**Advances of bio-synthesis of metal nanoparticles by using bacterial strain and their biological properties: A review**

Arpita Gope, Nilufa Yasmin, Jayeeta Khanrah and Anjali Rawani\*

**1** Laboratory of Parasitology, Vector Biology, Nanotechnology, Department of Zoology, The University of Gour Banga, Malda, West Bengal, India, PIN-732103

\***Address of corresponding author**

Dr. Anjali Rawani, Ph.D.

Assistant Professor

Laboratory of Parasitology, Vector Biology, Nanotechnology

Department of Zoology, The University of Gour Banga, Malda,

West Bengal, India, PIN-732103.

**Abstract**

In-depth research has been done on metal-based nanoparticles for a variety of biomedical applications. The World Health Organization (WHO) states that metal-based nanoparticles have been shown to be efficient against diseases in addition to their reduced size and selectivity for bacteria. Since they do not bind to a particular receptor in the bacterial cell, metal-based nanoparticles are known to have nonspecific bacterial toxicity mechanisms. This makes it more difficult for bacteria to acquire resistance to them and broadens the range of their antibacterial action. So far, the vast majority of investigations on the efficacy of metal-based nanoparticles against both Gram-positive and Gram-negative bacteria have yielded encouraging results. Metal nanoparticles produced by the plant and plant extracts are more stable as compared to those produced through different organisms. Extensive research as yielded different nanoparticles of controlled size and shape.Typically, diverse biomolecules are carried by metal nanoparticles made of gold, silver, platinum, iron, copper, zinc, etc. This review is based on the various metal nanoparticle kinds, their production process, physicochemical characterization, pharmacokinetics, and toxicological risk associated with their use as antimicrobial agents.

**Keywords:** antibacterial activity, bacterial resistance, nanotechnology, nanomedicine, metal-based nanoparticles, silver nanoparticles (Ag NPs), gold nanoparticles (AuNPs), zinc oxide (ZnONPs), copper nanoparticles (CuNPs).

**Introduction**

As the first living thing discovered on the planet, bacteria have evolved into an extremely adaptive species. It all started with the development of the drug Salvarsan, also known as 606, which was one of the first treatments for the contagious disease syphilis without being hazardous to patients (Bosch and Rosich, 2008). The "golden age" of antibiotic research, which ran from 1950 to 1960, saw the inception of this research and its climax. Between 1930 and 1962, more than 20 new classes of antibiotics were created, but as more resistant bacteria have emerged, the pharmaceutical industry is now facing greater difficulty in finding new compounds having antibacterial activity. In recent years, one of the biggest issues in the clinical profession has been the incorrect and excessive use of antibiotics, which results in antimicrobial resistance. Since the first incidence was recorded, we have seen a growth in bacteria that are resistant to standard antibiotics, which has led to the emergence of so-called multi-drug-resistant (MDR) strains. According to the Centers for Disease Control and Prevention (CDC), MDR bacteria are responsible for approximately 2 million infections each year as well as 23,000 fatalities. *The pathogenic bacteria that make up the ESKAPE group include Enterococcus faecalis, Staphylococcus aureus, Klebsiella pneumoniae, Acinetobacter baumannii, Pseudomonas aeruginosa,* and *Enterobacter species*. Antibiotic misuse and overuse, as well as inadequate infection prevention and control, are likely to be blamed for antibiotic resistance. Several antimicrobial resistance mechanisms have been described in the literature, including (i) reducing medication absorption, (ii) altering drug targets, (iii) rendering drugs inactive, and (iv) active drug efflux. These processes, which may be innate or learned, enable the persistence of resistant strains and the spread of those strains, leading to the failure of antibacterial treatments (Reygaert, 2018).

The use of nanoparticles as novel, non-traditional antibacterial agents has been researched as one of alternative strategies. Studies conducted in vitro have shown that nanoparticles have harmful effects on a variety of bacterial strains, indicating their viability for biological applications, including drug delivery and tissue engineering. Metal and metal oxide nanoparticles (NPs) are among the most promising nanomaterials (Nikolova et al, 2020).

Metal NPs have long been known to have antibacterial properties, but the mechanisms underlying these properties are still poorly understood. Reactive oxygen species (ROS) production, ion leaching, and/or ion dissolution are a few antibacterial mechanisms that have been proposed in recent years. These mechanisms involve the loss of cell wall and cell membrane integrity and, as a result, interfere with some metabolic pathways that are crucial for bacterial viability. In this regard, nanotechnology is an effective tool for designing NPs with the necessary physicochemical characteristics to lessen their cytotoxic effect and the danger associated with their usage in biomedical applications (Abbasi et al, 2023).

This review aims to present a summary of metal nanoparticle (NP) antibacterial processes relating to various bacterial species, higher microbial organizations (biofilm), and the physicochemical characteristics of NPs themselves. To further assess the viability of various therapies used in the clinical and human safety domains, bacterial resistance methods are also examined.

# What is nanoparticle?

Nanoparticles are particle which lie in dimensions between 1-100 nm (Horikoshi and Serpone, 2013). They are made up of tiny molecules in which the active substances have been dissolved, trapped, encapsulated, adsorbed, or connected. It is a colloidal particle that is solid.

Nanospheres and nano capsules are two different forms of nanoparticles.

1. Nanospheres: The medicine is physically and evenly spread inside nanospheres, which are matrix structures.
2. Nanocapsules: A special polymer membrane surrounds a chamber that contains the medicine in nano capsules.

# Applications of Nanoparticles

According to (Fadeel et al, 2009), nanomedicine is an emerging field of study with enormous potential for advancing human illness diagnostics and therapy. In nano biomedicine, dispersed nanoparticles are typically used as fluorescent biological markers (Otto S, 2015), medication and gene delivery agents, and in applications like the bio detection of infections, tissue engineering, tumor destruction via heating (hyperthermia), MRI contrast enhancement, and phagokinetic studies (Saman et al, 2022).

A plethora of reviews and research papers have been published studying the uses of nanoparticles in biomedicine (Emerich and Thanos, 2006) like targeted drug delivery, cancer treatment, gene therapy and DNA analysis, antibacterial agents, biosensors, accelerating reaction rates, separation science, and MRI.

**Drug Delivery**

A fundamental concern in the design and development to innovative drug delivery systems is the precise and safe delivery of the pharmaceuticals to their target areas at the appropriate time to have a controlled release and obtain the maximal therapeutic benefit. Through certain endocytotic and transcytotic transport systems that penetrate cellular barriers, they must enter target cells in order to make contact with cytoplasmic targets (Fadeel and Bennett, 2010).

Due to their small size, nanoparticle drug carriers can pass through the skin's tight epithelial junctions and the blood-brain barrier, which often prevent the delivery of medications to the intended target region. They make hydrophobic substances more soluble and appropriate for parenteral drug delivery. Additionally, they improve the stability of numerous medicinal substances, including peptides and oligonucleotides (Din et al, 2017).

# Antibacterial Agent

# Due to the frequency and proliferation of bacteria that are resistant to several antibiotics, the usage of silver-based antiseptics has increased recently. Silver nanoparticles were produced by a fungus called *Trichoderma virid* (Fayaz et al, 2010). It was found that the aqueous silver (Ag+) ions were decreased in solution when exposed to a *T. viride* filtrate, which produced exceptionally stable AgNPs with a size range of 5 - 40 nm.

# In the presence of AgNPs, test strain resistance to the antibacterial effects of ampicillin, kanamycin, erythromycin, and chloramphenicol was enhanced. The findings offered valuable information for the creation of new antimicrobial drugs and demonstrated that antibiotics and AgNPs together have improved antibacterial properties. Using *Fusarium oxysporum*, Durán et al, 2005 demonstrated how extracellularly generated silver nanoparticles may be integrated into textile textiles to prevent or reduce infection with harmful bacteria like *Staphylococcus aureus*.

# Biosensor

# Nanoparticles have fascinating electrical and optical properties that can be employed in biosensor applications. Bacillus subtilis has been reported to produce spherical selenium nanoparticles with sizes ranging from 50 to 400 nm (Ullah et al, 2021). Due to Se nanoparticles' excellent adhesive properties and biocompatibility, these sensors demonstrated good electro catalytic activity for the reduction of H2O2. These H2O2 biosensors had high sensitivity and affinity for H2O2 with a detection limit of metal. Additionally, their findings demonstrated that the electrochemical applications of various Se nanomaterial crystals were not significantly different.

# A wide range of applications involving the detection of H2O2 in food, pharmaceutical, clinical, industrial, and environmental investigations will thus likely show promise for the Se nanomaterials-modified electrode. According to (Zhang et al, 2013), yeast-produced Au-Ag alloy nanoparticles were used to create a sensitive electrochemical vanillin sensor. Electrochemical tests showed that the vanillin sensor based on glassy carbon electrode modified with Au-Ag alloy nanoparticles could increase the electrochemical responsiveness of vanillin by at least five times. This vanillin sensor was successfully used to measure the amount of vanillin in samples of vanilla bean and vanilla tea, indicating that it might be useful in vanillin monitoring systems. In a different study, glucose oxidase (GOx) biosensors based on AuNPs were created in response to findings indicating AuNPs can boost GOx's enzyme activity (Devasenathipathy et al, 2015). The glucose biosensor has a linear response range of 20 M to 0.80 mM glucose and a detection limit of 17 M (S/N = 3). The use of this kind of biosensor to ascertain the amount of glucose in commercial glucose injections was successful.

