

## Antimicrobial Activities of Gold Nanoparticles and Their Application in Food Preservation & Packaging

Mohammad Farooque Hassan<sup>1</sup>, Syed Sairum Hassan<sup>2\*</sup>, Ahmed Hussain<sup>3</sup>, Syeda Saba Sajjad<sup>4</sup>, Syeda Tooba Sajjad<sup>5</sup>, Jamal Muhammad Khan<sup>6\*</sup>

<sup>1</sup> Shaheed Benazir Bhutto University of Veterinary & Animal Sciences, Sakrand Sindh. [drfaruqmat72@gmail.com](mailto:drfaruqmat72@gmail.com)

<sup>2</sup> Bilawal Medical College, Liaquat University of Medical & Health Sciences, Jamshoro Sindh. [sairumhassan@yahoo.com](mailto:sairumhassan@yahoo.com)

<sup>3</sup> Liaquat University of Medical & Health Sciences, Jamshoro Sindh. [ahmedsajjad579@gmail.com](mailto:ahmedsajjad579@gmail.com)

<sup>4</sup> Liaquat University of Medical & Health Sciences, Jamshoro Sindh. [matee.saba@gmail.com](mailto:matee.saba@gmail.com)

<sup>5</sup> Azra Naheed Medical & Dental College Lahore. [toobasajjad11@gmail.com](mailto:toobasajjad11@gmail.com)

<sup>6</sup> Department of Parasitology, Cholistan University of Veterinary and Animal Sciences, Bahawalpur. [jamalmkhan@cuvas.edu.pk](mailto:jamalmkhan@cuvas.edu.pk)

\*Correspondence: [sairumhassan@yahoo.com](mailto:sairumhassan@yahoo.com) & [jamalmkhan@cuvas.edu.pk](mailto:jamalmkhan@cuvas.edu.pk)

DOI: <https://doi.org/10.63163/jpehss.v3i4.874>

### Abstract

The synthesis of antibacterial nanoparticles (NPs) is an efficient approach to tackle bacterial resistance, which is becoming more problematic. As a consequence of the fast advancement of nanotechnology, the manufacturing and use of NPs have increased tremendously. NPs are being used in the food industry to increase nutritional status and movement, as well as flavor, color, and stability, as well as improve stability. Metal NPs with antibacterial properties, such as Au, Zn, Ag, and Cu, have been recognized and employed for decades due to their diverse features, activity ranges, and modes of action. Gold nanoparticles (AuNPs) are stable and biocompatible, and they may be readily changed to improve their antibacterial capabilities. AuNPs are also effective medication transporters, enhancing the antibacterial properties of antibacterial medicines that have been loaded. The ability of AuNPs to inhibit microbial growth through mechanisms such as disruption of bacterial cell walls and interference with microbial metabolic processes is highlighted. Furthermore, the integration of AuNPs into food packaging materials can provide an additional layer of protection by preventing microbial contamination, thus ensuring food safety. To increase and prolong their efficacy in food preservation, bioactive components with an antibacterial action against food pathogens are encapsulated in NPs. After being upgraded and combined with other antibiotics, AuNPs may provide a better antimicrobial function for efficient therapeutic strategies toward specific resistant microorganisms. This review analysis looked at the antimicrobial elements of nano-packaging used in the food industry.

**Keywords:** Nanoparticles, AUNPs, Food preservation, Food packaging, Antimicrobial Agents, Food processing, Nanotechnology

### 1. Introduction

A diverse range of pharmaceutical medicines is derived from natural chemicals and widely utilized to target and treat a variety of ailments. These complex chemical molecules are extracted from

plants, animals, microbes, and minerals via a variety of extraction procedures, and they serve as a starter for future sinker molecules [1]. Gold is a biocompatible metal that is chemically inert. It was only known as a metal until recently. A nanoparticle is a small particle with a diameter of 1 to 100 nanometers [2]. In 1857, while synthesizing nanomaterials while seeing that AuNPs had a red color, Michael Faraday discovered biomolecules with at minimum each scale 1–100 nm for the first time [3]. This is the most clearly stated explanation for what is currently known as the Tyndall influence. This unique property of AuNPs may be owing to their small size. The term "nanoparticles (NPs)" refers to a special type of intermediary atom between bulk materials that allows them to have distinct photonic, electrical, catalytic, and medicinal properties [4]. Nanocarriers can absorb vast amounts of medications with poor pharmacodynamics or significant toxic effects on their behalf. Embedded medications can diffuse widely in tissues due to their small size. One example of a useful use is nanocapsules, which are used in food items to increase the absorption rate of nutrients. Vitamins are delivered to food and drink using organic and polymeric NPs that do not alter the taste or appearance [5].

Longer shelf life, safer packaging, improved traceability of food goods, and healthier food are all advantages of nanotechnology in food packaging. 'Nanofood' is defined as food that has been grown, created, processed, or packaged using nanotechnology processes or instruments, or to which manufactured NPs have been added [6]. Although more than 200 companies across the globe are actively involved in Nano-food research and development, it is more realistic to state that the potential of nanotechnologies in the food sector has yet to be recognized. Because of their capacity to interact with microbes, NPs can be used as antibacterial and antifungal agents. NPs adhere to the cell surface and exert their antibacterial capabilities. This contact results in structural damage and alterations [7]. Antibiotics frequently lose their potency over time as a consequence of both the formation and development of resistance to antibiotics in microbial pathogens. Every year, the so-called "antibiotic resistance crisis" including untreatable diseases associated with microbes that are resistant to antibiotics, cost billions of dollars in additional medical costs [8]. AuNPs are interesting in many disciplines of medicine because of their unique qualities, such as their variable shape, size, high stability, surface properties, optical properties, multi-functional potential, low cytotoxicity, and biocompatibility [9]. Although gold is a benign nanomaterial, the chemicals used in its manufacturing and alteration could be harmful. When the concentration of AuNPs is large, poisoning can occur, however, AuNPs also have antimicrobial properties. They had no harmful effects on normal cells at specific concentrations [10].

The production, manipulation, and application of materials on the Nano-scale (1–100 nm) are known as nanotechnology [11]. Many material properties are significantly different at this scale that are not generally observable in the same materials at bigger scales. Although standard physical and chemical processes can be used to make Nanoscale materials, environmentally beneficial sustainable sciences approaches may now be used to biologically create products [12, 13]. In modern history, the fusion of nanotechnology with biology has generated a new field known as "Nanobiotechnology," which includes bacteria, fungi, actinomycetes, algae, plants, viruses, and yeasts that are used in a variety of biophysical and biomechanical processes. [14]. Metallic NPs containing silver (Ag), gold (Au), copper (Cu), and platinum (Pt) were extensively employed in a variety of applications, including pharmaceuticals, cosmetics, and medical [15]. Antimicrobial medication development that is both new and effective appears to be a key concern. Metal NPs with antibacterial properties, such as Au, Zn, Ag and Cu, have been recognized and employed for decades due to their diverse features, activity ranges, and modes of action. Nanotechnology has recently opened up a world of possibilities in a variety of disciplines of science and technology. Combining medicines with nanotechnology, on the other hand, provides a variety of benefits and has piqued the interest of many researchers. [16, 17]. NPs have been explored in drug delivery

systems for more than 20 years, with encouraging results. Because of their great robust adsorption capacity, biocompatibility, and simplicity of surface modification owing to exterior small-size effects and quantum-size, NPs are fascinating for research in medical imaging, disease detection, and drug administration [18]. The electrical and optical properties of AuNPs, which are highly dependent on both size and shape, have attracted a lot of interest. By varying the ingredients and quantities, AuNPs of various forms and sizes may be easily synthesized [19, 20]. In both experimental and industrial settings, AuNPs may be created cage-like, circular, filament, and other morphologies. The majority of AuNP investigations have looked at how they interact with diverse biomolecules such as medicines, genes, peptides, and other targeted ligands [21].

