Nanomaterials for Sustainability: A Review on Green Synthesis of Nanoparticles Using Microorganisms

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Abstract

Nanotechnology has permeated all areas of sciences as one of the most propitious technology with the deployment of nanoparticles in environmental remediation and biomedical fields; their synthesis under greener conditions has been bourgeoned using microorganisms, plants, etc. to decrease the use of toxic chemicals. Synthesis of nanoparticles by exploiting microorganisms has opened up a new prospect at the interface of nanotechnology, chemistry, and biology enabling access via a biocompatible, safe, sustainable, eco-friendly, and reliable route; microorganisms offer crystal growth, stabilization, and prevention of aggregation thus performing a dual role of reducing and capping agent because of the presence of biomolecules such as enzymes, peptides, poly (amino acids), polyhydroxyalkanoate (PHA), and polysaccharides. Herein, the microorganisms-based synthesis of various nanoparticles comprising gold, silver, platinum, palladium, copper, titanium dioxide, zinc oxide, iron oxide, and selenium along with their appliances in waste treatment, biomedicine namely cancer treatment, antibacterial, antimicrobial, antifungal, and antioxidants, are deliberated.

1. Introduction

“Being green and clean is not just an aspiration but an action” is a small line delivered by “Christine Pelosi” (Jiwani et al. 2018) but has a bigger meaning which inspires everyone to be active in this domain (Varma 2016; Chen et al. 2020). Green and sustainable chemistry is a general strategy for the deployment of chemicals, reagents, solvents, and processes that helps in the reduction and use of hazardous chemicals to ensure the safety of the environment (Lu and Ozcan 2015; MacKellar et al. 2020; Monga et al. 2020; Ganesh et al. 2021). Greener biosynthesis pathways for nanomaterials has garnered immense interest as nanotechnology has spread its arms in all areas of sciences as one of the most propitious technology with the deployment of nanoparticles in environmental remediation and biomedical fields (Hu and Xianyu 2021). Nanotechnology combined with green technology provides a viable alternative to physical and chemical routes by utilizing safe, renewable, and non-toxic chemicals and eco-friendly means (Silva et al. 2020; Ajayi et al. 2021). This quest continues incessantly for the modification of shape and size for enhancing the properties of nanoparticles (Zare et al. 2020). Although, the synthesis of the nanoparticles has been accomplished by alternative activation methods such as sonochemical or microwave (MW)-assisted protocols (Kou and Varma 2013; Gawande et al. 2014) and photochemical reaction techniques, laser ablation (Nasrollahzadeh et al. 2020b), lithography, etc. they often entail the use of hazardous chemicals or specialized equipment (Sarfraz and Khan 2021), various methods for the synthesis of nanoparticles are presented in Figure 1 with immense potential appliances in environmental remediation and biomedical arena (Irvani and Varma 2020; Nasrollahzadeh et al. 2021; Rabiee et al. 2021). Green nanotechnology deploying safer solvents, and eco-friendly reducing and stabilizing (capping) agents comprise biological systems wherein plants, bacteria, fungi, algae, and other microorganisms fall into this category (Venil et al. 2021b) activity during the last two decades, according to Scopus, is depicted in Figure 2 (Mohammadinejad et al. 2019).

Green synthesis using plants extracts for sustainability has demonstrated immense potential in various applications which have been reviewed earlier (Jadoun et al. 2021). On the other hand, the microbial route has also attracted significant attention due to their environmental sustainability popularly known as bio factories for nanoparticle synthesis. Additionally, the microorganisms can withstand in variables extreme conditions of pH, pressure, temperature, etc. that attracts researchers and scientists to adopt the microbial route (Vetchinkina et al. 2019). Herein, the current status of the microbial-assisted synthesis of various nanoparticles and their broader applications in environmental remediation and biomedical fields such as photocatalysis, cancer therapy, tissue engineering, drug delivery, biosensors, antimicrobial, antibacterial, antifungal, antioxidant, etc. are deliberated, Figure 3.
2. Green Synthesis Of Nanoparticles By Microorganisms

Microorganisms hold great potential for nanoparticles synthesis being cost-effective, ecofriendly, avoiding harmful toxic, and harsh chemicals along with the reduced demand for high energy usage required by physiochemical methods. Assorted reductase enzymes help in the accumulation and detoxification of metals thus reducing the metal salts to nanoparticles with minimum polydispersity and narrow size distribution (Yadav et al. 2020). Extracellular synthesis has been adopted widely and has garnered a noticeable interest due to the elimination of downstream steps of processing in the intracellular method for nanoparticles recovery as it eliminates the cell wall breakdown by sonication, and centrifugation followed by some washing stages necessary for the purification of nanoparticles. Furthermore, metal resistance genes, enzymes (Virkutyte and Varma 2011), peptides, proteins, organic materials, and reducing cofactors play a key role in green synthesis by acting as reducing agents, thus helping in the synthesis of nanoparticles by functioning as a natural capping agent and preventing the aggregation and imparting additional stability to nanoparticles for a longer period (Purohit et al. 2019; Messaoudi and Bendahou 2020; Rana et al. 2020). For nanoparticles, stabilization and surface functionalization became greener by using biocompatible stabilizing agents, i.e., microbes, which can produce vast varieties of stable flower-shaped, spherical, and rod-shaped nanoparticles that have potential uses and diverse applications. Genetically engineered organisms are the ideal choice to attain environmentally friendly, and high-throughput bio reduction for the synthesis of nanoparticles due to easy genetic manipulation and resistance to toxicity (Iravani and Varma 2019). For multidrug-resistant bacteria, metals and metal oxide nanoparticles have been extensively studied. Numerous studies suggested the antimicrobial properties of these nanoparticles against a wide spectrum of bacterial species (Niño-Martínez et al. 2019). Metal and metal oxides nanoparticles synthesized using Lactobacillus sp. also showed this resistance (Jha and Prasad 2010).

Numerous types of nanoparticles such as Ag (Singh 2019; Chen et al. 2021), Au (Duran and Seabra 2018; Krishnan and Chadha 2020; Botteon et al. 2021), ZnO (Sanaeimehr et al. 2018; Mohd Yusof et al. 2019), TiO₂ (Seydi et al. 2019), Cu (Lalitha et al. 2020), Se (Afzal et al. 2021; Menon et al. 2021), Pd (Arya et al. 2020), Pt (Bloch et al. 2021), and many others have been synthesized using microbes as a reducing and capping agent and these nanoparticles are applicable in wide areas.

3. Mechanism Of Green Synthesis Of Nanoparticles

In recent years, nanoparticles synthesis via microbial agents such as algae, fungi, bacteria, yeast has attracted a lot of attention for potential applications in biomedical and other fields due to their cost-effective and ecofriendly potential (Figure 4) (Gahlawat and Choudhury 2019).