# Reaction Rate Enhancement Agent

# Due to their huge surface areas and unique properties, nanoparticles have been widely employed as reductants and/or catalysts to improve a variety of reactions (Hildebrand and Mackenzie, 2008). Microbiological response rates have been enhanced using magnetic nanoparticles. To complete the desulfurization of dibenzothiophene (Shan et al, 2015) used *Pseudomonas delafieldii* microbial cells covered with magnetic Fe3O4 nanoparticles. The addition of an external magnetic field increased the potential of cell collection for reuse and assured that the cells were evenly distributed in the solution even without mixing. The outcomes demonstrated that *P. delafieldii*'s desulfurization efficiency was unaffected and that the cells could be recycled multiple times.

# What is Green Synthesis?

# Green synthesis is a method for creating nanomaterials that is clean, safe, economical, and ecologically beneficial. Microorganisms like bacteria, yeast, fungi, algae species, and some plants are used as substrates in the green synthesis of nanomaterials (Huston et al, 2021).

# The green synthesis method offers straightforward, affordable, and reproducible methods for producing ecologically friendly metallic nanoparticles.

# Why Green synthesized?

In medical research, the use of antibiotics is used to control infections, but due to the advent of Multiple Drug Resistance (MDR) bacteria, it is extremely challenging to treat individuals who have MDR harmful bacterial infections (Duin and Paterson, 2016). An interesting alternative maybe found in the green synthesis of nanoparticles (Bahrulolum et al, 2021). For the synthesis of nanoparticle, researcher have tried different methods like physical and chemical methods. These methods were time consuming, expensive, electrical equipment. Synthesis of nanoparticle is important because the nanoparticles made by green technology are far superior to those manufactured with physical and chemical methods based on various aspects produced using physical and chemical processes. Green methods, for instance, produce ecologically friendly products and by products while using less energy and costlier chemicals.

# Various techniques have been utilized to create metal-based nanoparticles

**Thermolysis Methods:**

In order to prevent surface oxidation of the nanoparticles, this method relies on the dissociation of organometallic precursors in organic solvents at temperatures typically higher than 100 °C under inert atmosphere. As a drawback of this approach, reactions are challenging to apply to large-scale synthesis because of their exothermic and extremely diluted circumstances. The production of silver nanoparticles (AgNPs) without the use of organic solvents can also be accomplished utilizing various techniques, such as controlled thermolysis of silver alkyl carboxylates. The ability to use regulated thermolysis in commercial large-scale synthesis at a very cheap cost is a benefit of this approach (Iravani et al, 2014).

# Chemical Reduction Methods:

In these procedures, a metal precursor that has been dissolved in a solvent is combined with an appropriate reducing agent and a surfactant in a batch reactor that is constantly stirring while being enclosed in an inert gas. This method of producing metastable metal nanoparticles appears promising. The options for the reducing agents are numerous, but it may depend on the particular redox thermodynamics (Crisan et al, 2022). Additionally, the majority of the time, the pH of the solution has a significant impact on the activity of reducing agents. For instance, the precursor copper acetate is dissolved in swirling deionized water to create copper nanoparticles (CuNPs). After adding the reducing agent hydrazine to the solution, the nanoparticles start to form.

# Biochemical Methods:

Plants, algae, yeasts, fungus, bacteria, and even viruses have lately been employed in conjunction with chemical reagents in these approaches. The growth process uses enzymatic or nonenzymatic reduction activities and can take place inside or outside of cells. According to the particular host cells and process conditions, bacteria or fungus could produce gold and silver nanoparticles in a variety of shapes (cubes, triangles, spheres, plates, or wires). Although these techniques are mentioned in multiple patents, optimizing the biosynthesis process is still a challenge (Lopez et al, 2020).

# Electrochemical Method:

In the synthesis of size-or shape-selective, very pure metal nanoparticles, electrochemical approaches have shown certain significant advantages over chemical methods. Anodically dissolving a metal sheet creates an intermediate metal salt, which is then reduced at the cathode to create metallic particles stabilized by ammonium salts. Bimetallic Cd-Ag nano alloys have been reported to be created by sequentially electrode positing two distinct cations on a carbon electrode, according to certain publications. Other authors described the direct electro reduction of bulk gold ions to produce AuNPs, using polyvinylpyrrolidone (PVP) to promote the creation of gold nano particles and prevent metal deposition on the cathode (Nam and Luong, 2019).

Wave-Assisted Chemical Methods:

Sono chemical processes use an ultrasonic source to create cavitation in a solution comprising a metal precursor, a reducing agent, and a stabilizer (surfactant). During radiolytic procedures, a metal precursor combined with the proper reducing agent is exposed to electromagnetic or particle irradiation, including an accelerated electron beam, gamma rays, X-rays, and UV rays. AgNPs can be created by reducing AgNO3 with a strong reducing agent, like sodium borohydride, in the presence of ultrasonic waves (Suslick, 1990). Microwave aided synthesis has gained popularity as a quick and efficient process in recent years. This is true because less harmful substances, like chitosan and polymers, can be used in place of the stabilizer and complexing agent. Additionally, this technique may perform chemical transformations in a matter of minutes. AgNPs, for instance, can also be made by complexing PVP with Ag+ ion and reducing it with N, N-dimethylformamide.

# Cementation Methods:

When a very electropositive metal A (sacrificial element) is left in contact with a solution containing ions of a less electropositive metal B, the following spontaneous reaction is thermodynamically permitted, and metal B separates in elemental form as A+ n/ m Bm+ = An++n / m B.

This reaction, which is frequently used in industry to purify solutions in hydrometallurgy, can be utilized to decrease cations to obtain metal nanoparticles or aggregates with a fairly straight forward and inexpensive technique (Singh and Satija, 2022). The two main drawbacks of this approach are its inability to control nanoparticle aggregation and the cemented metal phase B's tendency to attach to surface element A. These issues can be avoided by mechanical damping combined with a customized hydrodynamic control. For instance, copper can be reduced from a copper nitrate salt in the presence of iron, which can lead to the development of copper nanoparticles (CuNPs).

**Biological Methods:**

Metal-based nanoparticles are created using biological techniques that take advantage of the defense systems found in particular species (against high concentrations of metal ions). These techniques can be extracellular (like bio absorption, biomineralization, complexation, or precipitation) or intracellular (like bioaccumulation. Since fungi are more resistant to the flow pressure and agitation of the bioreactors than bacteria are, using them to produce metal-based nanoparticles has advantages for industrial scale manufacturing. However, in recent years, the majority of studies have emphasized using plant extracts since, in addition to the benefits listed above, doing so makes it easier to treat samples, scale up production, and collect the desired output (Shah et al, 2015).

**Bio-Synthesis by bacterial strains:**

Fe (III)-reducing bacteria like *Geobacter* sp., *Magnetospirillum magnetotacticum*, and others can be used to bio-remediate toxic metals like Fe (III) through reduction, in which iron is actively taken up by the cell and re-oxidized to hydrous oxide (low density) to Fe (III) oxide (ferrihydrite). In the final phase, the Fe (III) ions are reduced, and the magnetosome vesicles undergo dehydration to create magnetite. The generated nanoparticles exhibit the qualities listed below, among others (Pacioni et al, 2015): high purity, few crystalline flaws, small size, mono-dispersive, etc. Antibacterial medicines that work against gram positive or negative bacteria have been created by MDR (multi-drug resistant) microorganisms. In contrast to gram-positive bacteria, which have a thick coating of cell wall and exhibit greater resistance to antibacterial treatments, gram-negative bacteria have a very thin layer of peptide glycan that makes them vulnerable to the action of nanoparticles. Accordingly, there is a chance that the gold nanoparticles will also be able to function against gram-positive bacteria (Gogineni et al, 2011).

**Biological Synthesis of Nanoparticles:**

Since the beginning of life on Earth, biological organisms and inorganic materials have been in constant communication with one another. This constant contact allowed life to exist on this planet with a well-organized mineral deposit. Numerous bacteria can create inorganic nanoparticles via extracellular or intracellular pathways, according to studies. The creation of different nanoparticles using biological processes is covered in this section, along with the categories of oxide nanoparticles made up of magnetic and nonmagnetic oxide nanoparticles, sulphide nanoparticles, and other ad hoc nanoparticles, such as gold, silver, alloy and other metal nanoparticles are also covered.