## 2. Synthesis of Gold Nanoparticles from Different Methods

There are various types of methods to synthesize gold nanoparticles. Nanoparticles can be manufactured using a variety of biological, physical, and chemical methods from fungus, microbes, and plants. This is a growing research topic [5, 22]. Extensive research on nanoparticle associations with cells or tissues is required to determine recommended particle size, shape, and interfacial properties for applicability [23]. A variety of physicochemical processes have been used to create NPs, many of which have resulted in significant external factors. AuNPs seem to be the most significant metallic nanostructures due to their long history of medicinal uses. AuNPs are the most extensively documented type in literature. Approximately 87,000 papers have been published since 1996 [5]. A variety of biological, physical, and chemical synthesis approaches have been established for the production of AuNPs. “The physicochemical properties of gold nanoparticles relevant to antimicrobial activity are summarized in Table 1.”

**Table 1.** Physicochemical Properties of Gold Nanoparticles Relevant to Antimicrobial Activity

Property	Description	Impact on Antimicrobial Activity
Size (1–100 nm)	AuNPs can be synthesized in controlled sizes	Smaller particles show stronger membrane penetration and ROS generation
Shape	Spherical, rod-like, triangular, star-shaped	Shape influences surface interaction with microbial cells
Surface Charge	Positive, negative, or neutral depending on capping agent	Positively charged AuNPs exhibit enhanced binding to negatively charged bacterial membranes
Surface Functionalization	Polymers, peptides, plant extracts, citrate, etc.	Improves stability, enhances targeted antimicrobial activity
Optical Properties	Surface plasmon resonance (SPR)	Enables photothermal antimicrobial effects when irradiated

### 2.1. Physical Method

Using polysaccharide alginate as a buffer, the irradiation process is one strategy for the manufacture of AuNPs with uniform size from 5-40 nm and exceptional quality. Using reducing agents like citric acid and a binding agent like cetyltrimethylammonium bromide (CTAB), microwave irradiation was utilized to create AuNPs. Furthermore, AuNPs can be generated by temperature or photochemical reduction, as well as citrate, tartrate, and malate reduction of HAuCl<sub>4</sub> [24]. The creation of gold-polyethylene glycol NPs by polymerization processes with sizes of 10-50 nm has been documented as a popular method of photochemical reduction.

Moreover, gold salt is decreased in this method by radical production and UV-reaction with polyethylene glycol diacrylate [25].

## **2.2. Biological Method**

The biosynthesis of NPs is a means of generating NPs that is safe, dynamic, and energy efficient. To generate NPs *in vivo*, this technique uses a variety of biological resources including several from prokaryotes to eukaryotes [5]. Carbohydrates, enzymes, proteins, phenolic substances, and fatty acids are all significant components in the stability of metallic ions to NPs and bioreduction. AuNPs produced using biological mechanisms are more precise while those produced utilize different approaches. The production of AuNPs via chemical pathways is efficient, but the creation of secondary metabolites that are hazardous to the environment and public health is a serious challenge. Various biological entities, such as fungus, yeasts, bacteria, and plants, are investigating innovative strategies for the production of pure nanoparticles to manufacture AuNPs [26].

## **2.3. Chemical Method**

Functionalization can be based on hydrophilicity, surfactants, activity, and stabilizers in the modeling of NPs for a given purpose. The most desirable condition of NPs is Au<sup>0</sup> (non-oxidized form). The main stage in the production of ionized AuNPs is to reduce the oxide of gold Au<sup>+1</sup> (aureus) or Au<sup>+3</sup> (auric) to Au<sup>0</sup> by introducing a reducing agent to the process, which is then quickly combined to produce relatively homogenous NPs of varied sizes [5, 27]. The AuNPs solution is then saturated, causing mild precipitation. To reduce aggregate NPs, a stabilization fluid that adsorbs on the surface of NPs is frequently utilized. [26, 28]. The premise is the same, but there are a few different ways to get there.

## **3. Types of Gold Nanoparticles**

The gold nanoparticle production procedures dictate the forms of AuNPs (gold nanorods, nanoshells, nanocages, and nanospheres). Table 2 lists the different types, shapes, sizes, and applications of AuNPs.

### **3.1. Gold Nanorods (AuNRs)**

Because of their unique optical and electrical characteristics, gold nanorods are regarded as a significant nano-theranostic tool in biomedicine. Due to the restricted clinical use of gold nanorods with diameters more than 6 nm, researchers are focusing their efforts on the production and gold nanorods of a diameter significantly lower than 6 nm size but have characteristics optical and electrical as larger gold nanorods are being used [29]. Gold nanorods' strong surface plasma resonance (SPR) allows them to absorb a considerable quantity of light even with a small number of them, and their intrinsic physicochemical features have made them a viable multifunctional tool in biomedicine research [29].

### **3.2. Gold Nanoshells**

A dielectric core is encircled by a thin gold shell in gold nanoshells. They have a wide range of physical, optical, and chemical properties as one-of-a-kind AuNPs. In comparison to other NPs, gold nanoshells have a unique structure. They do so in such a way that a single nanostructure has many ideal features. Gold nanoshells have large optical absorption and scattering cross-sections as a consequence of nanoscale vibrational mechanisms, making them suitable contrast agents for bioimaging [30].

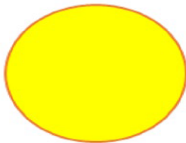

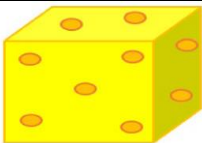
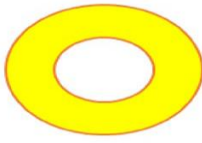
### 3.3. Gold Nanocages

Gold nanocages are gold nanostructures having adjustable optical characteristics and a denser volume, which can be used in a variety of biomedical applications. The synthesis of gold nanocages was reported by researchers as a result of chloroauric acid and silver in water, undergoing an electrolytic repair process. Gold nanocages are a novel type of NPs employed as photothermal sensors in biomedical agents due to their great optical assimilation in the closer range [31].

### 3.4. Gold Nanosphere

They can easily produce at the industrial scale which is why they are used in nanotechnology. The ratio of gold to sodium citrate can be changed to adjust the size of gold nanospheres. Faraday reported the use of Turkevich's citrate reduction method to make spherical AuNPs in 1857. Perrault and Chen published a paper in 2009 detailing the synthesis of gold nanospheres [32].

**Table 2.** Types, Synthesis, and Applications of AuNPs [33].

Types	Shapes	Size	Preparation Method	Applications
Gold Nanosphere		2-100 nm	Prepared by the reduction of HAuCl <sub>4</sub>	Cell imaging Photothermal therapy Photosensitizer
Gold Nanorods		10-100 nm	Prepared by template method	Tumor imaging Photothermal therapy Photosensitizer
Gold Nanocages		40-50 nm	Prepared by Galvanic replacement reaction between Ag and HAuCl <sub>4</sub>	Tumor imaging Photothermal therapy Photosensitizer Photodynamic therapy
Gold Nanoshell		The diameter of the core is ~100 nm and the shell of gold is 1-20nm	Prepared by dielectric core material coated by a thin gold layer	Tumor imaging Photothermal therapy Photosensitizer Photodynamic therapy