The nanoparticles synthesis by microorganisms occurs either intracellularly or extracellularly. In intracellular synthesis, ion transportation takes place in the microbial cell in which the microorganism's cell wall plays a key role. The positive charge ion of metal and cell wall's negative charge is involved in the electrostatic interaction. The cell wall of microorganisms possesses the enzymes which reduce the ions to nanoparticles where the cell wall further diffuses off the nanoparticle, Figure 5 (Patil and Kim 2018). The mechanism of nanoparticle synthesis involves three steps including trapping, bio reduction, and capping (Fariq et al. 2017). Intracellular synthesis of silver nanoparticles has been performed by using Rhodococcus sp. which was grown aerobically in an M9 medium containing salts for 24 hours at 30°C and agitated at 130 rpm. This was used as synthesis media after 24 hours with AgNO₃ salt at 7.0 pH. The color changed to brown from white during this period, the incubation was performed for more than 24 hours and collected after the period. When the cell surface encounters metal ions, electrostatic interaction and trapping of ions take place. For the reduction of metal ions to metal, enzymes found in the cell wall are responsible (Otari et al. 2015).
In extracellular synthesis, firstly microorganisms are cultured in a rotating shaker for 1-2 days under optimum conditions followed by the centrifugation of culture for biomass removal, and the supernatant is collected for nanoparticles synthesis with the addition of metal salt solution (filter-sterilized) and incubated again (Ammar et al. 2021). The synthesis of nanoparticles can be visibly followed by the color change of culture medium, for example, for the gold nanoparticles (Au NPs), these color changes to deep purple color from ruby red while color changes to dark brown for silver nanoparticles (Ag NPs). The removal of large particles or medium components can be accomplished via centrifugation of the reaction mixture. Lastly, these nanoparticles can be centrifuged with a density gradient or at high speed and washed carefully with ethanol/water, and collected (Singh et al. 2016).

4. Role Of Microorganisms

The role of microbes in the synthesis of inorganic nanomaterials with exquisite morphology is to reduce the use of harmful and toxic chemicals. Due to the inherent chemical detoxication mechanism of microbes and energy-dependent ion efflux by the membrane proteins of the cell, which functions either as the proton or chemiosmotic cation or ATPase anti transporters, microbes show resistance to toxic heavy metals. Changes in solubility are also a major point that play role in microbial resistance. Hence, the microbes play the role of detoxification of metal ions via precipitation or reduction to insoluble non-toxic metal nanoclusters from soluble toxic inorganic ions (Ogi et al. 2011). This microbial detoxication can be accomplished via intracellular bioaccumulation or precipitation or extracellular biosorption, biomineralization, complexation (Hansda et al. 2016). However, extracellular synthesis has a wide range of commercial applications. In such a biological process, optimization of monodispersed conditions should be precisely followed due to the major concern of polydispersity; formation of less polydispersed and accumulated particles of specific dimensions are found in intracellular synthesis (Giovagnoli et al. 2014; Bharathi et al. 2020). This microbial synthesis can be performed via various microbes such as algae, fungi, bacteria, and yeast and are discussed in this section.

4.1 Algae

Green synthesis of various nanoparticles via algae has been explored by many researchers which are summarized in Table 1. Green synthesis of Ag NPs via freshwater Chara vulgaris algae was explored by Hassan et al. (Hassan et al. 2021a). They initially dried the algae and ground it to form the 100-ppm aqueous extract followed by the addition of AgNO₃ in various ratios but the perfect synthesized nanoparticles of Ag were accessible by the ratio 3:1 of Chara vulgaris:AgNO₃; the size of these nanoparticles being 16.99 ± 0.3 nm by SEM imaging. These Ag NPs showed immense potential against bacteria Pseudomonas aeruginosa, Klebsiella pneumonia, and Escherichia coli. The complete process of synthesis and antibacterial activity is provided in Figure 6. Other than these, various algae have been used for nanoparticles synthesis such as Bifurcaria bifurcate, Caulerpa peltate, Hypnea Valencia, Sargassum myriocystum, Sargassum muticum, Sargassum muticum, etc. (AlNadhari et al. 2021).
Table 1
Green synthesis of nanoparticles using Algae.

| Year | Nanoparticle | Name of Algae                  | Size (nm) | Morphology   | Application                                      | References                                      |
|------|--------------|--------------------------------|-----------|--------------|-------------------------------------------------|------------------------------------------------|
| 2021 | Ag           | *Amphiroa rigida*              | 25        | Spherical    | Antibacterial and anticancer                     | (Gopu et al. 2021)                              |
| 2021 | Ag           | *Chara vulgaris*               | 16.99 ± 0.3 | -            | Antibacterial                                    | (Hassan et al. 2021a)                           |
| 2021 | ZnO          | *Tetraselmis indica*          | 20-40     | Spherical    | Textile, cosmetic, biomedical, and food packaging| (Thirumoorthy et al. 2021)                      |
| 2021 | Pd           | Padina boryana                | 11.16     | Crystal      | Nano drug against multidrug-resistant bacteria and cancer cells | (Sonbol et al. 2021)                           |
| 2021 | CuO          | *Macrocystis pyrifera*        | 2-50      | Spherical    | -                                                | (Araya-Castro et al. 2021)                      |
| 2020 | ZnO          | *Anabaena cylindrica*         | 40-60     | Rod shape    | Antimicrobial                                    | (Bhattacharya et al. 2020)                      |
| 2020 | Au and Ag    | *Neodesmus pupukensis*        | 5-34      | Circular     | Antioxidant and antimicrobial                     | (Omomowo et al. 2020)                          |
| 2020 | Ag           | Portieria homemannii          | -         | Spherical    | Antibiotics in the treatment of fish diseases    | (Fatima et al. 2020)                            |
| 2020 | Ag           | *Chlorella ellipsoidea*       | 220.8 ± 31.3 | Spherical   | Degradation of MB and MO, Antibacterial          | (Borah et al. 2020)                             |
| 2020 | Ag           | *Noctiluca scintillans*       | 4.5       | Spherical    | Anticancer and antibacterial                     | (Elgamouz et al. 2020)                         |
| 2019 | Ag           | *Botryococcus braunii*        | 40-90     | Spherical, cubical and truncated triangular      | Catalyst in synthesis of benzimidazoles        | (Arya et al. 2019)                              |
| 2019 | Ag           | Ulva armoricana               | 12.5      | Spherical    | Antibacterial                                    | (Massironi et al. 2019)                        |
| 2019 | Au           | *Gelidiella acerosa*          | 5.81-117.59 | Spherical   | alpha glucosidase enzyme inhibition, antibacterial, antioxidant | (Facile green synthesis of gold nanoparticles from marine algae Gelidiella acerosa and evaluation of its biological PotentialSenthilkumar et al. 2019) |
| 2019 | Ag           | *Chlorella vulgaris*          | 40-90     | Spherical, cubical and truncated triangular      | Catalyst for the synthesis of quinolines      | (Mahajan et al. 2019)                          |
| Year | Nanoparticle | Name of Algae          | Size (nm)         | Morphology                      | Application      | References                      |
|------|--------------|------------------------|------------------|--------------------------------|------------------|--------------------------------|
| 2019 | ZnO          | Cladophora glomerata   | 14.39 - 37.85    | Spherical                       | Biomedical       | (Abdulwahid et al. 2019)       |
| 2018 | Cu and Ag    | Botryococcus braunii   | 10-70 (Cu), and 40-100 (Ag) | Cubical and spherical (Cu), spherical, cubical, and truncated triangular (Ag) | Antimicrobial    | (Arya et al. 2018)            |
| 2018 | Ag           | Laminaria japonica     | 20-30            | Oval                           | Seed treatment, pharmacy | (Kim et al. 2018)             |
| 2018 | Ag           | Sargassum wightii      | 18.45–41.59      | Spherical                       | Pharmacological agent | (Deepak et al. 2018)          |
| 2018 | Au           | Sargassum crassifolium | 5-300            | Varied                         | Biomedical       | (Maceda et al. 2018)          |
| 2017 | Pd           | Chlorella vulgaris     | 15               | Spherical                       | -                | (Arsiya et al. 2017)          |
| 2017 | CdS          | Chlamydomonas reinhardtii | 2-7             | Spherical                       | Photodegradation of organic dyes | (Rao and Pennathur 2017) |
| 2017 | Ag           | Spyridia fusiformis    | 5-50             | Spherical and rounded Rectangle | Antibacterial    | (Murugesan et al. 2017)       |
| 2017 | Au           | Cystoseira baccata     | 8.4 ± 2.2        | Spherical                       | Anticancer       | (González-Ballesteros et al. 2017) |