**Table1: Biological activity of metal nanoparticles synthesized from bacterial strains**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Bacteria** | **Product** | **Size (nm)** | **Shape** | **Biological****activity** | **References** |
| *Sargassum wightii* | Au | 8–12 | planar | Anti-oxidant | Singaravelu et al., 2007 |
| *Rhodococcus sp.* | Au | 5–15 | spherical | Anti-microbial | Ahmad et al., 2004 |
| *Shewanella oneidensis* | Au | 12±5 | spherical | Anti-bacterial | Suresh et al., 2011 |
| *Plectonema boryanum* | Au | 25–100 | cubic | Anti-microbial | Lengke et al., 2006 |
| *Plectonema boryanum* | Au | 10–6 | octahedral | Anti-microbial | Lengke et al., 2006 |
| *Escherichia coli* | Au | 20–30 | Triangles,hexagons | Anti-cancer | Mazdeh et al., 2014 |
| *Yarrowia lipolytica* | Au | 15 | Triangles | Anti-fungal | Agnihotri et al., 2009 |
| *Rhodopseudomonas**capsulate* | Au | 10–20 | Spherical | Anti-microbial | He et al., 2007 |
| *Brevibacterium casei* | AuAg | 10–50 | Spherical | Anti-microbial | Kalishwaralal et al., 2010 |
| *Trichoderma viride* | Ag | 5–40 | Spherical | Anti-oxidant | Fayez et al., 2010 |
| *Phaenerochaete chrysosporium* | Ag | 50–200 | Pyramidal | Anti-fungal | Vigneshwaran et al., 2006 |
| *Corynebacterium**glutamicum* | Ag | 5–50 | Irregular | Anti-microbial | Krishnamurthy et al., 2010 |

**Gold nanoparticles:**

Gold nanoparticles (AuNOs) have attracted interest in biotechnology due to their distinctive optical and electrical properties, high chemical and thermolability, good biocompatibility, and potential applications in a variety of life sciences-related applications, such as biosensing, bioimaging, and drug delivery for cancer diagnosis and therapy (Kumar et al., 2013). The required functionalization of nanoparticles is very possible and exact thanks to their predictable and dependable surface modification chemistry, typically by gold-thiol binding. This method has been used to attach a range of medicinal chemicals, such as anti-cancer medications, bacterial agents, and different oligonucleotides for gene therapy (Zumaya et al., 2022). Microorganisms including bacteria, fungus, and algae have the ability to create AuNPs. For instance, Koul et al., 2021 used the mesophilic bacteria Shewan Ella algae with H2 asthe electron donor to produce microbial production of gold nanoparticles. He et al. (2007) incubated R. capsulate biomass along with an aqueous chloroauric acid (HAuCl4) solution. The pH of the solution played a significant role in both of these studies in regulating the location and morphology of biogenic gold deposition. These observations concur with those made by Klaus et al, 1999), who found that changes in incubation conditions affect particle size. The utilization of gold nano particles in numerous applications, such as the direct electrochemistry of proteins, is noteworthy (Du et al, 2007). Kalabegishvili et al. (2012) examined the creation of gold nanoparticles using two distinct strains of Arthrobactersp. 61 Band Arthrobacter globiformis 151B, which were obtained from basal trocks in Georgia. *Pseudomonas putida* DSM291, *Bacillus subtilis* DSM10, and *Pseudomonas stutzeri* NCIMB134 20 were reported to produce intracellular gold by Gericke and Pinches, 2006. Rhodopseudomona scapsulata was shown by He et al. (2007) to be able to produce gold particles extracellularly. The generated gold nanoparticles are soluble and stable. The extracellular manufacture of gold nanoparticles in the study by Malarkodi et al. (2013) is accomplished by a simple biological process using *Klebsiella pneumoniae* as the reducing agent.

**Table 2: Biological activity of gold nanoparticles synthesized from bacterial strain**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Microorganism** | **Size(nm)** | **Shape** | **Biological activity** | **Reference** |
| *Brevibacterium casei* | 10–50 | Spherical | Antimicrobial | Kalishwaralal et al, 2010 |
| *Escherichia coli* | 20–30 | Trianglehexagon | Anticancer | Gericke and Pinches, 2006 |
| *Klebsiella pneumoniae* | 5–32 | Spherical | Antibacterial | Malarkodi et al, 2013 |
| *Rhodococcus sp.* | 5–15 | Spherical | Antimicrobial | Ahmad et al, 2003 |
| *Rhodopseudomonas**apsulate* | 10–20 | Spherical | Antimicrobial | He et al, 2007 |
| *Shewanella oneidensis* | 12–17 | Spherical | Antibacterial | Suresh et al, 2011 |

**Silver Nanoparticles:**

Microorganisms produce silver nanoparticles as a result of their defense mechanism. The bacterium uses its cellular machinery as a defense mechanism to change the reactive silver ions into stable silver atoms. It is now understood that alkaline circumstances promote the synthesis of more nanoparticles than do acidic settings (Saklani et al, 2012). First, different Ag+ complexes are broken down to metallic silver atoms (Ag0). Ag0 then gathers into oligomeric clusters as a result (Sharma et al, 2009). Colloidal AgNPs are eventually formed from these clusters (El-Nour et al, 2010). It has been shown that the low molecular weight peptide glutathione (GSH), proteins like metallothioneins and phytochelatins, and enzymes like oxidoreductases, NADH-dependent reductases, nitro reductases, NADH-dependent nitrate reductases (NRs), and cysteine desulfhydrases all play a role in the formation of nanocrystals in yeast, bacteria, and fungi. The majority of the silver nanoparticles produced by these bacteria are discovered to be spherical particles, with the exception of some that are found to be asymmetrical (Mukherjee et al, 2001b; Ahmad et al, 2004; Fayaz et al, 2010). In one of the initial investigations into this technique, Slawson et al,1992 discovered that *Pseudomonas stutzeri* AG259, a silver-resistant bacterial strain obtained from silver mines, collected AgNPs in the periplasm. Importantly, the particle size was found to be between 35 and 46 nm (Iravani et al, 2014). Klaus et al. (1999) group described the difference in particle size to variations in cell growth and metal incubation conditions. According to Parikh et al, 2008, *Morganella* sp. RP-42 developed extracellular crystalline AgNPs measuring 205 nm when treated to silver nitrate (AgNO3). In *Morganella* sp, a silver-resistant species, three gene homologues (silE, silP, and silS) were found. The silE homologue from *Morganella* sp. shared 99% of its nucleotide sequence with the gene previously identified as silE, which codes for a protein that binds silver in the periplasm (Parikh et al, 2008). This is the only study to explain the molecular basis of bacteria's resistance to silver, which may be related to a synthesis mechanism. In a different study, Nair and Pradeep, 2002 exposed common Lactobacillus bacteria found in buttermilk to high metal ion concentrations, which led to the formation of tiny crystals of gold, silver, and gold-silver alloy with clearly defined shape. Amazingly, the cells maintained their viability even after crystal formation when the bacteria created them intracellularly (Nair and Pradeep, 2002). Notably, AgNP production has been seen in cyanobacteria as well. For instance, *Plectonemaboryanum* UTEX485, a filamentous cyanobacterium, has been used to successfully produce AgNPs (Lengke et al, 2007). The authors suggested that nitrate metabolism at 25 °C and/or organics released from dead cyanobacteria at 25 ° to 100 °C could be the methods through which AgNPs are produced by cyanobacteria AgNPs were produced by fungi *Verticillium, Fusarium oxysporum*, or *Aspergillus flavus* in the form of a film, in solution, or accumulating on their cell surfaces (Mukherjee et al, 2001b; Senapati et al, 2004; Bhainsa and D'Souza, 2006; Bakshi et al, 2017; Jain et al, 2011).Using the fungus *Verticillium*, Mukherjee et al, 2001b investigated the creation of intracellular AgNPs. The scientists found that when the fungal biomass is exposed to aqueous Ag+ions, the metal ions are reduced intracellularly and 25 nm AgNPs are produced. Bhainsa and D'Souza, 2006 reported that the filamentous fungus *Aspergillus fumigatus* was used in the extracellular production of AgNPs, and that the process was quick.

**Table 3: Biological activity of silver nanoparticles synthesized from bacterial Strain**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Microorganism** | **Size (nm)** | **Shape** | **Biological activity** | **Reference** |
| *Bacillus cereus* | 4–5 | Spherical | Anti-bacterial | Babu and Gunasekaran, 2009 |
| *Brevibacterium casei* | 10–50 | Spherical | Anti - microbial | Kalishwaralal et al., 2010 |
| *Corynebacterium**glutamicum* | 5–50 | Irregular | Anti-microbial | Gurunathan, 2009 |
| *Ureibacillus**thermosphaericus* | 50–70 | Spherical | Anti-microbial | Juibari et al., 2011 |
| *Pseudomonas stutzeri* | 200 | Spherical | Anti-microbial | Klaus et al., 1999 |