## 4. Gold Nanoparticles as Antimicrobial Agent

### 4.1. Anti-Viral

In chemotherapy, the potential of viruses to acquire resistance is a persistent issue [34]. Viruses employ a variety of genetic pathways to ensure their survival [35]. The development of viral resistance demands the production of novel antiviral agents. As a result, new antiviral drugs and procedures are still being developed. Nanotechnologies bring up lots of new possibilities for future medicine development [36, 37]. Nanogold-based approaches are a potential direction among known ways for treating viral infections. AuNPs have a high surface density of free electrons, which gives them natural optical, electrical, and catalytic capabilities; as a result, they're being studied as nanocarriers [38]. AuNPs have been suggested for a variety of biosensing functions and applications, including virus detection [39]. Because the adhesion of virus to the cell surface is

inhibited, AuNPs functionalized with sulfonate ligand are harmless and effective against viruses [40]. Another, longer sulfonate linker was also demonstrated to be advantageous for modification of AuNPs for subsequent multivalent virus binding and irreversible viral inactivation [41]. In comparison to a virustatic found for the 2-N-morpholino ethanesulfonic acid ligand, the virucidal mechanism for AuNPs modified with MOS was identified. At the same time, non-modified citrate-coated NPs showed no inhibitory action [42]. Mechanistic investigations using AuNPs capped with 2-N-morpholino ethanesulfonic acid demonstrated that NPs prevent viral infection by interfering with virus adhesion to the host's cell, viral invasion, and cell-to-cell dissemination [43]. Nontoxic antiviral agents include functionalized AuNPs with octanethiol, 3-mercaptopethylsulfonate, 8-mercaptopentan-1-aminium, and undecanesulfonic acid are most effective against COVID-19 [44]. Furthermore, these AuNPs are most effective in the treatment of human norovirus, Human papillomavirus (HPV), influenza virus herpes virus-2, and Respiratory syncytial virus (RSV) [45, 46].

#### 4.2. Anti-Fungal

Antifungal drugs such as itraconazole, nystatin, fluconazole, ketoconazole, amphotericin B, and flucytosine are resistant to several fungal species [47, 48]. Significantly, antimicrobial resistance has been identified being a key source of treatment failures in *Candida albicans* and other fungal infections [49]. *Candida* infections have developed resistance mechanisms, such as decreased drug adherence for its antigen, altered antibiotic metabolic processes, and reduced drug deposition [50]. To overcome antifungal resistance, Recently, various techniques based on novel substances, such as metal oxide NPs and metal, have been presented [51]. "As shown in Table 3, AuNPs exhibit significant antifungal activity against a range of pathogenic fungi."

Recent research has found that AuNP, alone or in combination with other materials, has antifungal effects with minimal toxicity in mammalian cells [52]. Due to their complicated eukaryotic structures, fungal infections have few treatment options, and the development of biofilms makes it much more difficult to treat them with standard medicines [53]. AuNPs are also manufactured and used in the fight against fungi that are toxic to humans. In another investigation, the antifungal efficacy of AuNPs having an average diameter of approximately 40 nm towards multiple unique strains was found to be comparable: 0.002-0.004 g/mL for fungal suppression and 0.002-0.008 g/mL for fungal distress. [54] used colloidal AuNPs in three distinct forms (flower-shaped, spherical, and star) to investigate their antimicrobial activities [55]. In the therapies of a fungus disease, lipid membrane flucytosine AuNP showed good results [56]. Moreover, photosensitizers such as aluminum phthalocyanine, methylene blue (MB), and Rose Bengal are used to coat AuNPs to treat *Candida* (biofilm) infections [57]. The use of methylene blue-coated AuNPs for superficial fungal infections has shown significant outcomes [58].

**Table 3.** Antifungal activity of AuNPs [59, 60].

Type	Size	Effectiveness
<i>Candida</i> spp.	7-15nm	Highly effective
<i>Cryptococcus</i> spp.	Gold phosphine complex	Effective
<i>P. graminis</i>	45-75nm	Effective
<i>C. albicans</i> MTCC 1833	18-80nm	Effective
<i>Candida</i> spp.	Gold phosphine complex	Effective
<i>Aspergillus</i> spp	Gold phosphine complex	Effective
<i>Candida</i> spp.	5nm	Effective

#### 4.3. Antibacterial-Activity

Gold, a valuable metal, has played a significant part in human history. It's been used in jewelry, and cashless transactions, but as the screening test for centuries. For several years, AuNPs are mostly applied, trying to date back to the Roman era [61]. Gold, a valuable metal, has played a significant part in human history. It has been used in jewelry, currency trade, and as a precious metal for centuries. In earlier history AuNPs have been used, spanning back to the Roman era [61]. The antibacterial efficacy of the produced gold nanoparticle was investigated using conventional good diffusion protocols against several clinical isolate bacteria [62]. Fresh overnight cultures were placed on a sterilized culture plate of nutrient agar. Boring 8 mm the well in the agar media surface was done with a sterile cork borer. These wells are filled with 50 $\mu$ l of nanostructures solution with 0.002 g/1000ml and 0.004 g/1000ml, as well as a positive control of 0.002 g/1000ml Streptomycin. The incubation was given for 28 hours at 37 °C. By analyzing the inhibition zones enclosing some areas saturated by AuNPs and determining the percent diameter of the inhibition zone, the antibacterial effect of the generated gold nanoparticle could be found. The antimicrobial research was conducted in triplicate. The strategy below is used to compute the percentage of inhibitory activity.

$$\text{PGI} = (\text{BDC} - \text{BDT}) / \text{BDC} \times 100,$$

PGI = Percent growth inhibition,  
BDC = Bacteria colony diameter in control,  
BDT = Bacteria colony diameter in treatment.

The antibacterial activity of AuNPs produced from a *muricata* leaves extract against a variety of microorganisms. The findings revealed that the produced AuNPs were injurious to all of the bacteria tested at several dosages. *Clostridium sporogenes* was the bacteria that was quite sensitive to AuNPs in every 0.002 g/1000ml and 0.004 g/1000ml concentrations, had the largest percentages of inhibitory activity of 50% and 54%, respectively, however, *Staphylococcus aureus* was the least predisposed species across both concentration levels, and *Enterococcus faecalis* was the least predisposed bacteria at 0.002 g/1000ml intensity of synthesized AuNPs, exhibiting 40% inhibitory activity. As the number of AuNPs grows, the efficiency of the microparticles even in contrast to test bacteria rises. *Staphylococcus aureus* > *Enterococcus faecalis* > *Klebsiella pneumoniae* > *Clostridium sporogenes* was the ranking of efficiency of such manufactured, at both levels of the nanostructure, the designated potentially damaging microbes were defeated. Plant-mediated metallic nanostructures have previously been shown to take an active part in medicine delivery which may be used to battle a broad spectrum of microbes due to their powerful antimicrobial abilities [63-65]. This suggests that the AuNPs were effective against bacteria and might be utilized to treat illnesses caused by bacteria. “Details regarding the antibacterial performance of gold nanoparticles against *E. coli* are provided in Table 4.”

**Table 4.** Antibacterial activity of AuNPs against *E. coli* [59, 60].

Size	Matrix, ligand	Effectiveness
5nm	Chemical reduction	Not effective
1-22	CTAB	Highly effective
5-12nm	<i>Shewanella oneidensis</i>	Not effective
33-65nm	<i>T. decandra</i>	Effective
150nm	<i>Mentha piperita</i>	Effective
6-70nm	<i>E. Hirta L.</i>	Effective

## 5. Gold Nanoparticles have an Antibacterial Impact.

Generally, AuNPs made by chemical techniques and covered with citrate, polyvinylpyrrolidone (PVP), or other benign stabilizers are thought to have no antibacterial action [66]. Antibacterial activity of AuNPs in the range of sizes of 20–30 nm stabilized by PVP/SDS towards *Escherichia coli* K12 NCTC 10538 and *Staphylococcus aureus* ATCC 6538 [67, 68]. AuNPs are widely thought to be physiologically nonreactive and exhibit no antimicrobial properties [69]. One compelling finding is that, as contrasted to silver NPs (AgNPs), they have a great MIC value or a tiny ZOI. versus *Staphylococcus aureus* ATCC 25923, evaluated that the PVP stabilized AgNPs (0.025 mm) and AuNPs (0.08mm) have antimicrobial efficacy. The MIC of ANPs was 4.86 2.71 g/mL, and the MBC was 6.25 g/mL, however, AuNPs only inhibited at a dosage of 197 g/mL [70] created AuNPs, AgNPs, Au–Ag [71], *Trianthema decandra* root extract (33–65 nm) [72] *Helianthus annuus* blossom derive (0.035 mm, with a range of 25–55 nm) [73] and *Carthamus tinctorius* dried flower extract (35 nm, ranged 30–50 nm) [74]. It's fascinating that those "green" AuNPs have effective antibacterial action against a specific variant of bacteria, specifically when contrasted to chemically generated AuNPs, which have almost little antibacterial activity against either strain [75]. The issue is where all the antibacterial action derives from in this scenario. It might be attributable to the extracts, AuNPs, or a mix of both. Some extracts, such as those from the plant *Euphorbia hirta*, have antibacterial properties [76]. The synergistic impact of AuNPs and isolates might demonstrate their antimicrobial property [76]. “As shown in Table 5, AuNPs demonstrate significant antibacterial activity against *Staphylococcus aureus*.”

