C. Li, and W.-D. He, "Macroporous oil-sorbents with a high absorption capacity and high-temperature tolerance prepared through cryo-polymerization," *Polymers*, vol. 11, no. 10, p. 1620, 2019, doi: 10.3390/polym11101620.
18. J. Yang, et al., "Keys to enhancing mechanical properties of silica nanoparticle composites hydrogels: the role of network structure and interfacial interactions," *Compos. Sci. Technol.*, vol. 95, pp. 1–7, 2014, doi: 10.1016/j.compscitech.2013.11.021.
19. G. Mago, et al., "Polymer nanocomposite processing, characterization, and applications," *J. Nanomaterials*, 2010, p. 594395, 2010, doi: 10.1155/2010/594395.
20. W. S. Khan, N. N. Hamadneh, and W. A. Khan, "Polymer nanocomposites–synthesis techniques, classification and properties," *Science and Appl. Tailored Nanostructures*, vol. 50, pp. 259–267, 2016, doi: 10.1016/j.sans.2016.06.003.
21. D. Bikiaris, "Can nanoparticles really enhance thermal stability of polymers? Part II: An overview on thermal decomposition of polycondensation polymers," *Thermochim. Acta*, vol. 523, no. 1-2, pp. 25–45, 2011, doi: 10.1016/j.tca.2011.04.001.
22. E. T. Thostenson, Z. Ren, and T.-W. Chou, "Advances in the science and technology of carbon nanotubes and their composites: a review," *Compos. Sci. Technol.*, vol. 61, no. 13, pp. 1899–1912, 2001, doi: 10.1016/S0266-3538(01)00095-0.
23. N. Geng, et al., "A sono-photocatalyst for humic acid removal from water: Operational parameters, kinetics and mechanism," *Ultrason. Sonochem.*, vol. 57, pp. 242–252, 2019, doi: 10.1016/j.ultsonch.2019.01.019.
24. C. N. Lok, C. M. Ho, R. Chen, et al., "Silver nanoparticles: partial oxidation and antibacterial activities," *J. Biol. Inorg. Chem.*, vol. 12, pp. 527–534, 2007, doi: 10.1007/s00775-007-0193-5.
25. I. Sondi, and B. Salopek-Sondi, "Silver nanoparticles as antimicrobial agent: a case study on E. coli as a model for Gram-negative bacteria," *J. Colloid Interface Sci.*, vol. 275, no. 1, pp. 177–182, 2004, doi: 10.1016/j.jcis.2004.02.012.
26. E. M. Mateo, and M. Jiménez, "Silver nanoparticle-based therapy: can it be useful to combat multi-drug resistant bacteria?," *Antibiotics*, vol. 11, no. 9, p. 1205, 2022, doi: 10.3390/antibiotics11091205.
27. K. Brimo, et al., "In situ long-term modeling of phenanthrene dynamics in an aged contaminated soil using the VSOIL platform," *Sci. Total Environ.*, vol. 619, pp. 239–248, 2018, doi: 10.1016/j.scitotenv.2017.11.034.
28. Y. Cui, et al., "The molecular mechanism of action of bactericidal gold nanoparticles on Escherichia coli," *Biomaterials*, vol. 33, no. 7, pp. 2327–2333, 2012, doi: 10.1016/j.biomaterials.2011.11.053.
29. B. Niu, and G. Zhang, "Effects of different nanoparticles on microbes," *Microorganisms*, vol. 11, no. 3, p. 542, 2023, doi: 10.3390/microorganisms11030542.
30. G. Kiaee, et al., "Laponite-based nanomaterials for drug delivery," *Adv. Healthcare Mater.*, vol. 11, no. 7, p. e2102054, 2022, doi: 10.1002/adhm.202102054.
31. F. Hussain, M. Hojjati, M. Okamoto, and R. E. Gorga, "Polymer-matrix nanocomposites, processing, manufacturing, and application: an overview," *J. Compos. Mater.*, vol. 40, no. 17, pp. 1511–1575, 2006, doi: 10.1177/0021998306040192.
32. D. R. Paul, and L. M. Robeson, "Polymer nanotechnology: Nanocomposites," *Polymer*, vol. 49, no. 14, pp. 3187–3204, 2008, doi: 10.1016/j.polymer.2008.04.017.
33. M. Ghadiri, W. Chrzanowski, and R. Rohanizadeh, "Antibiotic-eluting clay mineral (Laponite) for wound healing application: an in vitro study," *J. Mater. Sci. Mater. Med.*, vol. 25, no. 12, pp. 2513–2526, 2014, doi: 10.1007/s10856-014-5246-4.