**Cadmium Nanoparticles:**

Over the past 50 years, researchers have studied the health dangers that cadmium poisoning poses. Cadmium causes oxidative stress at the cellular level by depleting natural antioxidants like glutathione. It is also linked to mitochondrial damage, the activation of apoptosis, and disruption of intracellular calcium signaling. Macro-Raman spectrum of silver nanoparticles drop-cast on Si (100) single crystals notwithstanding the considerable studies on cadmium toxicity. Regarding its method of action, intracellular harm, and environmental exposure, there is still a lot of ground to cover in Nanoparticles Synthesized by Microorganisms. CdSe was created by Cui et al., (2009) using the yeast strain Saccharomyces cerevisiae. The anaerobic bacterium *Veillonellaa typica* created selenide (Se [II]) from selenite (Se [IV]), and Pearce et al. (2008) added CdCl2O8 to create CdSe nanoparticles. Due to its toxicity to bacteria, cadmium was introduced for CdSe production after microbial selenide creation in the last twoinvestigations (Pearce et al, 2008; Cui et al, 2009). As a result, they created CdSe by two-vessel methods that involved reducing selenite to selenide and then creating CdSe from selenide and cadmium ion. In contrast, a one-vessel process in which the fungus generates CdSe when selenite and cadmium ions are present was only reported by Kumar et al, 2007. This method may be more economically efficient due to the fact that it requires fewer reaction vessels to operate. Ayano et al, 2014 discovered CdSe synthesis in *Pseudomonas* sp. RB. When grown in the same medium as the enrichment culture, this strain accumulated nanoparticles (10–20 nm) made up of selenium and cadmium inside and on the cells, as shown by transmission electron microscopy and Energy Dispersive Spectroscopy (EDS). The isolation of a selenite-reducing and cadmium-resistant bacteria is described in this article for the first time (Ayano et al, 2014). Cadmium telluride (CdTe), a substantial group II-VI semiconductor material with a large exciton Bohr radius (7.3 nm) and a tiny bulk band gap of 1.5 eV, has demonstrated tremendous potential for LED (energy), FRET (electronics), and biological applications due to its size-dependent characteristics. These nanoparticles are investigated in live cell bio-imaging because they outperform organic dyes in terms of photostability, narrow emission, and quantum yield ([Svechkarev](https://pubmed.ncbi.nlm.nih.gov/?term=Svechkarev%20D%5BAuthor%5D) and [Mohs](https://pubmed.ncbi.nlm.nih.gov/?term=Mohs%20AM%5BAuthor%5D), 2019). *Fusarium oxysporum* is a fungus that Syed and Ahmad, 2013 use to create extremely fluorescent extracellular CdTe (quantum dot) nanoparticles. The procedure enables bottom-up, one- step nanoparticle production by using highly diluted Cd and Te precursors. Different methods, including Selected Area Electron Diffraction (SAED) and X Ray – Diffraction (XRD), were used to characterize them, confirming the crystalline nature of the bio synthesized nanoparticles. Against both Gram-positive and Gram-negative bacteria, the se nanoparticles demonstrated antibacterial action. This study shows that using a fungus-based strategy to synthesize nanomaterials offers a fresh, logical, and environmentally benign synthesis protocol. According to Syed and Ahmad, 2013 this is the first instance of a fungal-mediated method for the manufacture of Cd Te quantum dots.

# Oxide Nanoparticles:

# Over the past ten years, there has been a sharp increase in the industrial use of metallic oxide nanoparticles in a wide range of applications. These applications use silicon, titanium, iron, and other metallic oxide nanoparticles, increasing the exposure of humans and other species to these nanoparticles in the workplace and other environments (Lai et al, 2008). However, due to the lack of regulatory oversight of their environmental impact, the health impacts of metallic oxide nanoparticle exposure on humans and other species have not been thoroughly studied (Lai et al, 2008). Li et al, 2011 reviewed the biogenesis of oxide nanoparticles in this section. The majority of instances of biological systems that produce magnetic oxide nanoparticles and nonmagnetic oxide nanoparticles using magneto tactic bacteria.

**Zinc Oxide:**

Zinc oxide (ZnO) NPs are a wide band gap semiconductor with special optical and electrical properties that have made them increasingly useful in biosensors, nanoelectronics, and solar cells. Because of their transparency and capacity to reflect, scatter, and absorb UV radiation, these NPs are also utilized as food additives and in the cosmetic and sunscreen industries. The use of zinc oxide NPs in future biological applications, such as antibacterial agents, drug delivery systems, and bioimaging probes, is also being studied (Jayaseelan et al, 2012). It has been reported on a low-cost and straight forward method for producing zinc oxide nanoparticles utilizing the repeatable bacterium *Aeromonas hydrophila*. The crystalline nature of nanoparticles was established by X-ray diffraction (XRD). Atomic force microscopy (AFM) revealed that the nanoparticles were created by Microorganisms and their morphology was spherical and oval with an average size of 57.72 nm. With comparable good diffusion and minimal inhibitory concentration, the antibacterial and antifungal activities came to a stop. According to Jayaseelan et al. (2012), ZnO NPs (25 g/mL) showed the greatest zone of inhibition against *Pseudomonas aeruginosa* (\*22 1.8 mm) and *Aspergillus flavus* (\*19 1.0mm).

# Table:4 Biological Activity of Zinc Nanoparticle Synthesized from Bacterial Strain

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Microorganism** | **Size**  | **Shape** | **Biological Activity** | **Reference** |
| *Serratia nematodiphila* | 1.05µm | Rod shaped | Antimicrobial | Bajpai et al, 2012 |
| *Fucus vesiculosus* | 2.5cm | Disc shaped | Antibacterial | Hamouda et al, 2023 |
| *Pseudomonas aeruginosa* | 0.51.0µm | Rod shaped | Antibacterial | Salomoni et al., 2017 |
| *Lactobacillus plantarum* | 0.91.2µm | Rod shaped | Antifungal | Yusof et al., 2020 |

**Copper Nanoparticle:**

# Copper precursor is easily available in the marker, as well as it is cheap as compare to silver or gold precursors. Copper nanoparticles are having good thermal properties, which can be utilized in lubricants for heat dissipation. Copper nanoparticles or having remarkable trin biological properties, low hardness leads to reduction in friction, and low elastic modulus reduces the wear.

# Table:5 Biological Activity of Copper Nanoparticle Synthesized from Bacterial Strain

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Microorganism** | **Size** **(nm)** | **Shape** | **Biological Activity** | **Reference** |
| *Pseudomonas flurescens* | 2.0-2.5µm | Rod shaped | Anti-fungal | Castaldi et al., 2021 |
| *Bacillus cereus* | 9×2microns | Rod shaped | Anti-fungal | Ingle and Rai, 2017 |
| *Streptomyces sp.* | 0.5-2.0µm | Spherical shaped | Anti-bacterial | Liu et al., 2019 |
| *Stenotrophomonas sp.* | 0.4-0.7µm | Rod shaped | Anti-microbial | Talebian et al., 2023 |

**Cerium Oxide:**

Nanoparticles researchers in the fields of physics, chemistry, biology, and materials science have been particularly interested in cerium since it is the first element in the lanthanide group to have four free electrons. Cerium dioxide, out of all the Cerium minerals, has drawn the most interest in the worldwide nanotechnology industry because of its practical uses in catalysts, fuel cells, and fuel additives. For usage in manufacturing and pharmaceuticals, a number of minerals containing the Ce-carbonate, -phosphate, -silicate, and-(hydr)oxide ions have historically been mined and processed. Cerium nanoparticles' potent antioxidant properties have a wide range of biomedical applications for them. According to Dhall and Self, 2018, industrial uses for this substance include polishing agents, ultraviolet-absorbing compounds for sunscreen, solid electrolytes for solid oxide fuel cells, fuel additives to accelerate combustion, and automotive exhaust catalysts. CeONPs have also been utilized to treat cancer, inflammation, and to shield cells from radiation (Kaliberov and Buchsbaum, 2012). The physicochemical characteristics of CeO2 nanoparticles in low temperature geochemical environments have a significant impact on their environmental fate. While it is obvious that aquatic and terrestrial creatures have been exposed to CeO2NPs, there is room for improvement in the analytical method for detecting/ quantifying these nanoparticles in various environmental media. This could have severe influence on human and ecosystem health. It's interesting to note that conflicting data exist about the toxicological effects of CeO2 nanoparticles, which can either operate as an antioxidant or a factor in the generation of reactive oxygen species (Nita and Grzybowski, 2016). This presents a problem for future environmental risk assessments and legislation governing the use of CeO2 nanoparticles. *Gloriosa superba* L. leaf extract is used by Arumugam et al., (2015) to successfully synthesize CeO2 nanoparticles. The cubic structure of the synthesized nanoparticles was preserved, and X-ray diffraction analyses supported this claim. XPS investigations verified the elements' oxidation states (C [1s], O [1s], and Ce [3d]). According to antibacterial investigations conducted on a variety of bacterial strains, Gram-positive bacteria were more vulnerable to NPs than Gram-negative bacteria. Due to the synthetic NPs' uneven ridges and oxygen flaws, CeO2 NPs' toxicological behavior was discovered. The fungus *Curvularia lunata* has been successfully used to create CeO2nanoparticles (Munusamy et al, 2014). Studies on the SAED patterns, Micro Raman spectra, and XRD patterns point to the creation of a cubic CeO2 NPs fluorite structure. The spherical form was visible in the TEM pictures, with an average size of 5nm.The antibacterial activity of synthesized CeO2 NPs was studied. The analysis revealed that 100 g of CeO2 NPs had the most notable antibacterial impact because the bacterial cell membrane was bound by high electrostatic forces, which prevented bacterial growth.