PG-AuNPs were assayed for antimicrobial effect against *Klebsiella pneumoniae* (MTCC 109), *Bacillus subtilis* (MTCC 2394), and *Escherichia coli* (MTCC 448), using the conventional well diffusion technique [77]. 8 mm wells were drilled using a sterilized cork borer in the plates of agar and were used to disperse freshly produced colonies over a sterilized nutrient agar medium. The wells were filled with various concentrations of PG-AuNPs (10 L, 20 L, 30 L, and 40 L), with 10 L of ciprofloxacin acting as a control. Then after, plates were then incubated overnight at 37 °C to assess the antimicrobial activities of the PG-AuNPs by calculating the largest diameter of the inhibition zone surrounding each PG-AuNPs-impregnated well.

**Table 5.** Antibacterial Effects of AuNPs against *S. aureus* [59].

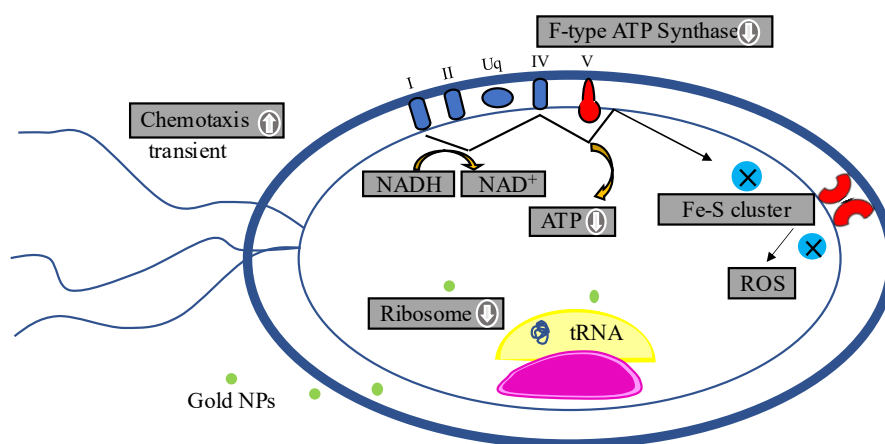
Size	Matrix, ligand	Effectiveness
80nm	PVP	Effective (200 µg/µl)
5-30nm	<i>Euphorbia hirta</i> L.	Effective (512 µg/µl)
1-3nm	<i>Cationic peptide</i>	Effective
4-8nm	<i>Polyamidamine</i>	Effective (2 µg/µl)
33-65nm	<i>T. decandra</i>	Effective

## 6. Gold nanoparticles' Mode of Action

In contrast to silver NPs, some research has been conducted recently on examining the spectrum of activity of solitary AgNPs on diverse bacteria, and they have been tested in concert with other chemicals and treatments. Nanotechnologies, on the other hand, claim that the transformation of molecules into NPs has various impacts. Increasing the surface-to-volume ratio [78]. The presence of Gold ions in the surroundings of bacterium, and the generation of reactive oxygen species seem to be likely the main reasons for AuNPs' antibacterial action [79]. Gold NPs work against bacteria in two directions: one, they disintegrate membrane potential by blocking ATPase activity, lowering ATP levels, and the other; they prevent the ribosomal component from binding tRNA. In the initial stages of a reaction, AuNPs improve chemotaxis [80]. Gold nanoparticle aggregates of various sorts have been found. Some bacteria cause numerous layers to grow around the cell walls, while

others only possess aggregates under certain areas and still others have NPs scattered across the cell surface [81].

On Gram<sup>+</sup> and Gram<sup>-</sup> microorganisms, AuNPs form multimodal aggregating patterns. The type of the bacteria and the size of the AuNPs dictate the patterns [82, 83]. Because they have been proven to change the cell surface, cationic AuNPs may be useful as adjuvants to recognized antibiotics [84]. AuNPs (AuNPs) with diameters of 6 or 2 nm interacted with *Bacillus subtilis* (Gram<sup>+</sup>) and *Escherichia coli* (Gram<sup>-</sup>) cell membranes, resulting in remarkably different AuNP surface aggregating patterns or rupture, relying on the dimension of the AuNPs [79]. Binding studies done during a bacterium's invasion of a eukaryotic cell or bacterial cell division can be used to discover and describe zones of specialized biological activity. Bacteria may be harmed by carbon-based substances due to oxidation or structural degradation [85, 86]. Gold NPs could be advantageous in the formulation of antibacterial techniques because of their environmental friendliness, adaptability in surface treatment, and chemically diverse effects, including photothermal effects [87-89].



**Fig. 1** Schematic diagram of the mechanism of action of bactericidal AuNPs on *Escherichia coli*.

Gold NPs induce the downregulation of the oxidative phosphorylation pathway (F-type ATP synthase and ATP level) and ribosome pathways, and the transient upregulation of chemotaxis.

Gold NPs do not induce the change of ROS-related processes [80].

## 7. Food Processing, Food Packaging, and Preservation

Food safety has benefited greatly from the use of AuNPs in the food industry. Nanotechnology has the potential to provide high-throughput and convenient diagnostic tools for detecting pathogenic microorganisms and toxins in food samples [90]. By conjugating AuNPs with a DNA-zyme probe, researchers reported developing a simple and easy sensing method for detecting the *invA* gene of *Salmonella*. The gold nanoparticle-based method has a sensitivity of  $3 \times 10^3$  CFU/ml and takes 5 minutes to complete [91]. The nano-ELAAS method, which uses AuNPs to create an enzyme-linked antibody sandwich, proved to be sensitive, specific, fast, and quantitative in detecting *Salmonella enterica* serovar Typhimurium (STM). The sensitivity and time of that assay were reported to be  $1 \times 10^3$  CFU/ml and 5 min [90].

NPs are being used in the food industry to increase nutritional status and movement, as well as flavor, color, and stability, as well as improve stability. Furthermore, NPs have the potential to aid in the production of healthy alternatives that are reduced in sugar, fat, and salt content that address