### 4.2 Fungi

The synthesis of nanoparticles by fungi has more advantages as compared to other microorganisms (Dhillon et al. 2012). As compared to bacteria and plants, the fungal mycelial mesh can withstand agitation, flow pressure, and some other conditions in chambers and bioreactors, being easy to grow, handle, and fabricate. Fungi have outstanding metal bioaccumulation capacity with high binding capacity, their tolerance, and some other conditions such as intracellular uptake which is facile to handle under research conditions (Yadav et al. 2015). Nowadays, many fungi are in demand for nanoparticle synthesis such as *Volvariella volvacea* (Bedlovicová and Salayová 2017), *Trichotheicum sp.* (Qu et al. 2019), *Aspergillus fumigatus* (Vasanthi bharinayarayan et al. 2013), *Penicillium brevicompactum* (Shaligram et al. 2009), *Aspergillus niger* (Soni and Prakash 2012), *Colletotrichum sp.* (Suryavanshi et al. 2017), *Fusarium semitectum* (Basavaraja et al. 2008), *Phoma glomerata* (Gade et al. 2014), *Penicillium fellutanum* (Kathiresan et al. 2009; Chandrappa et al. 2016), *Phaenerochaete chrysosporium* (Laxmi Sharma et al. 2021), *Fusarium oxysporum* (Gupta and Chundawat 2020), *Cladosporium cladosporioides* (Manjunath Hulikere and Joshi 2019).

Kaplan et al. (Kaplan et al. 2021) synthesized Ag NPs with the extract of *Boletus edulis* and *Coriolus versicolor*. They dried and pulverized these with a laboratory blender and 5 g of that powdered mushroom in 50 mL of distilled water was heated for 90 minutes at 60°C followed by filtration and centrifugation (10 minutes at 6000 rpm) of mushroom extract and stored at 4°C. For the synthesis of nanoparticles, 25 mL of mushroom extract were allowed to react in the microwave (MW) for 2 minutes at 475 W with AgNO₃ solution (25 mL of 10 mM) while pH was adjusted to 12 for
*Coriolus versicolor* and 10 for *Boletus edulis* using NaOH. After that, the mixture was kept for centrifugation (20000 g for 10 min), the nanoparticles designated BE-Ag NPs and CV-Ag NPs were precipitated which were washed several times and dried for further use (Figure 7) (Kaplan et al. 2021). Recently synthesized several nanoparticles by adopting green routes via fungi are summarized in Table 2.
| Year | Nanoparticle | Name of Fungi | Size (nm) | Morphology | Application | References |
|------|--------------|---------------|-----------|------------|-------------|------------|
| 2021 | ZnO | *Phanerochaete chrysosporium* | 50 | Hexagones | Antimicrobial | (Sharma et al. 2021) |
| 2021 | Ag | *Trichoderma harzianum* | 21.49 | Cubes | Antioxidant, antibacterial | (Konappa et al. 2021) |
| 2021 | MgO | *Rhizopus oryzae* | 20.38 ± 9.9 | Spherical | Antimicrobial, mosquitocidal action, and tanning effluent treatment | (Hassan et al. 2021b) |
| 2021 | Au | *Morchella esculenta* | 16.51 | - | Biomedical | (Acay 2021) |
| 2021 | Ag | *Aspergillus sydowii* | 1-24 | Spherical | Antifungal and antiproliferative activity to HeLa cells | (Wang et al. 2021) |
| 2020 | Cu | *Aspergillus flavus* | 2-60 | Spherical | Biomedical | (Saitawadekar and Kakde 2020) |
| 2020 | Ag | *Ganoderma lucidum* | 15-22 | Spherical | Antimicrobial, antibacterial, antifungal | (Aygün et al. 2020) |
| 2020 | ZnO | *Periconium sp.* | 16-78 | Quasi spherical | Antimicrobial and antioxidant | (Ganesan et al. 2020) |
| 2020 | Au | *Fusarium solani* | 40-45 | Needle and flower like | Anticancer | (Clarance et al. 2020) |
| 2020 | Ag, CuO and ZnO | *Trichoderma harzianum* | 5-18 | Spherical | In biotechnological process | (Consolo et al. 2020) |
| 2019 | Au | *Fusarium oxysporum* | 22-30 | Spherical or hexagonal | Therapeutic | (Naimi-Shamel et al. 2019) |
| 2019 | SeS | *Saccharomyces cerevisiae* | 5-7 | Spherical | Antifungal | (Asghari-Paskiabi et al. 2019) |
| 2019 | Ag | *Pleurotus sp.* | 2-100 | Spherical | Biomedical field | (Owaid 2019) |
| 2019 | Fe$_2$O$_3$ | *Trichoderma asperellum* | 18-32 | Spherical | Biomedical and waste water treatment | (Mahanty et al. 2019) |
| 2018 | Ag | *Aspergillus fumigatus* | 1-50 | Spherical | Antimicrobial | (Kalyani et al. 2018) |
| 2018 | Ag | *Aspergillus niger* | 61 | Spherical | Antimicrobial and anticancer | (Rayaman et al. 2018) |
| 2018 | MgO | *Penicillium chrysogenum* | 5-12 | Irregular | Antimicrobial | (El-Sayyad et al. 2018) |
| 2018 | Ag | *Pleurotus sajorcaju* | 16.8 | Spherical | Antifungal | (Musa et al. 2018) |
| Year | Nanoparticle | Name of Fungi           | Size (nm) | Morphology                                                                 | Application                                      | References                  |
|------|--------------|-------------------------|-----------|----------------------------------------------------------------------------|-------------------------------------------------|----------------------------|
| 2018 | Au           | *Pleurotus ostreatus*   | 2-20      | Spherical                                                                  | Biotechnological applications                    | (Vetchinkina et al. 2018)  |
| 2018 | Ag           | *Lenzites betulina*     | 14-50     | Spherical                                                                  | Antioxidant                                     | (Sytu and Camacho 2018)    |
| 2017 | Ag           | *Pleurotus ostreatus*   | 40        | Spherical                                                                  | Antibacterial                                   | (Al-Bahrani et al. 2017)   |
| 2017 | Ag           | *Aspergillus oryzae*    | 61.15±11.45 | Triangular                                                                 | Antimicrobial                                   | (Silva et al. 2017)        |
| 2017 | Au           | *Aspergillum sp.*       | 50.3      | Spheres, triangles, hexagons and irregular                                | Efficient catalysts for aromatic pollutants degradation | (Qu et al. 2017a)         |
| 2017 | Ag           | *Aspergillus niger*     | 41.9      | Spherical                                                                  | Antibacterial and antioxidant                   | (Hemashekhar et al. 2017)  |
| 2017 | Au           | *Mariannaea species*    | 37.4      | Sphere, hexagon, and irregular shapes                                      | Catalytic reduction of 4- NP                    | (Pei et al. 2017)          |
| 2017 | Ag           | *Aspergillus terreus*   | 16.54     | Spherical                                                                  | Antibacterial                                   | (Rani et al. 2017)         |