**Silica Dioxide:**

In the natural world, quartz and beaches are both made of silica. Silica is a poor conductor of heat and electrons, unlike metals like gold and iron. Despite these drawbacks, silicon oxide nanoparticles serve as the structural foundation of silica aerogels. Silica aerogels are made of silica nanoparticles that are dotted with air-filled nanopores. Nano aerogels are among the greatest thermal insulators in existence because of these characteristics. By attaching molecules to a nanoparticle that can also connect to another surface, such a cotton fiber, silica nanoparticles can also be functionalized. Nanoscale pores adorn another variety of silica nanoparticles. In order to slowly release therapeutic molecules in a diseased area of the body, such as close to a cancer tumor, researchers are developing drug delivery techniques (Argyo et al, 2014). Due to the rising demand for innovative materials with superior thermal, mechanical, physical, and chemical properties, the use of silica nanoparticles as fillers in the creation of nanocomposite of polymers has received significant attention. *Acinetobacter* sp. was shown by Singh et al, 2008 to produce silicon/ silica nanoparticle composites. It is demonstrated that when the bacteria is exposed to K2SiF6 precursor at ambient circumstances in silicon/ silica nanocomposite forms. This bacterium is thought to release reductases and oxidizing enzymes that result in the creation of Si/SiO2 nanocomposite materials. The ability of bacteria to produce silica nanoparticles illustrates the organism's adaptability, and the production of elemental silicon using this ecologically acceptable method broadens the potential applications of microorganism-based nanomaterial synthesis.

**Table 6: Biological activities of silica nanoparticles synthesized from bacterial strain**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Microorganism** | **Type of nanoparticle****synthesized** | **Size****(nm)** | **Shape** | **Biological activities** | **Reference** |
| *Curvularia lunata* | CeO2 | 5 | Spherical | Antimicrobal | Singh et al., 2008 |
| *Fusarium oxysporum* | TiO2 | 6–13 | Spherical | Anti-fungal | Gaber et al., 2023 |
| *Fusarium oxysporum* | BaTiO3 | 4–5 | Spherical | Anti-fungal | Rai et al., 2020 |
| *Fusarium oxysporum* | ZrO2 | 3–11 | Spherical | Anti-fungal | Bansal et al., 2004 |
| *Lactobacillus sp.* | BaTiO3 | 20–80 | Tetragonal | Anti-bacterial | Jha and Prasad, 2010 |
| *Lactobacillus sp.* | T1O2 | 8–35 | Spherical | Antibactrial | Jha et al., 2009 |
| *Saccharomyces cerevisiae* | Sb2O3 | 2–10 | Spherical | Anti-oxidant | Jha et al, 2009 |

**Conclusion**

# Engineering and biomedical sciences both make substantial use of metal-based nanoparticles. The present study, updated the key characteristics of AgNPs, CuoNPs, AuNPs, and ZnoNPs, which are frequently used in pharmaceutical and medical applications, such as antibacterial, antifungal, antiviral, anti-amoebic, anticancer, and anti-angiogenic medicines. Due to their well-documented anti-bacterial effect against Gram-positive and Gram-negative bacteria, these particles have been proposed as an alternative to traditional antibiotics to tackle bacterial resistance. With the benefit of being effective against bacteria that have already evolved antibiotic resistance, nanoparticles use different methods of action than conventional therapies. They also target several biomolecules, which hinders the emergence of resistant strains. The physicochemical characteristics, dosage, and mode of administration of metal nanoparticles, which control their pharmacokinetics and pharmacodynamics, are responsible for any potential risk of toxicological effects in humans. In the early stages of pharmaceutical development, a thorough physicochemical characterization is advised because these particles can have a limited therapeutic window. Additionally, for the success of pharmaceutical development, understanding their in vivo behavior throughout preclinical and clinical trials is a crucial source of information, preventing failures in the last stages of research and development.

**References**

Abbasi R, Shineh G, Mobaraki M, Doughty S, Tayebi L. Structural parameters of nanoparticles affecting their toxicity for biomedical applications: a review. J Nanopart Res. 2023; 25 (3). Doi: 10.1007/s11051-023-05690-w. Epub 2023 Feb 27. PMID: 36875184.

Agnihotri M, Joshi S, Kumar AR, Zinjarde S, Kulkarni S. Biosynthesis of gold nanoparticles by the tropical marine yeast *Yarrowia Lipolytica* NCIM 3589. Materials Letters, 2009; 63 (15): 1231-1234, ISSN - 0167-577X. <https://doi.org/10.1016/j.matlet.2009.02.042>.

Ahmad A, Mukherjee P, Senapati S, Mandal D, Khan MI, Kumar R, Murali Sastry. Extracellular biosynthesis of silver nanoparticles using the fungus *Fusarium oxysporum*, Colloids and Surfaces B: Biointerfaces, 2005; 28 (4), : 313-318, ISSN - 0927-7765, [https://doi.org/10.1016/S0927-7765(02)00174-1](https://doi.org/10.1016/S0927-7765%2802%2900174-1).

Ahmad A, Senapati S, Khan MI, Kumar R, Ramani R, Srinivas V, Sastry M. Intracellular synthesis of gold nanoparticles by a novel alkalotolerant actinomycete, *Rhodococcus* species. Nanotechnology. June 2004; 14 (7). **Doi:** 10.1088/0957-4484/14/7/323.

Argyo C, Weiss V, Brauchle C, Bein T*.* Multifunctional Mesoporous Silica Nanoparticles as a Universal Platform for Drug Delivery*. Chem. Mater.* 2014; 26 (1): 435–445. <https://doi.org/10.1021/cm402592t>.

Arumugam A, Karthikeyan C, Haja Hameed AS, Gopinath K, Gowri S, Karthika V. Synthesis of cerium oxide nanoparticles using Gloriosa superba L. leaf extract and their structural, optical and antibacterial properties. Mater Sci Eng C Mater Biol Appl. 2015; 49: 408-415. Doi: 10.1016/j.msec.2015.01.042. Epub 2015 Jan 10. PMID: 25686966.

Ayano H, Miyake M, Terasawa K, Kuroda M, Soda S, Sakaguchi T, Ike M. Isolation of a selenite-reducing and cadmium-resistant bacterium Pseudomonas sp. strain RB for microbial synthesis of CdSe nanoparticles. J Biosci Bioeng. 2014 May;117 (5): 576 - 581. Doi: 10.1016/j.jbiosc.2013.10.010. Epub 2013 Nov 9. PMID: 24216457.

Babu MMG, Gunasekaran P. Production and structural characterization of crystalline silver nanoparticles from Bacillus cereus isolate. *Coll Surf B.*2009; 74: 191–195. Doi: 10.1016/j.colsurfb.2009.07.016.

Bahrulolum H, Nooraei S, Javanshir N, Tarrahimofrad H, Mirbagheri VS, Easton AJ, Ahmadian G. Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. J Nanobiotechnology. 2021 Mar 26;19 (1). Doi: 10.1186/s12951-021-00834-3. PMID: 33771172; PMCID: PMC7995756.

Bajpai, S.K., Chand, N. & Chaurasia, V. Nano Zinc Oxide-Loaded Calcium Alginate Films with Potential Antibacterial Properties. *Food Bioprocess Technol* **5**, 2012, 1871–1881. <https://doi.org/10.1007/s11947-011-0587-6>.

Bakshi M, Mahanty S, Chaudhuri P. Fungi mediated biosynthesis of nanoparticles and application in metal sequestration, 2017, doi - 10.1201/9781315153353.

Bansal V, Debabrata R, Ahmad A, Sastry M. Biosynthesis of Zirconia Nanoparticles Using the Fungus *Fusarium oxysporum*. Journal of Materials Chemistry. 2004; 14: 3303-3305. 10.1039/b407904c.

Bansal V, Poddar P, Ahmad A, Sastry M. Room-Temperature Biosynthesis of Ferroelectric Barium Titanate Nanoparticles. *J. Am. Chem. Soc.* 2006;128 (36): 11958–11963. <https://doi.org/10.1021/ja063011m>.

Bhainsa KC, D’souza SF. Extracellular Biosynthesis of Silver Nanoparticles Using the Fungus *Aspergillus fumigates*. Colloids and Surfaces B: Biointerfaces, 2006, 47: 160-164.<http://dx.doi.org/10.1016/j.colsurfb.2005.11.026>.

Bosch F, Rosich L. The contributions of Paul Ehrlich to Pharmacology: A tribute on the occasion of the centenary of his Nobel Prize. Pharmacology, 2008; 82: 171 – 179.

Castaldi S, Masi M, Sautua F, Cimmino A, Isticato R, Carmona M, Tuzi A, Evidente A. *Pseudomonas fluorescens* Showing Antifungal Activity against *Macrophomina phaseolina,* a Severe Pathogenic Fungus of Soybean, Produces Phenazine as the Main Active Metabolite. Biomolecules. 2021 Nov 19;11 (11): 1728. Doi: 10.3390/biom11111728. PMID: 34827726; PMCID: PMC8615785.

Crisan, M.C.; Teodora, M.; Lucian, M. Copper Nanoparticles: Synthesis and Characterization, Physiology, Toxicity and Antimicrobial Applications. *Appl. Sci.* **2022**, *12* (141). <https://doi.org/10.3390/app12010141>.

Cui R, Liu HH, Xie HY, Zhang ZL, Yang YR, Pang DW, Xie ZX, Chen BB, Hu B, Shen P. Living yeast cells as a controllable biosynthesizer for fluorescent quantum dots. *Adv. Funct. Mater.* **2009**; 19: 2359–2364. 10.1002/adfm.200801492.