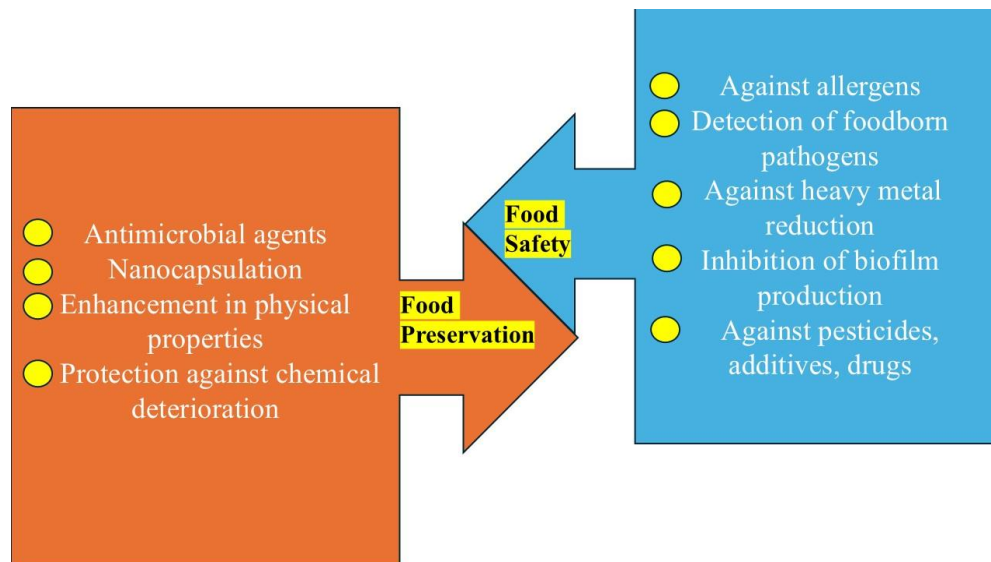
several food-related disorders [92]. Food additives containing bulk quantities of SiO<sub>2</sub> and TiO<sub>2</sub> oxides (E551 and E171, respectively) have recently been approved [93, 94]. It's been suggested that effective olive oil hydrolysis can be achieved by covalently immobilizing porcine triacylglycerol lipase onto functionalized nanoscale SiO<sub>2</sub> with a reactive aldehyde group for greater flexibility, durability, and reuse [95, 96]. For the embedding of food products, functional foods, additives, and nutritional supplements, numerous nanoscale and micro-structured modules of nanomaterials were developed. "As shown in Table 6, gold nanoparticles have been widely applied in food packaging for antimicrobial and preservation purposes."

Throughout human history, gold has been regarded as a valuable commodity. Because gold atoms have such distinct and uncommon properties, gold chemistry has garnered a lot of interest. Over the years, in addition to jewelry, dentistry, cosmetics, and, of course, money, gold has been widely employed for material science, catalytic reasons, and medical [97, 98]. Gold compounds have been shown to exhibit antimicrobial and antifungal effects, as well as antiamebic, antileishmanial, and antitrypanosomal activity. Several gold compounds, including N-heterocyclic-L-cysteine, and phosphine-type ligands, including anti-malarial drugs, are in use as antibacterial agents for certain pathogens. There has been a lot of interest in packaging employing various NPs in recent years, as shelf life, mechanical properties, and gas blocking characteristics are all affected. In addition, the effects of NPs on bacterial growth inhibition have inspired greater research into the concentration, size, and shape of NPs used in packaging, depending on the product; the type of packing matrix is critical [99-101]. Figure 2 represents the role of nanotechnology in daily life.

**Table 6.** Application of Gold Nanoparticles in Food Packaging.

Application Area	Role of AuNPs	Benefits
Active Packaging	Incorporation into films/coatings	Extended shelf life through antimicrobial action
Smart Packaging (Sensors)	Colorimetric/optical sensing via SPR	Detect pathogens, spoilage chemicals
Barrier Enhancement	Improves mechanical + gas barrier properties	Reduces oxygen/moisture exposure
Edible Coatings	AuNPs blended into edible films	Safe antimicrobial surface layer

Antibacterial properties, mechanical qualities, thermal resistance, and gas barrier capabilities, are predicted to increase when metal NPs such as gold and silver are added to polymer matrices when compared to standard polymers [102, 103]. Many of these NPs also increase packing resistance at elevated pressure, such as mechanical and thermally resistance. Antifungal storage for cherries, antimicrobial packaging for raw meat with antioxidant and silver zeolite protection for fungus are among the food coatings available. Although silver NPs have significantly more applications in the food business, gold nanoparticle packing can be used in food products due to its unique properties [104]. Because of their nontoxic and inert behavior, oxidative catalytic characteristics, and medicinal potential, gold NPs have piqued the interest of both the meat and pharmaceutical manufacturing sectors. The application of nanotechnology in the food industry, such as the diffusion of NPs into foodstuff, can help reduce the incidence of foodborne infections. Due to their high surface-to-volume ratio, AuNPs interact extensively with biological molecules and bacterial cell bonds, inducing bacterial degradation [92, 105].



**Fig. 2** Schematic presentation of nanotechnology in daily life.

### 8. Drug Distribution

Administration of nano-vehicles to sick regions with pinpoint accuracy, analysis of the medication load and zone, increasing drug accessibility at the target location, and enhancing drug solubility and durability are just a few of the appealing characteristics of nanoparticle-based therapy that lower mortality [106]. In medicine, metallic NPs, liposomes, polymers, and dendrimers were employed, however, AuNPs offer unique features that further make them the best medication substrate. AuNPs are appropriate for nanocarrier construction because they are simple to prepare, bio-inert, and non-toxic [107, 108]. AuNPs manufacturing tenability enables the creation of particles with Various critical diameters and complete area distribution management. For comparison purposes, tumor cells become hypersensitive to chemical therapy due to repetitive medication administration; nanostructures, on the other hand, are capable of increasing intracellular drug accumulation due to their ability to target and distribute more precise medications. AuNP scans connected to doxorubicin (DOX) aid in medication aggregation and retention. As a result, as compared to free DOX, cells with increased intracellular DOX content had better cytotoxicity [5, 109]. “As shown in Table 7, gold nanoparticles exhibit strong antimicrobial activity and have promising applications in food preservation and packaging.”

**Table 7.** Antimicrobial Activities of Gold Nanoparticles and Their Application in Food Preservation & Packaging

Aspect	Description	Key Applications	Challenges	Future Prospects
Gold Nanoparticles (AuNPs) Properties	Surface-area-to-volume ratio: High, enhancing reactivity and stability. Functionalization: Easy modification with biomolecules for targeted	Food Packaging: Improves material antimicrobial properties. Biomedical: Drug delivery and diagnostics.	Cost of Production: High synthesis costs can limit industrial use. Scale-up Issues: Challenges in mass production for food applications.	Green Synthesis: Focus on eco-friendly, sustainable production methods. Wider Use in Biomedicine: Expanding use

	applications. Biocompatibility: Non-toxic and suitable for biomedical and food industry uses.			in drug delivery and diagnostics.
Antimicrobial Mechanisms of AuNPs	Cell Wall Disruption: Interaction with microbial cell walls, causing structural damage. Metabolic Interference: Interferes with microbial metabolism, affecting processes like respiration. ROS Production: Generates reactive oxygen species causing oxidative stress.	Bacteria Inhibition: Targets foodborne pathogens such as <i>E. coli</i> and <i>Salmonella</i> . Fungi and Viruses: Inhibition of fungal growth and viral particles.	Potential Resistance: Microbial resistance to nanoparticles may develop over time. Nanoparticle Aggregation: Potential loss of efficacy due to aggregation of particles.	Multi-functional Nanoparticles: Combining AuNPs with other antimicrobial agents for enhanced effect. Targeted Action: Developing AuNPs for specific pathogens.
Application in Food Preservation	Antimicrobial Packaging: AuNPs incorporated into packaging materials to prevent microbial growth. Shelf-life Extension: Inhibits spoilage by controlling microbial contamination.	Smart Packaging: Active packaging that reacts to changes in the food environment. Food Preservation: Prolonging shelf life and reducing food waste.	Regulatory Approval: Must comply with food safety regulations. Consumer Concerns: Public perception and acceptance of nanoparticle-containing products.	Advanced Smart Packaging: AuNPs combined with sensors or release mechanisms. Sustainable Materials: Developing biodegradable and eco-friendly nanoparticle-based packaging.
Synthesis Methods of AuNPs	Chemical Reduction: Gold salts are reduced to form	Chemical Synthesis: Common in lab-scale	Scalability: Difficulty in scaling biological methods for	Eco-friendly Synthesis: Focus on developing