### 4.3 Bacteria

Bacteria is one of the best candidates for reducing metal ions to nanoparticles with its unique abilities because of its high growth rate and ease of handling. Bacteria is easy to genetically mold and manipulate for metal ion's biomineralization as compared to other microbes (Liu et al. 2011; Vaseghi et al. 2018). Due to high exposure to continual toxic and harsh environmental conditions, generally, its surroundings have a high concentration of heavy metal ions. They have developed some natural defense mechanisms such as extracellular precipitation, intracellular sequestration, change in metal ion concentration, and efflux pumps, which enables them to survive these harsh and stressful conditions and these mechanisms have been fruitfully utilized by bacteria for nanoparticle's synthesis.

When some bacteria such as *Sulfolobus acidocaldarius*, *T. thiooxidans*, and *Thiobacillus ferrooxidans*, were grown on elemental sulfur as an energy source, they could reduce ferric ions to the ferrous state. *T. thiooxidans* was able to complete the reduction at low pH medium aerobically but it was unable to oxidize the ferrous ions again, hence the ferrous ions were stable to autooxidation. The bio reduction by *T. ferrooxidans* from ferric ions was not aerobic because the presence of oxygen boosts the bacterial reoxidation of ferrous ions (Brock and Gustafson 1976). Some bacteria used in nanoparticles synthesis are *Pseudomonas rhodesiae*, *Bacillus megaterium*, *Dietzia maris*, *Bacillus haynesii*, *Streptomyces sp.*, *Actinomycetes sp.*, etc (Alsamhary 2020; Costa et al. 2020; Golińska 2020; Hamed et al. 2020; Huq 2020a; Akintelu et al. 2021; Goel et al. 2021; Hashem et al. 2021). The other synthesized nanoparticles by various bacteria, their properties, and their applications are presented in Table 3.
Table 3
Green synthesis of nanoparticles using bacteria.

| Year | Nanoparticle | Name of Bacteria          | Size (nm)       | Morphology | Application                                                                 | References                          |
|------|--------------|----------------------------|-----------------|------------|------------------------------------------------------------------------------|-------------------------------------|
| 2021 | ZrO          | Enterobacter sp.           | 33 - 75         | Spherical  | Antifungal activity against bayberry twig blight disease                      | (Ahmed et al. 2021)                 |
| 2021 | Ag           | Bacillus subtilis          | 2–26            | Spherical  | Antibacterial                                                                | (Yu et al. 2021)                    |
| 2021 | TiO$_2$      | Achromobacter sp.         | 5-10            | Irregular  | Antimicrobial                                                                | (Farag et al. 2021)                 |
| 2021 | Ag           | Dietzia maris             | 40-50           | Spherical  | Wound healing activity                                                       | (Venil et al. 2021a)                |
| 2020 | Ag           | Pseudomonas sp. and Enterobacter | 63.50 and 45.81 | Spherical  | Antibacterial                                                                | (Saleh 2020)                        |
| 2020 | Ag           | Bacillus amyloliquefaciens| 1.23 -10.80     | Spherical  | Antimicrobial potential against phytopathogens                               | (Abd El Aty and Zohair 2020)        |
| 2020 | Ag           | Serratia spp.             | -               | -          | -                                                                            | (De Silva et al. 2020)              |
| 2020 | Ag           | Pseudoduganella eburnea   | 8-24            | Spherical  | Antimicrobial agent for various therapeutic applications.                    | (Huq 2020b)                         |
| 2019 | Au           | Bacillus licheniformis    | 40              | Irregular  | Antimicrobial                                                                | (Scala et al. 2019)                 |
| 2019 | Ag           | Pseudomonas rhodesiae     | 20-100          | Spherical  | Antibacterial                                                                | (Hossain et al. 2019)               |
| 2019 | ZnO          | Bacillus haynesii         | 20-100          | Spherical  | Medical and non-medical fields                                               | (Rehman et al. 2019)                |
| 2018 | Ag           | Nostoc linckia            | 5-60            | Spherical  | Antibacterial                                                                | (Vanlalveni et al. 2018)            |
| 2018 | ZnO          | Bacillus megaterium       | 45-95           | Rod and cube shape                                                          | Antibacterial and therapeutic agents| (Saravanan et al. 2018)             |
| 2017 | Au           | Streptomyces griseoruber  | 5-50            | Spherical to triangular and hexagonal | Degradation of MB                  | (Ranjitha and Rai 2017)             |
| 2017 | Ag           | Streptomyces genus        | 160             | Spherical  | Nanomedicine and cosmetology industries.                                     | (Silva-Vinhote et al. 2017)         |
| 2017 | Ag           | Actinomycetes sp.         | -               | -          | Antibacterial                                                                | (Thomas 2017)                       |
| 2017 | Ag           | Streptomyces Sp.          | 11-38           | Spherical  | Antibacterial                                                                | (Gupta et al. 2017)                 |

4.4 Yeast
Yeast extract plays the role of reducing and capping agent which encompasses carbohydrates, vitamins, and amino acids whereas metal ions serve as an electron acceptor. The organic capping agents provide stability to the synthesized monodispersed nanoparticles and as a result, these can be preserved without precipitation for more than a year (Boroumand Moghaddam et al. 2015; Skalickova et al. 2017). The synthesis of Ag NPs using yeast has been described by Shu and coworkers with the formation of yeast micelles in yeast extract by self-assembly of biomolecules followed by reduction of Ag\(^+\) via \textit{in situ} method which provided stabilization to the nanoparticles. Affinity to the bacterial membrane is enhanced by the coating of the surface of Ag NPs wherein the permeability of the cell wall also increased. When peptidoglycan interacted with Ag NPs, the change in configuration of peptidoglycan occurred which resulted from the damage of bacteria by the apoptosis process (Figure 8) (Shu et al. 2020). Yeast-assisted synthesis of nanoparticles and their applications are provided in Table 4.