Devasenathipathy, Rajkumar & Mani, Veerappan & Chen, Shen-Ming & Huang, Sheng-Tung & Huang, Tsung-Tao & Lin, Chun-Mao & Hwa, Kuoyuan & Chen, Ting-Yo & Chen, Bo-Jun. Glucose biosensor based on glucose oxidase immobilized at gold nanoparticles decorated graphene-carbon nanotubes. Enzyme and Microbial Technology. 2015; 78. 10.1016/j.enzmictec.2015.06.006.

Dhall A, Self W. Cerium Oxide Nanoparticles: A Brief Review of Their Synthesis Methods and Biomedical Applications. Antioxidants (Basel). 2018 Jul;7 (8): 97 – 110. Doi: 10.3390/antiox7080097. PMID: 30042320; PMCID: PMC6116044.

Din FU, Aman W, Ullah I, Qureshi OS, Mustapha O, Shafique S, Zeb A. Effective use of nanocarriers as drug delivery systems for the treatment of selected tumors. Int J Nanomedicine. 2017 Oct; 12: 7291-7309. Doi: 10.2147/IJN.S146315. PMID: 29042776; PMCID: PMC5634382.

Du L, Jiang H, Liu X, Wang E. Biosynthesis of gold nanoparticles assisted by Escherichia coli DH5α and its application on direct electrochemistry of hemoglobin, Electrochemistry Communications. 2007: 9 (5): 1165-1170, ISSN - 1388-2481. <https://doi.org/10.1016/j.elecom.2007.01.007>.

Duin VD, Paterson DL. Multidrug-Resistant Bacteria in the Community: Trends and Lessons Learned. Infect Dis Clin North Am. 2016 Jun; 30(2):377-390. Doi: 10.1016/j.idc.2016.02.004. PMID: 27208764; PMCID: PMC5314345.

Durán N, Marcato PD, Alves OL, Gabriel DS, Esposito E. Mechanistic aspects of biosynthesis of silver nanoparticles by several *Fusarium oxysporum* strains. *J Nanobiotechnol.2005;*  **3** (8). <https://doi.org/10.1186/1477-3155-3-8>.

El-Nour KMM, Eftaiha A, Al-Warthan A, Ammar RAA. Synthesis and applications of silver nanoparticles. Arabian Journal of Chemistry. 2010; 3 (3): 135-140. ISSN - 1878-5352. <https://doi.org/10.1016/j.arabjc.2010.04.008>.

Emerich DF, Thanos CG. The pinpoint promise of nanoparticle-based drug delivery and molecular diagnosis. Biomol Eng. Sep 2006; 23 (4): 171-84. Doi: 10.1016/j.bioeng.2006.05.026. Epub 2006 Jun 10. PMID: 16843058.

Fadeel B, Garcia-Bennett AE. Better safe than sorry: Understanding the toxicological properties of inorganic nanoparticles manufactured for biomedical applications. Adv Drug Deliv Rev. 2010 Mar; 62 (3): 362-74. Doi: 10.1016/j.addr.2009.11.008. Epub 2009 Nov 10. PMID: 19900497.

Fadeel B, Kasemo B, Malmsten M, Stromme M. Nanomedicine: reshaping clinical practice. Journal of Internal Medicine. Dec 2009, 267: 2-8. <https://doi.org/10.1111/j.1365-2796.2009.02186>.

Fayaz AM, Balaji K, Girilal M, Yadav R, Kalaichelvan PT, Venketesan R. Biogenic synthesis of silver nanoparticles and their synergistic effect with antibiotics: a study against gram-positive and gram-negative bacteria. Nanomedicine. Feb 2010; 6 (1): 103-109. Doi: 10.1016/j.nano.2009.04.006. Epub 2009 May 15. PMID: 19447203.

Gaber SE, Hashem AH, El-Sayyad GS, Attia MS. Antifungal activity of myco-synthesized bimetallic ZnO-CuO nanoparticles against fungal plant pathogen *Fusarium oxysporum*. *Biomass Conv. Bioref.* 2023. <https://doi.org/10.1007/s13399-023-04550-w>.

Gericke M, Pinches A. Microbial production of gold nanoparticles. *Gold Bull.*2006; **39**: 22–28. Doi: 10.1007/BF03215529.

Gogineni A, Revati K, Pandey BD. Microbial synthesis of iron-based nanomaterials -A review. Bulletin of Materials Science, Aug 2011; 34: 191-198.https://doi.org/10.1007/s12034-011-0076-6.

Gurunathan S. Rapid biological synthesis of silver nanoparticles and their enhanced antibacterial effects against Escherichia fergusonii and Streptococcus mutans, Arabian Journal of Chemistry. 2019; 12 (2). Doi: 10.1016/j.arabjc.2014.11.014.

Hamouda RA, Alharbi AA, Al-Tuwaijri, MM, Makharita RR. The Antibacterial Activities and Characterizations of Biosynthesized Zinc Oxide Nanoparticles, and Their Coated with Alginate Derived from *Fucus vesiculosus*. *Polymers*.**2023**;15, 2335. <https://doi.org/10.3390/polym15102335>.

He S, Guo Z, Zhang Y, Zhang S, Wang J, Gu N. Biosynthesis of gold nanoparticles using the bacteria *Rhodo pseudomonas* capsulate. Materials Letters. 2007; 61 (18): 3984-3987, ISSN - 0167-577X. <https://doi.org/10.1016/j.matlet.2007.01.018>.

Hildebrand H, Mackenzie K. Novel nano-catalysts for wastewater treatment. Global Net Journal. 2008; 10 (1), Corpus ID: 54776194. Doi: 10.30955/gnj.000507.

Horikoshi S, Serpone N. Microwaves in Nanoparticle Synthesis: Fundamentals and Applications. Wiley VCH Verlag GmbH, Baden, Aug 2013; ISBN – 9783527331970: 1–24. <https://doi.org/10.1002/9783527648122>.

Huston M, DeBella M, DiBella M, Gupta A. Green Synthesis of Nanomaterials. Nanomaterials (Basel). 2021 Aug 21; 11 (8): 2130. Doi: 10.3390/nano11082130. PMID: 34443960; PMCID: PMC8400177.

Ingle AP, Rai M. Copper nanoflowers as effective antifungal agents for plant pathogenic fungi. IET Nanobiotechnol. 2017 Aug; 11 (5): 546-551. Doi: 10.1049/iet-nbt.2016.0170. PMID: 28745287; PMCID: PMC8676366.

Iravani S, Korbekandi H, Mirmohammadi SV, Zolfaghari B. Synthesis of silver nanoparticles: chemical, physical and biological methods. Res Pharm Sci. 2014 Nov; 9 (6): 385-406. PMID: 26339255; PMCID: PMC4326978.

Jain N, Bhargava A, Majumdar S, Tarafdar JC, Panwar J. Extracellular biosynthesis and characterization of silver nanoparticles using Aspergillus flavus NJP08: a mechanism perspective. Nanoscale. 2011 Feb; 3 (2): 635-641. Doi: 10.1039/c0nr00656d. Epub 2010 Nov 18. PMID: 21088776.

Jayaseelan C, Rahuman AA, Kirthi AV, Marimuthu S, Santhoshkumar T, Bagavan A, Gaurav K, Karthik L, Rao KV. Novel microbial route to synthesize ZnO nanoparticles using *Aeromonas hydrophila* and their activity against pathogenic bacteria and fungi. Spectrochim Acta A Mol Biomol Spectrosc. 2012 May; 90: 78-84. Doi: 10.1016/j.saa.2012.01.006. Epub 2012 Jan 9. PMID: 22321514.

Jha AK, Prasad K, Prasad KA. Green low-cost biosynthesis of Sb2O3 nanoparticles. *Biochemical engineering journal* 2009; 43 (3) : 303-306.

Jha AK, Prasad K. Biosynthesis of metal and oxide nanoparticles using Lactobacilli from yoghurt and probiotic spore tablets. Biotechnol J. 2010 Mar; 5 (3): 285-91. Doi: 10.1002/biot.200900221. PMID: 20108273.

Juibari MM, Abbasalizadeh S, Salehi G, Noruzi M. Intensified biosynthesis of silver nanoparticles using a native extremophilic ureibacillus thermosphaericus strain. Mat lett. 2011; 65 (6): 1014 – 1017.

Kalabegishvili TL, Kirkesali EI, Rcheulishvili AN, Ginturi EN, Ivane M, Pataraya DT, Manana G, Tsertsvadze, G, Vakhtang G, Levan L, Gvarjaladze D, Marina F, Pavlov SS, Inga Z, Raven MJ, Seaga MMF, Arnaud F. Synthesis of gold nanoparticles by some strains of Arthrobacter genera. Journal of Materials Science and Engineering. 2012.Corpus ID: 82923890.

Kaliberov SA, Buchsbaum DJ. Chapter seven--Cancer treatment with gene therapy and radiation therapy. Adv Cancer Res. 2012; 115: 221-63. Doi: 10.1016/B978-0-12-398342-8.00007-0. PMID: 23021246; PMCID: PMC3664947.

Kalishwaralal K, BarathManiKanth S, Pandian SRK, Deepak V, Gurunathan S. Silver nanoparticles impede the biofilm formation by *Pseudomonas aeruginosa* and *Staphylococcus epidermidis*, Colloids and Surfaces B: Biointerfaces, 2010; 79 (2): 340-344, ISSN - 0927-7765, <https://doi.org/10.1016/j.colsurfb.2010.04.014>.