	nanoparticles. Physical Methods: Laser ablation and vapor deposition. Biological Methods: Using plant extracts or microorganisms.	experiments. Biological Synthesis: More sustainable, using natural sources for nanoparticle formation.	industrial use. Standardization: Variability in properties from different synthesis methods.	green methods for large-scale production. Hybrid Approaches: Combining different synthesis techniques for better control.
Challenges in Food Packaging	Regulatory Compliance: Ensuring nanoparticles used in food packaging meet safety standards. Cost and Accessibility: High cost of AuNPs limits widespread use in food products.	Food Packaging Innovations: AuNPs used in packaging materials like films and coatings.	Migration: Risk of nanoparticles migrating into food. Toxicity: Potential risks to human health from ingestion.	Regulatory Clarification: Establishing clear guidelines for nanoparticle use in food packaging. Long-term Safety Studies: Conducting thorough toxicological assessments for consumer safety.
Consumer Safety & Public Perception	Non-toxic at Low Concentrations: AuNPs are generally safe at low concentrations used in food products. Human Health: Biocompatible and poses minimal risk when properly regulated.	Nanotechnology Education: Raising awareness about the benefits and safety of nanoparticles in food.	Public Concerns: Misunderstandings about nanotechnology and its risks. Regulatory Gaps: Lack of clear safety standards in some regions.	Consumer Trust: Building trust through transparency and clear labeling. Public Awareness Campaigns: Educating consumers on the safety and benefits of nanoparticle use.

## Conclusion

This investigation looked at how nanoparticles are employed in the food industry. Metal oxide nanoparticles are primarily used to reduce food pathogens and minimize food contamination. Nanoparticles having a large surface area and the ability to change their size can be employed in a variety of applications. Several nanoparticles are employed as sensors to identify pathogens in food. Microorganisms that contaminate food are quickly detected by them. To recognize foodborne infections, we can employ nanoparticles and thin films as biosensors. To combat foodborne

infections, several nanoparticles such as gold, silver, zinc oxide, titanium oxide, and graphene oxide are employed in commercial goods. Food pathogens are also detected using biosensors composed of thin films. The features and uses of AuNPs have been steadily defined, however due to a lack of consistent detection and assessment criteria, there are still conflicting results and a lack of clarity about antimicrobial activity and toxicity. Further research should develop standardized standards to make cross-study comparisons easier.

### Conflict of Interest

The authors declare no conflict of interest.

### Authors' Contribution

MFH conceived the original idea and designed the outlines of the study. All the authors equally contributed and wrote the 1<sup>st</sup> draft of the manuscript. SSH revised the whole manuscript and formatted it accordingly. All authors have read and approved the final manuscript.

### Funding

None.

### References:

1. Li, G. and H.X. Lou, *Strategies to diversify natural products for drug discovery*. Medicinal research reviews, 2018. **38**(4): p. 1255-1294.
2. Yang, T., et al., *Synthesis, characterization, and self-assembly of protein lysozyme monolayer-stabilized gold nanoparticles*. Langmuir, 2007. **23**(21): p. 10533-10538.
3. Das, S.K. and E. Marsili, *Bioinspired metal nanoparticle: synthesis, properties and application*. 2011: Croacia: InTech.
4. Makhlof, A.S.H. and A. Barhoum, *Fundamentals of nanoparticles: classifications, synthesis methods, properties and characterization*. 2018: William Andrew.
5. Hammami, I. and N.M. Alabdallah, *Gold nanoparticles: Synthesis properties and applications*. Journal of King Saud University-Science, 2021. **33**(7): p. 101560.
6. Bratovcic, A., *Nanomaterials in food processing and packaging, its toxicity and food labeling*. Acta Scientific Nutritional Health, 2020. **4**(9): p. 07-13.
7. Burygin, G., et al., *On the enhanced antibacterial activity of antibiotics mixed with gold nanoparticles*. Nanoscale research letters, 2009. **4**(8): p. 794-801.
8. Su, C., et al., *Antibacterial properties of functionalized gold nanoparticles and their application in oral biology*. Journal of Nanomaterials, 2020. **2020**.
9. Khan, A., et al., *Gold nanoparticles: synthesis and applications in drug delivery*. Tropical journal of pharmaceutical research, 2014. **13**(7): p. 1169-1177.
10. Gu, X., et al., *Preparation and antibacterial properties of gold nanoparticles: A review*. Environmental Chemistry Letters, 2021. **19**(1): p. 167-187.
11. Singh, A., S. Dubey, and H.K. Dubey, *Nanotechnology: the future engineering*. Nanotechnology, 2019. **6**(2): p. 230-3.
12. Shah, M., et al., *Green synthesis of metallic nanoparticles via biological entities*. Materials, 2015. **8**(11): p. 7278-7308.
13. Marooufpour, N., et al., *Biological synthesis of nanoparticles by different groups of bacteria*, in *Microbial Nanobionics*. 2019, Springer. p. 63-85.
14. Khan, T., et al., *Microbes: Nature's cell factories of nanoparticles synthesis*, in *Exploring the realms of nature for nanosynthesis*. 2018, Springer. p. 25-50.
15. Jagadish, K., et al., *Ecofriendly synthesis of metal/metal oxide nanoparticles and their application in food packaging and food preservation*, in *Impact of nanoscience in the food industry*. 2018, Elsevier. p. 197-216.

16. Adibkia, K., et al., *Piroxicam nanoparticles for ocular delivery: physicochemical characterization and implementation in endotoxin-induced uveitis*. Journal of drug targeting, 2007. **15**(6): p. 407-416.
17. Adibkia, K., et al., *Inhibition of endotoxin-induced uveitis by methylprednisolone acetate nanosuspension in rabbits*. Journal of Ocular Pharmacology and Therapeutics, 2007. **23**(5): p. 421-432.
18. Mukherjee, S., et al., *Green synthesis and characterization of monodispersed gold nanoparticles: toxicity study, delivery of doxorubicin and its bio-distribution in mouse model*. Journal of Biomedical Nanotechnology, 2016. **12**(1): p. 165-181.
19. Tao, C., *Antimicrobial activity and toxicity of gold nanoparticles: research progress, challenges and prospects*. Letters in applied microbiology, 2018. **67**(6): p. 537-543.
20. Verma, H.N., P. Singh, and R. Chavan, *Gold nanoparticle: synthesis and characterization*. Veterinary world, 2014. **7**(2): p. 72.
21. Kumar, A., et al., *Gold nanoparticles functionalized with therapeutic and targeted peptides for cancer treatment*. Biomaterials, 2012. **33**(4): p. 1180-1189.
22. Kalimuthu, K., et al., *Eco-friendly synthesis and biomedical applications of gold nanoparticles: A review*. Microchemical Journal, 2020. **152**: p. 104296.
23. Hoshyar, N., et al., *The effect of nanoparticle size on in vivo pharmacokinetics and cellular interaction*. Nanomedicine, 2016. **11**(6): p. 673-692.
24. Guo, W., et al., *Layer-by-layer assembled gold nanoparticles modified anode and its application in microbial fuel cells*. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2012. **415**: p. 105-111.
25. Chen, K.-S., et al., *Preparation of thermosensitive gold nanoparticles by plasma pretreatment and UV grafted polymerization*. Thin Solid Films, 2010. **518**(24): p. 7557-7562.
26. Teimouri, M., et al., *Gold nanoparticles fabrication by plant extracts: synthesis, characterization, degradation of 4-nitrophenol from industrial wastewater, and insecticidal activity—a review*. Journal of Cleaner Production, 2018. **184**: p. 740-753.
27. Tikariha, S., et al., *Biosynthesis of gold nanoparticles, scope and application: a review*. International Journal of Pharmaceutical Sciences and Research, 2012. **3**(6): p. 1603.
28. De Souza, C.D., B.R. Nogueira, and M.E.C. Rostelato, *Review of the methodologies used in the synthesis gold nanoparticles by chemical reduction*. Journal of Alloys and Compounds, 2019. **798**: p. 714-740.
29. An, L., et al., *Small gold nanorods: recent advances in synthesis, biological imaging, and cancer therapy*. Materials, 2017. **10**(12): p. 1372.
30. Kah, J.C.Y., et al., *Critical parameters in the pegylation of gold nanoshells for biomedical applications: an in vitro macrophage study*. Journal of drug targeting, 2009. **17**(3): p. 181-193.
31. Chen, J., et al., *Gold nanocages as photothermal transducers for cancer treatment*. Small, 2010. **6**(7): p. 811-817.
32. Austin, L.A., et al., *The optical, photothermal, and facile surface chemical properties of gold and silver nanoparticles in biodiagnostics, therapy, and drug delivery*. Archives of toxicology, 2014. **88**(7): p. 1391-1417.
33. Irshad, A., et al., *A proactive model on innovative biomedical applications of gold nanoparticles*. Applied Nanoscience, 2020. **10**(8): p. 2453-2465.
34. Irwin, K.K., et al., *Antiviral drug resistance as an adaptive process*. 2016. **2**(1).
35. Lauring, A.S., J. Frydman, and R.J.N.R.M. Andino, *The role of mutational robustness in RNA virus evolution*. 2013. **11**(5): p. 327-336.