Table 4
Green synthesis of nanoparticles using Yeast.
| Year | Nanoparticle | Name of Yeast                  | Size (nm) | Morphology                  | Application                     | References                   |
|------|--------------|-------------------------------|-----------|-----------------------------|---------------------------------|------------------------------|
| 2021 | Ag           | *Saccharomyces cerevisiae*    | 6.72      | Irregular                   | Antibacterial                   | (Elnagar et al. 2021)        |
| 2021 | Au           | *Candida parapsilosis*        | -         | -                           | The catalyst for aryl amines synthesis | (Krishnan et al. 2021)      |
| 2021 | Ag           | *Pichia kudriavzevii HA-NY₃, and Saccharomyces uvarum HA-NY₃* | 20.655 ± 9.48 (AgNPsK) and 2.4 ± 6.02 (AgNPsU) | Cubic (AgNPsK) and round (AgNPsU) | Anticancer                     | (Ammar et al. 2021)         |
| 2020 | AgCl         | *Commercial yeast*            | 9-51      | Spherical                   | Anti-mycobacterial Activity     | (Sivaraj et al. 2020)        |
| 2020 | Ag           | Yeast extract                 | 13.8      | Spherical                   | Disinfection of multidrug-resistant bacterial strains, | (Shu et al. 2020)            |
| 2019 | Se           | *Magnusomyces ingens*         | 70-90     | Spherical and quasi-spherical | Antibacterial                   | (Lian et al. 2019)           |
| 2019 | Pd           | *Ogataea polymorpha*          | 20-40     | Spherical and hexagonal     | Biosensors and fuel cell         | (Gayda et al. 2019)          |
| 2019 | Se           | *Saccharomyces boulardii*     | 20 -240   | Spherical                   | -                               | (Bartosiak et al. 2019)      |
| 2019 | Ag           | Brewer’s yeast                | -         | Spherical                   | -                               | (Yantcheva et al. 2019)      |
| 2019 | Au           | *Yarrowia lipolytica*         | 104       | Polygonal or spherical      | Anticancer                      | (Ben Tahar et al. 2019)      |
| 2018 | Ag           | Yeast extract peptone dextrose | -         | -                           | Antibacterial                   | (Daphne et al. 2018)         |
| 2018 | Ag           | *Saccharomyces cerevisiae*    | 10-60     | Spherical                   | Antibacterial                   | (Sowbarnika et al. 2018)     |
| 2018 | Ag           | *Rhodotorula sp. strain ATL72* | 8.8 – 21.4 | spherical and oval          | Antimicrobial                   | (Soliman et al. 2018)        |
| 2018 | Au and Ag    | *Phaffia rhodozyma*           | 2.22±0.7 (Au) and 4.1±1.44 (Ag) | Spherical (Au) and Quasi spherical (Ag) | Antifungal                     | (Rónavári et al. 2018)      |
| 2018 | Ag           | *Meyerozyma guilliermondii KX008616* | 2.5–30    | Spherical                   | Biomedical                      | (Alamri et al. 2018)         |
| 2018 | Au           | *Magnusomyces ingens LH-F1*   | 20.3      | Uniform                     | Catalysts in reduction of organic contaminants. | (Qu et al. 2018)            |
| Year | Nanoparticle | Name of Yeast          | Size (nm)         | Morphology | Application                  | References                  |
|------|--------------|------------------------|-------------------|------------|------------------------------|-----------------------------|
| 2018 | TiO$_2$      | Baker's yeast          | 6.7 ± 2.2         | Spherical  | Antimicrobial                | (Peiris et al. 2018)        |
| 2018 | Ag           | Candida albicans       | 2.0 - 7.3         | Spherical  | Antimicrobial                | (Ananthi et al. 2018)       |
| 2017 | Au           | Saccharomyces cerevisiae | 9.99 ± 1.63      | Spherical  | High catalytic dechlorination efficiency | (Shi et al. 2017) |
| 2017 | ZnO and Ag   | Marine yeast           | 86.27 (ZnO) and 31.78 (Ag) | Round for both | Antioxidant          | (Aswathy et al. 2017)       |
| 2017 | Se and Ag    | Pichia pastoris       | 70-180            | Spherical  | Biomedical                   | (Elahian et al. 2017)       |
| 2017 | Ag           | Rhodotorula mucilaginosa. | 11.0             | Spherical  |                             | (Salvadori et al. 2017)     |
| 2017 | ZnO          | Pichia kudriavzevii   | 10–61             | Hexagonal  | Antimicrobial and antioxidant | (Moghaddam et al. 2017)     |

5. Types Of Nanoparticles Produced Using Microorganisms

5.1 Ag nanoparticles (Ag NPs):

In old human civilizations, people used silver and silver salts, but in recent years the fabrication of Ag NPs has been in demand due to their outstanding applications in the biomedical field such as antifungal, antibacterial, antioxidants as well as in agricultural and environmental remediation. These nanoparticles hold a specific place among other metals used in the biomedical field and have been widely explored via the greener routes (Jadoun and Difil 2021; Uthaman et al. 2021). Gevorgyan et al. (Gevorgyan et al. 2021) reported the use of Ag NPs as an excellent inhibitor of Gram-positive \textit{S. aureus} and Gram-negative \textit{S. typhimurium}. The synthesis, properties and applications of Ag NPs produced by microbes are discussed in this section.

5.1.1 Synthesis and properties

Synthesis of Ag NPs using the bacteria, \textit{Bacillus Licheniformis}, as a reducing and capping agent was performed by adding the aqueous solution of silver nitrate (AgNO$_3$) to the biomass of bacterial extract; the size of nanoparticles being 50 nm, (Figure 8a). (Kalimuthu et al. 2008) The culture supernatants of \textit{Staphylococcus aureus} were also used for Ag NPs synthesis (Nanda and Saravanan 2009). Fungi have been used to procure Ag NPs where the reduction of AgNO$_3$ was performed by the enormous amount of enzymes secreted by fungi and was further characterized and deployed in antimicrobial, antiviral, and wound dressing activities (Khan et al. 2018) (Figure 8b). The same nanoparticles were synthesized by using 5 mL of \textit{Botryococcus braunii} algal extract when mixed with 1mM AgNO$_3$ and stirred. After saturation of reaction, the mixture was centrifuged for 20 minutes and the pellets were separated with supernatant. The obtained nanoparticles were washed several times and dried at 55°C for 5 hours (Figure 9c).

\textit{Enterobacteriaceae} sp. bacteria were found useful for the quick synthesis of Ag NPs as Ashraf et al. (Ashraf et al. 2020) described their preparation using \textit{Enterobacter cloacae} (SMP1) bacteria’s cell-free supernatant protein. The bacterial strain was inoculated in liquid Luria Bertani (LB) broth for incubation in a rotatory shaker at 120 rpm at 37°C overnight followed by the centrifugation of the same at 600 g for 15 minutes. The supernatant was collected by
filtering it with 0.22 µm pore size filter paper and stored at 4°C and the pellet was discarded. For the synthesis of nanoparticles, 1.5 mM AgNO\textsubscript{3} solution was added to 1% of cell-free culture supernatant, and the analysis of the samples was done for 6 days. In different time intervals after 24 hours, the harvesting of aliquots of 200 µL sample was performed. For confirmation of synthesis, UV-Visible spectroscopy was used which indicated the reduction of silver ions (Ag\textsuperscript{+}) to zero-valent silver (Ag\textsuperscript{0}) affirmed by the typical peak of Ag found at 450 nm, (Figure 10i). The TEM micrographs revealed spherical shape and 10-20 nm size of nanoparticles while X-ray diffraction pattern and elemental mapping suggested crystalline nature and showed the presence of four elements (Figure 10ii).