Kalishwaralal K, Deepak V, Ram Kumar Pandian S, Kottaisamy M, BarathmaniKanth S, Kartikeyan B, Gurunathan S. Biosynthesis of silver and gold nanoparticles using *Brevibacterium casei*. Colloids Surf B Biointerfaces. 2010 . Jun 1;77 (2): 257-62. Doi: 10.1016/j.colsurfb.2010.02.007. Epub 2010 Feb 11. PMID: 20197229.

Klaus T, Joerger R, Olsson E, Granqvist CG. Silver based crystalline nanoparticles, microbially fabricated, Proc Natl Acad Sci USA. 1999; 96: 13611- 13614.

Koul B, Poonia AK, Yadav D, Jin JO. Microbe-Mediated Biosynthesis of Nanoparticles: Applications and Future Prospects. Biomolecules. 2021 ;11 (6): 886. Doi: 10.3390/biom11060886. PMID: 34203733; PMCID: PMC8246319.

Krishnamurthy S, Sathishkumar M, Juan M, Kwak I, Yeoung-Sang Y. Corynebacterium Glutamicum-Mediated Crystallization of Silver Ions Through Sorption and Reduction Processes. Chemical Engineering Journal. 2010; 162: 989-996. Doi - 10.1016/j.cej.2010.07.006.

Kumar A, Liang XJ. Gold Nanomaterials as Prospective Metal-based Delivery Systems for Cancer Treatment. In: Kretsinger, R.H., Uversky, V.N., Permyakov, E.A. (eds) Encyclopedia of Metalloproteins. Springer, New York, NY. 2013: 875 – 887. [https://doi.org/10.1007/978-1-4614-1533-6\_579. ISBN -978-1-4614-1533-6](https://doi.org/10.1007/978-1-4614-1533-6_579.%20ISBN%20-978-1-4614-1533-6).

Kumar D, Saini N, Jain N, Sareen R, Pandit V. Gold nanoparticles: an era in bionanotechnology. Expert Opin Drug Deliv. 2013 Mar;10 (3): 397-409. Doi: 10.1517/17425247.2013.749854. Epub 2013 Jan 7. PMID: 23289421.

Kumar SA, Ansary AA, Ahmad A, Khan M. Extracellular biosynthesis of CdSe quantam dots by the fungus, Fusarium oxysporum. Journal of Biomedical Nanotechnology. 2007; 3 (2): 190 – 194.

Lai JC, Lai MB, Jandhyam S, Dukhande VV, Bhushan A, Daniels CK, Leung SW. Exposure to titanium dioxide and other metallic oxide nanoparticles induces cytotoxicity on human neural cells and fibroblasts. Int J Nanomedicine. 2008; 3 (4): 533-545. Doi: 10.2147/ijn. s3234. PMID: 19337421; PMCID: PMC2636591.

Lengke MF, Fleet ME, Southam G. Biosynthesis of Silver Nanoparticles by Filamentous Cyanobacteria from a Silver (I) Nitrate Complex, Langmuir, 2007; 23 (5): 2694–2699. https://doi.org/10.1021/la0613124.

Lengke MF, Fleet ME, Southam G. Morphology of Gold Nanoparticles Synthesized by Filamentous Cyanobacteria from Gold (i)−thiosulfate and Gold (iii)−chloride Complexes. Langmuir. 2006; 6 (22): 2780-2787. <https://doi.org/10.1021/la052652c>.

Li X, Xu H, Chen Z, Chen G. "Biosynthesis of Nanoparticles by Microorganisms and Their Applications", *Journal of Nanomaterials*. 2011, Article ID 270974. <https://doi.org/10.1155/2011/270974>.

Liu X, Tang J, Wang L, Liu R. Mechanism of CuO nano-particles on stimulating production of actinorhodin in *Streptomyces coelicolor* by transcriptional analysis. Sci Rep. 2019 Aug; 9 (1). Article No - 11253. Doi: 10.1038/s41598-019-46833-1. PMID: 31375702; PMCID: PMC6677739.

López ES, Gomes D, Esteruelas G, Bonilla L, Lopez-Machado AL, Galindo R, Cano A, Espina M, Ettcheto M, Camins A, Silva AM, Durazzo A, Santini A, Garcia ML, Souto EB. Metal-Based Nanoparticles as Antimicrobial Agents: An Overview. Nanomaterials (Basel). 2020 Feb;10 (2): 292. Doi: 10.3390/nano10020292. PMID: 32050443; PMCID: PMC7075170.

M. Gericke, A. Pinches. Biological synthesis of metal nanoparticles, Hydrometallurgy, 2006: 83 (3): 132-140, ISSN - 0304-386X. doi - <https://doi.org/10.1016/j.hydromet.2006.03.019>.

Malarkodi C, Rajeshkumar S, [KanniahPaulkumar](https://link.springer.com/article/10.1186/2193-8865-3-30#auth-Kanniah-Paulkumar-Aff1) V, [Gnanajobitha](https://link.springer.com/article/10.1186/2193-8865-3-30#auth-Gnanadhas-Gnanajobitha-Aff1)  G, [Annadurai](https://link.springer.com/article/10.1186/2193-8865-3-30#auth-Gurusamy-Annadurai-Aff1) G. Eco-friendly synthesis and characterization of gold nanoparticles using  *Klebsiella pneumoniae*. J Nanostruct Chem. 2013; **3** (30). Doi - <https://doi.org/10.1186/2193-8865-3-30>.

Mazdeh KS, [Hossein](https://www.ingentaconnect.com/search?option2=author&value2=Motamedi,+Hossein) M, [Khiavi AA,](https://www.ingentaconnect.com/search?option2=author&value2=Akbarzadeh+Khiavi,+Azim)Mehrabi RM. Gold Nanoparticle Biosynthesis by E. coli and Conjugation with Streptomycin and Evaluation of its Antibacterial Effect. [Current Nanoscience](https://www.ingentaconnect.com/content/ben/cnano). 2014;10 (4): 553-561. Doi - 10.2174/1573413709666131203231344.

Mukherjee P, Ahmad A, Deendayal M, Senapati S, Sudhakar S, Khan M, Renu P, Ajaykumar PV, Mansoor A, Kumar R, Sastry M. Fungus-Mediated Synthesis of Silver Nanoparticles and Their Immobilization in the Mycelial Matrix: A Novel Biological Approach to Nanoparticle Synthesis. Nano Letters. 2001; 1 (10); Doi -10.1021/nl0155274.

Munusamy S, Bhakyaraj K, Vijayalakshmi L, Stephen A, Narayanan V. Synthesis and characterization of cerium oxide nanoparticles using *Curvularia lunata* and their antibacterial properties. Int J Innovative Res Sci Eng. 2014; 2 (1): 318–323.

Nair B, Pradeep T. Coalescence of Nanoclusters and Formation of Submicron Crystallites Assisted by *Lactobacillus* Strains. Crystal Growth & Design. 2002; 2: 293-298.<https://doi.org/10.1021/cg0255164>.

Nam NH, Luong NH. Nanoparticles: synthesis and applications. Materials for Biomedical Engineering. 2019: 211–240. Doi: 10.1016/B978-0-08-102814-8.00008-1. Epub 2019 Mar 29. PMCID: PMC7151836.

Natalia P, Claudio B, Rey V, Veglia A. Feb (2015). Synthetic Routes for the Preparation of Silver Nanoparticles: A Mechanistic Perspective. 2015 Feb; Chapter 2: 13 – 46. Publisher: Springer. Editors: Emilio I. Alarcón, May Griffith, Klas I. Udekwu. Doi: 10.1007/978-3-319-11262-62.

Nikolova MP, Chavali MS. Metal Oxide Nanoparticles as Biomedical Materials. Biomimetics (Basel). 2020 Jun 8;5 (2): 27. Doi: 10.3390/biomimetics5020027. PMID: 32521669; PMCID: PMC7345077.

Nita M, Grzybowski A. The Role of the Reactive Oxygen Species and Oxidative Stress in the Pathomechanism of the Age-Related Ocular Diseases and Other Pathologies of the Anterior and Posterior Eye Segments in Adults. Oxid Med Cell Longev. 2016 :3164734. doi: 10.1155/2016/3164734. Epub 2016 Jan 10. PMID: 26881021; PMCID: PMC4736974.

Otto SW. An overview of nanoparticles commonly used in fluorescent bioimaging. [*Chem. Soc. Rev.*](https://doi.org/10.1039/1460-4744/1972), 2015 Jan**; 44:** 4743-4768. ISSN 1878-5352. <https://doi.org/10.1015/j.arabjc.2014.11.014>.

Parikh RY, Ramanathan R, Coloe PJ, Bhargava SK, Patole MS, Shouche YS, Bansal V. Genus-Wide Physicochemical Evidence of Extracellular Crystalline Silver Nanoparticles Biosynthesis by Morganella spp. PLoS ONE. 2011; 6 (6): e21401. <https://doi.org/10.1371/journal.pone.0021401>.

Parikh RY, Singh S, Prasad BL, Patole MS, Sastry M, Shouche YS. Extracellular synthesis of crystalline silver nanoparticles and molecular evidence of silver resistance from *Morganella* sp.: towards understanding biochemical synthesis mechanism. Chembiochem. 2008 Jun 16; 9 (9): 1415-1422. Doi: 10.1002/cbic.200700592. PMID: 18491326.