36. Khyliko, O., et al., *Influence of the virus-nanoparticles system illumination on the virus infectivity*. 2016. **10**(6): p. 453-459.
37. Rafiei, S., et al., *Gold nanoparticles impair foot-and-mouth disease virus replication*. 2015. **15**(1): p. 34-40.
38. Draz, M.S. and H.J.T. Shafiee, *Applications of gold nanoparticles in virus detection*. 2018. **8**(7): p. 1985.
39. Shevtsov, M., et al., *Applicability of metal nanoparticles in the detection and monitoring of hepatitis B virus infection*. 2017. **9**(7): p. 193.
40. Baram-Pinto, D., et al., *Inhibition of HSV-1 attachment, entry, and cell-to-cell spread by functionalized multivalent gold nanoparticles*. 2010. **6**(9): p. 1044-1050.
41. Cagno, V., et al., *Broad-spectrum non-toxic antiviral nanoparticles with a virucidal inhibition mechanism*. 2018. **17**(2): p. 195-203.
42. Piret, J. and G.J.R.i.m.v. Boivin, *Antiviral drug resistance in herpesviruses other than cytomegalovirus*. 2014. **24**(3): p. 186-218.
43. Paradowska, E., et al., *Antiviral effect of nonfunctionalized gold nanoparticles against herpes simplex virus type-1 (HSV-1) and possible contribution of near-field interaction mechanism*. 2021. **26**(19): p. 5960.
44. Mehranfar, A. and M.J.T.j.o.p.c.l. Izadyar, *Theoretical design of functionalized gold nanoparticles as antiviral agents against severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)*. 2020. **11**(24): p. 10284-10289.
45. Babaei, A., et al., *Gold nanoparticles show potential in vitro antiviral and anticancer activity*. 2021. **284**: p. 119652.
46. Kim, J., et al., *Porous gold nanoparticles for attenuating infectivity of influenza A virus*. 2020. **18**(1): p. 1-11.
47. Alves, I.A., et al., *Effects of antifungal agents alone and in combination against Candida glabrata strains susceptible or resistant to fluconazole*. 2012. **174**(3): p. 215-221.
48. Scheid, L.A., et al., *In vitro activities of antifungal agents alone and in combination against fluconazole-susceptible and-resistant strains of Candida dubliniensis*. 2012. **16**(1): p. 78-81.
49. Mishra, N., et al., *Pathogenicity and drug resistance in Candida albicans and other yeast species*. 2007. **54**(3): p. 201-235.
50. Sanglard, D., A. Coste, and S.J.F.y.r. Ferrari, *Antifungal drug resistance mechanisms in fungal pathogens from the perspective of transcriptional gene regulation*. 2009. **9**(7): p. 1029-1050.
51. Stoimenov, P.K., et al., *Metal oxide nanoparticles as bactericidal agents*. 2002. **18**(17): p. 6679-6686.
52. Jebali, A., et al., *Silver and gold nanostructures: antifungal property of different shapes of these nanostructures on Candida species*. 2014. **52**(1): p. 65-72.
53. Zangeneh, M.M., et al., *Preparation, characterization, and evaluation of cytotoxicity, antioxidant, cutaneous wound healing, antibacterial, and antifungal effects of gold nanoparticles using the aqueous extract of Falcaria vulgaris leaves*. 2019. **33**(11): p. e5216.
54. Liu, K., et al., *Investigating the role of gold nanoparticle shape and size in their toxicities to fungi*. 2018. **15**(5): p. 998.
55. Jebali, A., et al., *Triangular gold nanoparticles conjugated with peptide ligands: a new class of inhibitor for Candida albicans secreted aspartyl proteinase*. 2014. **90**(4): p. 349-355.

56. Salem, H.F., et al., *Liposomal flucytosine capped with gold nanoparticle formulations for improved ocular delivery*. 2016. **10**: p. 277.
57. Maliszewska, I., et al., *Enhancement of the efficacy of photodynamic inactivation of Candida albicans with the use of biogenic gold nanoparticles*. 2017. **93**(4): p. 1081-1090.
58. Tawfik, A.A., et al., *A study of the treatment of cutaneous fungal infection in animal model using photoactivated composite of methylene blue and gold nanoparticle*. 2016. **15**: p. 59-69.
59. Paidari, S. and S.A. Ibrahim, *Potential application of gold nanoparticles in food packaging: a mini review*. Gold Bulletin, 2021. **54**: p. 31-36.
60. López-Lorente, Á.I., S. Cárdenas, and Z.I. González-Sánchez, *Effect of synthesis, purification and growth determination methods on the antibacterial and antifungal activity of gold nanoparticles*. Materials Science and Engineering: C, 2019. **103**: p. 109805.
61. Louis, C. and O. Pluchery, *Gold nanoparticles for physics, chemistry and biology*. 2017: World Scientific.
62. Coutts, M.J., et al., *Rapid and controllable sintering of gold nanoparticle inks at room temperature using a chemical agent*. The Journal of Physical Chemistry C, 2009. **113**(4): p. 1325-1328.
63. Fouad, H., et al., *Synthesis and characterization of silver nanoparticles using Bacillus amyloliquefaciens and Bacillus subtilis to control filarial vector Culex pipiens pallens and its antimicrobial activity*. Artificial Cells, Nanomedicine, and Biotechnology, 2017. **45**(7): p. 1369-1378.
64. Diane, C., C. Sidney, and G. Jet, *Biosynthesized Gold Nanoparticles (AuNPs) for the Quantitation of Mercury (II) Ions by Digital Imaging Colorimetry*. 2019.
65. Avan, E., et al., *Effects of Annona muricata biofunctionalized gold nanoparticles on erythrocyte osmotic fragility and hematological profile in rat model*. Covenant Journal of Physical and Life Sciences (Special Edition), 2018. **1**(2).
66. Amin, R.M., et al., *Rapid and sensitive microplate assay for screening the effect of silver and gold nanoparticles on bacteria*. Nanomedicine, 2009. **4**(6): p. 637-643.
67. Mukha, I., et al., *Antibacterial action and physicochemical properties of stabilized silver and gold nanostructures on the surface of disperse silica*. Journal of Water Resource and Protection, 2010. **2010**.
68. Chatterjee, S., A. Bandyopadhyay, and K. Sarkar, *Effect of iron oxide and gold nanoparticles on bacterial growth leading towards biological application*. Journal of Nanobiotechnology, 2011. **9**(1): p. 1-7.
69. Allahverdiyev, A.M., et al., *Coping with antibiotic resistance: combining nanoparticles with antibiotics and other antimicrobial agents*. Expert review of anti-infective therapy, 2011. **9**(11): p. 1035-1052.
70. Shankar, S., et al., *Synthesis, characterization, in vitro biocompatibility, and antimicrobial activity of gold, silver and gold silver alloy nanoparticles prepared from Lansium domesticum fruit peel extract*. Materials Letters, 2014. **137**: p. 75-78.
71. MubarakAli, D., et al., *Plant extract mediated synthesis of silver and gold nanoparticles and its antibacterial activity against clinically isolated pathogens*. Colloids and Surfaces B: Biointerfaces, 2011. **85**(2): p. 360-365.
72. Geethalakshmi, R. and D. Sarada, *Gold and silver nanoparticles from Trianthema decandra: synthesis, characterization, and antimicrobial properties*. International journal of nanomedicine, 2012. **7**: p. 5375.