Santos \textit{et al.} (Santos \textit{et al.} 2021) adopted an extracellular biosynthetic route for Ag NPs assembly using 10 g of Entomopathogenic Fungi Biomass after the addition of deionized water (100 mL). The solution was incubated for three days at 25°C on a rotatory shaker at 100 rpm. Subsequently, the biomass was filtered and stored at 4°C for the synthesis of Ag nanoparticles. Afterward, 1 mL and 10 mM solution of an aqueous solution of AgNO\textsubscript{3} was added with 9 mL of fungal extract biomass and the solution was magnetically stirred, away from the sunlight, for 72 hours at 25°C. The mean diameter of obtained nanoparticles was found between 40.14 and 289.13 nm using DLS. Recently, the spherical nanoparticles of Ag were obtained by using \textit{Trichoderma harzianum} (Guilger-Casagrande \textit{et al.} 2021) while 10-30 nm of spherical shaped nanoparticles with little agglomeration could be obtained by \textit{Bjerkandera sp.} R1 white-rot fungus (Osorio-Echavarria \textit{et al.} 2021).

Kashyap \textit{et al.} (Kashyap \textit{et al.} 2021) adopted an intracellular green synthetic route using the microalgae \textit{Scenedesmus sp.} for Ag/AgCl nanohybrids synthesis. The 0.5 and 1 mM of AgNO\textsubscript{3} precursor with extract of \textit{Scenedesmus sp.} as a reducing agent was used for the synthesis; spherical particles with 10–20 nm and 10–50 nm in size were obtained, respectively. The change from transparent to deep brown color of the mixture of AgNO\textsubscript{3} and bacterial strain solution indicated the formation of hexagonal shaped Ag nanoparticles using \textit{Bacillus anthracis} PAFB\textsubscript{2}, showed 0.428 with −15.5 mV Zeta potential value for polydispersity (PDI) index which indicated their good colloidal nature and long-term stability of nanoparticles; the size of nanoparticles being ~ 84 nm by AFM analysis (Banerjee \textit{et al.} 2021). Some spherical shapes, ranging between 13–27 nm, were synthesized using \textit{Paenarthrobacter nicotinovorans} MAHUQ-43 bacterial strain (Huq and Akter 2021).

### 5.1.2 Applications

Ag NPs synthesized using \textit{Bacillus subtilis} were studied against five strains of multidrug-resistant microbes such as \textit{Candida albicans}, \textit{Klebsiella. Pneumoniae}, \textit{Staphylococcus epidermidis}, \textit{Staphylococcus aureus}, and \textit{Escherichia coli}. The rate of MICs (minimum inhibitory concentrations) versus the clinical isolates revealed outstanding antimicrobial efficiency and revealed 100, 180, 200, 230, 300 µgmL\textsuperscript{−1} for \textit{Candida albicans}, \textit{Staphylococcus epidermidis}, \textit{Escherichia coli, Staphylococcus aureus}, and \textit{Klebsiella pneumonia}, respectively. Ag NPs were indicated to be toxic for gram-positive and gram-negative bacteria. These nanoparticles showed high antifungal activity and could be used to treat multidrug-resistant microorganisms (Alsamhary 2020). Ag NPs synthesized from green algae showed excellent catalytic activity in the reduction of 2-nitroaniline. The reduction of 2-nitroaniline (100 mg, 0.724 mmol) into \textit{o}-phenylenediamine was performed in presence of Ag NPs (0.10 mg, 10% w/w of 2-nitroaniline) and sodium borohydride (60 mg). The reaction mixture was adjusted to ~6 pH using glacial acetic acid for the removal of sodium borohydride. The product was further cyclized for 10-12 hours at 80°C with substituted aldehydes (0.724 mmol) to produce 2-aryl benzimidazoles (Figure 11a) (Arya \textit{et al.} 2019). On the other hand, Ag NPs synthesized from a new bacterial strain showed outstanding antibacterial effect against standard and multi-drug resistant strains according to the Clinical and Laboratory Standards Institute (CLSI) which were analyzed using a good diffusion method. The nanoparticles inhibited the growth of the strains including \textit{Salmonella paratyphi}, \textit{Staphylococcus epidermidis} (ATCC 12228), \textit{Bacillus subtilis}
(ATCC 6633), Escherichia coli (ATCC 10536), Shigella dysenteriae (PTCC 1188), Proteus vulgaris (PTCC 1182), and Klebsiella pneumonia (ATCC 10031) around the wells, Figure 11 (b) (Nazari and Jookar Kashi 2021).

Ag NPs synthesized using Anabaena variabilis revealed antioxidant activity and antimicrobial activity (Ahamad et al. 2021). The IC$_{50}$ value found in the DPPH (2,2-diphenyl-1-picrylhydrazyl) scavenging activity was 13.22 ± 1.25 µg mL$^{-1}$ while in the case of Ag nanoparticles synthesized by Ecklonia cava it was found 198 µg mL$^{-1}$. These nanoparticles were used in anticancer activity (Venkatesan et al. 2016). In the case of 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid (ABTS), Ag NPs synthesized using Acutodesmus dimorphus, revealed an IC$_{50}$ value of 14.41 µg mL$^{-1}$ while using Anabaena variabilis, it was 2.67 ± 0.5 µg mL$^{-1}$ (Chokshi et al. 2016). The antimicrobial activity against Bacillus amyloliquefaciens, Streptococcus pyogenes, Staphylococcus aureus, and Salmonella was analyzed by disc diffusion method and after incubation of 24 hours, the difference in the zone of inhibition was observed between control samples and green synthesized nanoparticles treated with microorganisms (Ghiuta et al. 2021).

Lactobacillus bulgaricus mediated Ag NPs showed antibacterial activity against Salmonella typhi, Staphylococcus epidermidis, and Staphylococcus aureus, which revealed 17-mm mean values of zone inhibition for the Salmonella typhi and Staphylococcus epidermidis while 15-mm for Staphylococcus aureus. The antibiotics effects were studied according to Birmingham Children's Hospital guidelines (2014); antibiotic activities were varying against selected bacterial strains resulted in sensitivity to antibacterial activity in comparison of antioxidant activity (Naseer et al. 2021). Recently, The Ag NPs fabricated using Cedecea sp. showed immense potential in antibiofilm activity. These Ag NPs unveiled strong MIC and MBC (minimum bactericidal concentration) values against E. coli (12.5 µg/µl and 12.5 µg/mL) and P. aeruginosa 6.25 µg/µl and 12.5 µg/mL), respectively and were extremely stable for more than one year with strong antibacterial activity against biofilms of P. aeruginosa and E. coli. (Singh et al. 2021). Ag NPs acquired via extracellular synthesis using Gloeophyllum striatum were antibacterial. The cytotoxic and hemolytic activity was checked towards mammalian cells which revealed that after 24 hours, more than 30 µM triggered 50% hemolysis of RBC, and no toxicity was found at 0.5–10 µM concentrations, IC$_{50}$ value at 24 hours being 28.76 µM. For the ecotoxicity study, the aquatic crustaceans Artemia franciscana and Daphnia magna were selected. In the saline ecosystem, Artemia franciscana showed higher tolerance than Daphnia magna towards Ag nanoparticles. The EC$_{50}$ values for Daphnia magna and Artemia franciscana were found to be 0.275 and 61.97 µM, respectively (Zawadzka et al. 2021).