Pearce CI, Coker VS, Charnock JM, Pattrick RA, Mosselmans JFW, Law N, Beveridge TJ, Lloyd JR. Microbial manufacture of chalcogenide – based nanoparticles via the reduction of selenite using Veillonella atypica: an in – situ EXAFS study. Nanotechnology. 2008; 19 (15): 155603 – 155616.

Prasad K, Jha AK. ZnO nanoparticles: synthesis and adsorption study. Natural Science 1.02. 2009: 129. Proc Natl Acad Sci USA 96:13611–13614.

Rai M, Bonde S, Golinska P, Trzcińska-Wencel J, Gade A, Abd-Elsalam KA, Shende S, Gaikwad S, Ingle AP. *Fusarium* as a Novel Fungus for the Synthesis of Nanoparticles: Mechanism and Applications. Journal of Fungi. 2021; 7 (2):139. <https://doi.org/10.3390/jof7020139>.

Reygaert WC. An overview of the antimicrobial resistance mechanisms of bacteria. AIMS Microbiol. 2018 Jun 26; 4 (3): 482-501. doi: 10.3934/microbiol.2018.3.482. PMID: 31294229; PMCID: PMC6604941.

Saklani V, Suman, Jain VK. Microbial Synthesis of Silver Nanoparticles: A Review. J Biotechnol Biomaterials. 2012; 13: 007. Doi:10.4172/2155-952X.S13-007.

Salomoni R, Leo P, Montemor AF, Rinaldi BG, Rodrigues M. Antibacterial effect of silver nanoparticles in *Pseudomonas aeruginosa*. Nanotechnol Sci Appl. 2017 Jun; 10: 115-121. Doi: 10.2147/NSA.S133415. PMID: 28721025; PMCID: PMC5499936.

Saman S, Iqra F, Maria HK, Vahideh Md, Rabia A, Muhammad B, Abbas R, Ana DP, Razieh B. Fluorescent-based nanosensors for selective detection of a wide range of biological macromolecules: A comprehensive review. International Journal of Biological Macromolecules. May 2022, 206: 115-147.https://doi.org/10.1016/j.ijbiomac.2022.02.137.

Senapati S, Mandal D, Ahmad A, Khan MI, Sastry M, Kumar R. Fungus mediated synthesis of silver nanoparticles: A novel biological approach. Indian J Phys. 2004; 78: 101-105.

Shah M, Fawcett D, Sharma S, Tripathy SK, Poinern GEJ. Green Synthesis of Metallic Nanoparticles via Biological Entities. Materials (Basel). 2015 Oct; 8 (11): 7278-7308. doi: 10.3390/ma8115377. PMID: 28793638; PMCID: PMC5458933.

Shan C, Ma Z, Tong M, [Ni](https://www.sciencedirect.com/author/7201636727/jinren-ni) J. Removal of Hg (II) by poly (1-vinylimidazole) grafted Fe3O4@SiO2 magnetic nanoparticles. [Water Research](https://d.docs.live.net/92e3f3bb1a7eeacb/Documents/Desktop/jayeeta%20picture/Water%20Research). 2015 Feb; [69](file:///C%3A%5CUsers%5CDr%20Avijit%5CDownloads%5C69) : 252-260. <https://doi.org/10.1016/j.watres.2014.11.030>.

Sharma VK, Yngard RA, Lin Y. Silver nanoparticles: green synthesis and their antimicrobial activities. Adv Colloid Interface Sci. 2009 Jan; 145 (1-2): 83-96. Doi: 10.1016/j.cis.2008.09.002. Epub 2008 Sep 17. PMID: 18945421.

Singaravelu G, Arockiamary JS, Kumar VG, Govindaraju K. A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, *Sargassum wightii* Greville. Colloids Surf B Bio interfaces. 2007 May; 57 (1): 97-101. Doi: 10.1016/j.colsurfb.2007.01.010. Epub 2007 Feb 1. PMID: 17350236.

Singh MM, Satija J. Enzyme-assisted metal nanoparticles etching based plasmonic ELISA: Progress and insights. Anal Biochem. 2022 Oct; 654:114820. Doi: 10.1016/j.ab.2022.114820. Epub 2022 Jul 15. PMID: 35850200.

Singh N, Arya RS, Sharma T, Dhuria RK, Garg DD. Effect of feeding of cluster bean (*Cyamopsis tetragonoloba*) straw based complete feed in loose and compressed form on rumen and haemato-biochemical parameters in Marwari sheep. Vet. Pract. 2008; 9 (2): 110-115.

Singh S, Bhatta UM, Satyam PV, Dhawan A, Sastry M, Prasad PLV. Bacterial synthesis of silicon / silica nanocomposites. J MATER CHEM. 2008, 18: 2601- 2606.

Slawson RM, Trevors JT, Lee H. Silver accumulation and resistance in *Pseudomonas stutzeri*. *Archives of microbiology*. 1992; *158*: 398-404.

Suresh AK, Pelletier DA, Wang W, Broich ML, Moon JW, Gu B, Allison DP, Joy DC, Phelps TJ, Doktycz MJ. Bio fabrication of discrete spherical gold nanoparticles using the metal-reducing bacterium *Shewanella oneidensis.* Acta Biomater. 2011 May; 7 (5): 2148-52. Doi: 10.1016/j.actbio.2011.01.023. Epub 2011 Jan 15. PMID: 21241833.

Suslick KS. Sonochemistry. Science. 1990 Mar; 247 (4949): 1439-45. Doi: 10.1126/science.247.4949.1439. PMID: 17791211.

Svechkarev D, Mohs AM. Organic Fluorescent Dye-based Nanomaterials: Advances in the Rational Design for Imaging and Sensing Applications. Curr Med Chem. 2019; 26 (21): 4042-4064. Doi:10.2174/0929867325666180226111716. PMID: 29484973; PMCID: PMC6703954.

Syed A, Ahmad A. Extracellular biosynthesis of CdTe quantum dots by the fungus *Fusarium oxysporum* and their antibacterial activity, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy. 2013; 106: 41 – 47. ISSN – 1386 – 1425. DOI: 10.1016/j.saa.2013.01.002.

Talebian S, Shahnavaz B, Nejabat M, Abolhassani Y, Rassouli FB. Bacterial-mediated synthesis and characterization of copper oxide nanoparticles with antibacterial, antioxidant, and anticancer potentials. Front Bioeng Biotechnol. 2023 Mar; 11: 1140010. Doi: 10.3389/fbioe.2023.1140010. PMID: 36949885; PMCID: PMC10025390.

Ullah A, Yin X, Wang F, Xu B, Mirani ZA, Xu B, Chan MWH, Ali A, Usman M, Ali N, Naveed M. Biosynthesis of Selenium Nanoparticles (via *Bacillus subtilis* BSN313), and Their Isolation, Characterization, and Bioactivities. Molecules. 2021 Sep; 26 (18): 5559. Doi: 10.3390/molecules26185559. PMID: 34577029; PMCID: PMC8468162.

Vigderman L, Zubarev ER. Therapeutic platforms based on gold nanoparticles and their covalent conjugates with drug molecules. Advanced Drug Delivery Reviews. 2012; 65 (5). 2013: 663-676. ISSN 0169-409X. <https://doi.org/10.1016/j.addr.2012.05.004>.

Vigneshwaran N, Kathe AA, Varadarajan PV, Nachane RP, Balasubramanya RH. Biomimetics of silver nanoparticles by white rot fungus, *Phaenerochaete chrysosporium* Colloids and Surfaces B: Biointerfaces. 2006; 53 (1): 55-59,ISSN 0927-7765. <https://doi.org/10.1016/j.colsurfb.2006.07.014>.

Yasuhiro K, Tsukiyama T, Kaori O, Norizoh S, Toshiyuki N, Shinsuke N. Intracellular recovery of gold by microbial reduction of AuCl4− ions using the anaerobic bacterium *Shewanella* alga. Hydrometallurgy. 2006; 81: 24-29. 10.1016/j.hydromet.2005.09.006.

Yusof HM, Mohamad R, Zaidan UH, RahmanNA*.* Sustainable microbial cell nanofactory for zinc oxide nanoparticles production by zinc-tolerant probiotic *Lactobacillus plantarum* strain TA4. *Microb Cell Fact*. 2020; **19** (10)<https://doi.org/10.1186/s12934-020-1279-6>.

Zhang Z, Tsai PC, Ramezanli T, Michniak-Kohn BB. Polymeric nanoparticles-based topical delivery systems for the treatment of dermatological diseases. Wiley Interdiscip Rev Nanomed Nanobiotechnol. 2013 Jun; 5 (3): 205-18. Doi: 10.1002/wnan.1211. Epub 2013 Feb 5. PMID: 23386536; PMCID: PMC3631287.

Zumaya ALV, Mincheva R, Raquez JM, Hassouna F. Nanocluster-Based Drug Delivery and Theranostic Systems: Towards Cancer Therapy. Polymers (Basel). 2022 Mar;14 (6): 1188. Doi: 10.3390/polym14061188. PMID: 35335518; PMCID: PMC8955999.