73. Liny, P., et al., *Preparation of gold nanoparticles from Helianthus annuus (sun flower) flowers and evaluation of their antimicrobial activities*. International Journal of Pharma and Bio Sciences, 2012. **3**(1).
74. Nagajyothi, P., et al., *Harvesting Au nanoparticles from Carthamus tinctorius flower extract and evaluation of their antimicrobial activity*. Advanced Science Letters, 2012. **5**(1): p. 124-130.
75. Mishra, A., S.K. Tripathy, and S.-I. Yun, *Bio-synthesis of gold and silver nanoparticles from Candida guilliermondii and their antimicrobial effect against pathogenic bacteria*. Journal of nanoscience and nanotechnology, 2011. **11**(1): p. 243-248.
76. Annamalai, A., et al., *Green synthesis, characterization and antimicrobial activity of Au NPs using Euphorbia hirta L. leaf extract*. Colloids and Surfaces B: Biointerfaces, 2013. **108**: p. 60-65.
77. Sathiyaraj, S., et al., *Biosynthesis, characterization, and antibacterial activity of gold nanoparticles*. Journal of Infection and Public Health, 2021. **14**(12): p. 1842-1847.
78. Li, X., et al., *Functional gold nanoparticles as potent antimicrobial agents against multi-drug-resistant bacteria*. ACS nano, 2014. **8**(10): p. 10682-10686.
79. Hayden, S.C., et al., *Aggregation and interaction of cationic nanoparticles on bacterial surfaces*. Journal of the American Chemical Society, 2012. **134**(16): p. 6920-6923.
80. Cui, Y., et al., *The molecular mechanism of action of bactericidal gold nanoparticles on Escherichia coli*. Biomaterials, 2012. **33**(7): p. 2327-2333.
81. Verma, M.S., et al., *Interactions between bacterial surface and nanoparticles govern the performance of "chemical nose" biosensors*. Biosensors and Bioelectronics, 2016. **83**: p. 115-125.
82. Zhao, Y., et al., *Small molecule-capped gold nanoparticles as potent antibacterial agents that target gram-negative bacteria*. Journal of the American Chemical Society, 2010. **132**(35): p. 12349-12356.
83. Stachowiak, J.C., C.C. Hayden, and D.Y. Sasaki, *Steric confinement of proteins on lipid membranes can drive curvature and tubulation*. Proceedings of the National Academy of Sciences, 2010. **107**(17): p. 7781-7786.
84. Agasti, S.S., et al., *Nanoparticles for detection and diagnosis*. Advanced drug delivery reviews, 2010. **62**(3): p. 316-328.
85. Kang, S., et al., *Antibacterial effects of carbon nanotubes: size does matter!* Langmuir, 2008. **24**(13): p. 6409-6413.
86. Lyon, D.Y., et al., *Antibacterial activity of fullerene water suspensions (nC60) is not due to ROS-mediated damage*. Nano letters, 2008. **8**(5): p. 1539-1543.
87. Boisselier, E. and D. Astruc, *Gold nanoparticles in nanomedicine: preparations, imaging, diagnostics, therapies and toxicity*. Chemical society reviews, 2009. **38**(6): p. 1759-1782.
88. Giljohann, D.A., et al., *Gold nanoparticles for biology and medicine*. Spherical Nucleic Acids, 2020: p. 55-90.
89. Jin, R., *Super robust nanoparticles for biology and biomedicine*. Angewandte Chemie International Edition, 2008. **47**(36): p. 6750-6753.
90. Krishna, V.D., et al., *Nanotechnology: Review of concepts and potential application of sensing platforms in food safety*. Food microbiology, 2018. **75**: p. 47-54.
91. Luo, R., et al., *A colorimetric assay method for invA gene of Salmonella using DNAzyme probe self-assembled gold nanoparticles as single tag*. Sensors and Actuators B: Chemical, 2014. **198**: p. 87-93.
92. Nile, S.H., et al., *Nanotechnologies in food science: applications, recent trends, and future perspectives*. Nano-micro letters, 2020. **12**(1): p. 1-34.

93. Medina-Reyes, E.I., et al., *Food additives containing nanoparticles induce gastrotoxicity, hepatotoxicity and alterations in animal behavior: The unknown role of oxidative stress*. Food and Chemical Toxicology, 2020. **146**: p. 111814.
94. Creutzenberg, O., *Nanoparticles and Their Regulation*. Regulatory Toxicology, 2020: p. 1-17.
95. Jafarizadeh-Malmiri, H., et al., *Nanobiotechnology in Food: Concepts, Applications and Perspectives*. 2019: Springer.
96. Cavalcante, F.T., et al., *Current status and future perspectives of supports and protocols for enzyme immobilization*. Catalysts, 2021. **11**(10): p. 1222.
97. Morse, K.T., *The nature of gold: an environmental history of the Klondike Gold Rush*. 2003: University of Washington Press.
98. Kenny, S.L. and S.L. Venable, *Gold: a cultural encyclopedia*. 2011: ABC-CLIO.
99. Dash, K.K., et al., *Applications of inorganic nanoparticles in food packaging: A Comprehensive Review*. Polymers, 2022. **14**(3): p. 521.
100. Mei, L. and Q. Wang, *Advances in using nanotechnology structuring approaches for improving food packaging*. Annual Review of Food Science and Technology, 2020. **11**: p. 339-364.
101. Huang, Y., et al., *Recent developments in food packaging based on nanomaterials*. Nanomaterials, 2018. **8**(10): p. 830.
102. Omerović, N., et al., *Antimicrobial nanoparticles and biodegradable polymer composites for active food packaging applications*. Comprehensive Reviews in Food Science and Food Safety, 2021. **20**(3): p. 2428-2454.
103. Idumah, C., et al., *A review on innovations in polymeric nanocomposite packaging materials and electrical sensors for food and agriculture*. Composite Interfaces, 2019.
104. Motelica, L., et al., *Biodegradable antimicrobial food packaging: Trends and perspectives*. Foods, 2020. **9**(10): p. 1438.
105. Jafarzadeh, S., A. Salehabadi, and S.M. Jafari, *Metal nanoparticles as antimicrobial agents in food packaging*, in *Handbook of Food Nanotechnology*. 2020, Elsevier. p. 379-414.
106. Mishra, D., J.R. Hubenak, and A.B. Mathur, *Nanoparticle systems as tools to improve drug delivery and therapeutic efficacy*. Journal of Biomedical Materials Research Part A: An Official Journal of The Society for Biomaterials, The Japanese Society for Biomaterials, and The Australian Society for Biomaterials and the Korean Society for Biomaterials, 2013. **101**(12): p. 3646-3660.
107. Kazmi, S.A.R., et al., *In vitro drug release and biocatalysis from pH-responsive gold nanoparticles synthesized using doxycycline*. Langmuir, 2019. **35**(49): p. 16266-16274.
108. Das, S.S., et al., *Stimuli-responsive polymeric nanocarriers for drug delivery, imaging, and theragnosis*. Polymers, 2020. **12**(6): p. 1397.
109. Beik, J., et al., *Gold nanoparticles in combinatorial cancer therapy strategies*. Coordination Chemistry Reviews, 2019. **387**: p. 299-324.