### 5.2 Au nanoparticles (Au NPs)

Gold nanoparticles (Au NPs) are the topic of interest and received much attention due to their simple synthesis and extensive applications. Initially, Beveridge and Murray used Bacillus subtilis for the synthesis of octahedral 5-25 nm-sized Au nanoparticles (Beveridge and Murray 1980). Au NPs have been used as therapeutics, disease diagnostic materials, biocatalysts, and nanomedicine. Biocompatibility is the major concern for use in nanomedicine, hence, adopting green synthesis via microbes is an alternative to achieve this objective (Aminabad et al. 2019; Nejati et al. 2021); greener synthesis and the applications are discussed in this section.

#### 5.2.1 Synthesis and properties

Synthesis of Au NPs using extract of Gelidiella acerosa marine algae (10 mL) was completed by mixing the algal extract with the aqueous solution of HAuCl$_4$·3H$_2$O (gold chloride; 90 mL of 1 mM) and keeping the mixture under the static condition at 37°C. The Au NPs were washed and centrifuged for 15 minutes at 10,000 rpm to separate the nanoparticles which were dried at 50°C and kept at 4°C for further characterization and applications; crystalline nanoparticles had a size between 5.81 nm to 117.59 with spherical and hexagonal shapes. These Au NPs were found...
outstanding against inhibition of α-glucosidase and α-amylase enzyme with 2.8 ± 0.02, 4.1 ± 0.01 and 2.1 ± 0.01, 3.7 ± 0.01 µg/mL, respectively, Figure 12 (Senthilkumar et al. 2019).

Clarance et al. (Clarance et al. 2020) fabricated Au NPs using extract of Fusarium solani. They cultured the fungi in YEPD (yeast extract peptone dextrose) broth, and the culture was incubated at 28°C in the shaker at 120 rpm and kept for 9 days for further incubation. After that, it was filtered with cheesecloth and washed multiple times. Sterile Milli Q water (100 mL) was added to that biomass and kept undisturbed for 2 days. Further, it was filtered through Whatman No-1 filter paper and maintained the pH at 8.5 with 0.1 N NaOH. HAuCl₄ (99 mL of 1 mM) solution was added to the above fungal extract (1.0 mL) and kept for incubation under dark for 48 hours. Formation of pink-ruby red color indicated the formation of nanoparticles of Au and the peak between 510 and 560 nm was observed for plasmon band while the peaks at 1413 cm⁻¹ in FTIR attributed to the amine II bands of protein. The nanoparticles were flower-like and needles shaped with 40-45 nm size.

Marine microbe (Vibrio alginolyticus) was used for the synthesis of Au NPs adopting the extracellular synthesis route. The culture was inoculated and incubated for 24 hours at 40°C on an orbital shaker at 120 rpm. After that, the mixture was centrifuged for 15 minutes at 8000 rpm and the supernatant was collected followed by the addition of aqueous HAuCl (chloroaauric acid) (1mM) and again incubated under the same conditions. The nanoparticles were precipitated out and were separated by centrifugation, washed, and dried to achieve powder of nanoparticles. The 50-100 nm irregular monodispersed nanoparticles were suggested by TEM analysis (Shunmugam et al. 2021). Sargassum wightii, a marine alga was used for the extracellular synthesis of 8 to 12 nm-sized monodisperse Au NPs and a peak at 527 nm in the UV-visible spectrum suggested the plasmon absorbance of Au nanoparticles (Singaravelu et al. 2007). The same method was adopted by Mukherjee et al. (Mukherjee et al. 2002) for the fabrication of nanoparticles using fungus Fusarium oxysporum by exposing aqueous AuCl₄⁻ ions to the fungus extract. Three different fungi, Fusarium oxysporum, Fusarium sp., and Aureobasidium pullulans were used for the synthesis of Au NPs via mixing the fungal strain cells with AuCl₄⁻ ions solution (Zhang et al. 2011).

Salouti et al. (Zonooz et al. 2012) used Streptomyces sp. ERI-3 for the synthesis of Au NPs. The culture was incubated at 200 rpm for 48 hours at 28°C and HAuCl₄ solution (50 mL of 1 mM) was added to the supernatant (10 mL) and kept on an orbital shaker at the same aforementioned conditions. TEM studies suggested spherical and cylindrical-shaped nanoparticles ranging in between 80-200 nm. The synthesis was optimized with different reaction conditions and the best optimum conditions were found to be, pH 6, incubation time 12-hours, temperature: 30°C, and HAuCl₄ concentration 3 mM. Cladosporium cladosporioides (marine endophytic fungus) were used for 60 nm average-sized Au NPs synthesis and showed noteworthy antioxidant activity compared to ascorbic acid (M et al. 2017). Au NPs have been synthesized using various bacteria such as Bacillus subtilis, Shewanella algae, Pseudomonas aeruginosa, Escherichia coli, Lactobacillus sp., Thermomonospora sp., and Rhodococcus sp (Ahmad et al. 2003a, b; Mandal et al. 2006; He et al. 2007; Moghaddam 2010).

5.2.2 Applications

The organic solvent-free nature and high photocatalytic dechlorination have been accomplished by the Au NPs synthesized using Saccharomyces cerevisiae yeast. These 9.99 ± 1.63 nm-sized mono-dispersed Au NPs revealed the conversion of quinclorac to 8-quinoline-carboxylic acid by dechlorination using sodium borohydride which followed pseudo-first-order kinetics. (Figure 13a) (Shi et al. 2017). Qu et al. (Qu et al. 2017b) synthesized Au NPs from Trichoderma sp. for their potential application in azo dyes decolorization in contaminated water; these dyes absorb and reflect the sunlight which affects the aquatic organism’s growth as well as the photosynthesis process. The above nanoparticles could decolorize the Acid Brilliant Scarlet GR up to 94.7% in 120 minutes (Figure 13b) at various
concentrations of dye; at a dye concentration of 25 mg/L, degradation was more than 90% in 40 minutes while at 50 mg/L, 90% of decolorization was observed in 100 minutes (Qu et al. 2017b).

*Psychrotolerant Antarctic* mediated synthesis of Au NPs showed antimicrobial activity against sulfate-reducing bacteria (*Desulfovibrio desulfuricans*) which was assessed by the optical density of bacteria culture. The nanoparticles reduced the *Desulfovibrio desulfuricans* numbers to 12% (10⁶ to 10³ cells mL⁻¹) along with the reduction of sulphate reducing activity to 7% (0.0246 nanomoles mL⁻¹ day⁻¹ to 0.0016 nanomole mL⁻¹ day⁻¹); MIC was calculated to be 200 µg mL⁻¹ concentrations. The nanoparticles revealed the antimicrobial activity against *Bacillus, Pseudomonas aeruginosa, Escherchia coli, Klebsiella pneumonia,* and *Staphylococcus aureus.* The Au NPs deteriorate the cells of microbes by connecting with the surface, creating an aperture in the cell wall which induces seeping of cell contents resulting in death. They could inhibit the transcription by inhibiting the DNA (Shunmugam et al. 2021).

The Au NPs showed immense potential in anticancer activity which was assessed against colon cancer cell line by a dose-dependent inhibition activity. These nanoparticles were synthesized as a chemotherapeutic alternative to escape from drugs that are toxic and exhibit numerous side effects in the body; IC₅₀ value was found to be 15 µg/mL by comparing it with standard (Figure 14a). The morphological analysis revealed a cytotoxicity effect on the HCA-7 (human colon cancer) cell line when treated with Au NPs. There was a clear difference seen in treated and untreated cell organelles and unveiled noteworthy cell damage by Au NPs with undistinguished cell debris which indicated a significant contribution of these biogenic Au NPs for human colon cancer cells (Figure 14b) (Shunmugam et al. 2021).

*Ecklonia cava,* a marine alga mediated spherical (20-50 nm size) Au NPs showed antimicrobial activity against some pathogenic organisms and revealed the diameter of the zone of inhibition (20 µL) for *Candida albicans* ATCC 10231, *Aspergillus niger* ATCC 1015, *Bacillus subtilis* ATCC 6633, *Aspergillus fumigates* ATCC 1022, *Escherichia coli* ATCC 10536, *Aspergillus brasiliensis* ATCC 16404, *Staphylococcus aureus* ATCC 6538 and, *Aspergillus brasiliensis* ATCC 27853 about 23.3 ± 0.25, 24.6 ± 0.23, 19.7 ± 0.21, 21.5 ± 0.25, 31.8 ± 0.32, 19.3 ± 0.26, 16.6 ± 0.30 and 21.3 ± 0.28 mm, respectively. The highest antimicrobial activity was shown against *Aspergillus niger* ATCC 1015 and *Escherichia coli* ATCC 10536 (Venkatesan et al. 2014).

**5.3 Pt nanoparticles (Pt NPs)**

Platinum is a rare metal, used in cancer treatments, fuel cells, or catalytic converters. Its enormously low abundance makes it the topic of immense interest due to its unique structural, catalytic, and optical properties with huge potential in biomedical applications and catalysis (Yamada et al. 2015; Siddiqi and Husen 2016; Pedone et al. 2017).

**5.3.1 Synthesis and properties**

The cultivation of the control yeast and hydrogenase-displaying yeasts was performed anaerobically in AHLU + SDC medium (synthetic dextrose medium). The centrifugation of the cells was accomplished in 5 minutes at 3000×g. and incubated in 7.4 pH PBS comprising 100 µM PtCl₄²⁻ salt. The mixture was allowed to react anaerobically at a rotatory shaker at 37°C for 72 hours and the black precipitate was separated from the solution and reduced Pt NPs were collected (Ito et al. 2016) Green synthesis of Pt NPs has been reviewed by Puja *et al.* (Puja and Kumar 2019) wherein the syntheses are described by various biological species using H₂PtCl₆ as a precursor and the indication of nanoparticles synthesis by a color change and their potential application in biomedical fields (Figure 15a). *Fusarium oxysporum* was incubated with H₂PtCl₆ for extracellular synthesis of stable Pt NPs of 5-30 nm size (Syed and Ahmad 2012). The same fungi were used by Govender *et al.* (Govender et al. 2009) by isolating 10 mL of 120 nmol min⁻¹ mL⁻¹ purified hydrogenase and reacting with 10 mL of 1 mM solution of PtCl₂ or H₂PtCl₆ under the hydrogen atmosphere
and optimized temperature (38°C) and pH (7.5). For hydrogenase reactions, these conditions were found optimum as after 2 hours 30% reduction of PtCl₂ was observed, after 4 hours 70% and after 8 hours 90% reduction was noticed although for H₂PtCl₆, these results didn’t match, after 8 hours also, 96% platinum salt was remaining. It was concluded that during the redox mechanism, H₂PtCl₆ functioned as an electron acceptor and indicated that the enzymes and metal/metal ions transferred electrons directly. Some hydrophobic active channels existed in between the molecular surfaces and the active site which were used as the passage by metal ions having 0.45-0.60 nm diameter. It was assumed that these channels were not small for PtCl₂ but were indeed very small for H₂PtCl₆ (Figure 15b).

The culture of Neurospora crassa extract was kept for 5 to 10 days at 28°C to attain macroconidia and harvested at 4°C in glycerol for further use, 100 mL of potato dextrose broth was inoculated with 100 µl of macroconidia for obtaining its biomass. Subsequently, the steps of incubation and filtration were performed at optimized temperature and time for starting the reduction process. The absorption spectra of both the control and Pt NPs were performed in which a peak at 530 nm was obtained for Pt NPs with quasi-spherical shape and 4-35 size by HRTEM analysis. From dark-field images, the size distribution of nanoparticles showed a total of 234 nanoparticles in which 60% of particles were between 40 to 50 nm in size and more than 70 nm size was found only for 2% nanoparticles (Figure 14c) (Castro-Longoria et al. 2012) Acinetobacter calcoaceticus mediated synthesis of Pt NPs was performed by Gaidhani et al. (Gaidhani et al. 2014) where they described the reduction of H₂PtCl₆. The entrenchment of nanoparticles within the cells was seen by AFM analysis and average surface roughness was found to change when compared to control cells which indicated the formation of Pt NPs. The size of nanoparticles was 2-3.5 nm while the shape was found cuboidal by HRTEM analysis.

5.3.2 Applications

The nanoparticles fabricated using P. chrysogenum were assessed for anticancer activity on myoblast C2C12 cancer cells. To evaluate the mitochondrial activity, death of cell and survival in presence of biogenic Pt NPs, MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay was performed as it is the most vigorous method for analysis of nanotoxicology which elucidated the response of cells to metal toxicity along with evidence for the death of the cell, metabolic activities, and survival. The Pt NPs revealed a significant decrease in cell viability and mitochondrial reduction (90.4%) at 100 µg concentration while the control cell unveiled no mitochondrial reduction with maximum cell viability; nanoparticles of size less than 20 nm showed no cytotoxic against cancer cells. With the pre-treatment by Pt NPs, cell viability was reduced in human squamous carcinoma and A431 at 24 hours; IC₅₀ values were found to be 41.09%, (Subramaniyan et al. 2018). The Pt NPs were synthesized using various bacterial strains such as Pseudomonas kunmingensis, Psychrobacter faecalis, Vibrio fischeri, Jeotgalicoccus coquina, Sporosarcina psychrophile, Kocuria rosea, Pseudomonas putida, Rhodotorula mucilaginosawhich exhibited antioxidant activity against the DPPH radical scavenging assay. The purple color of DPPH radicals changed to pale yellow by interacting with nanoparticles as Pt NPs provide transferability of electrons/hydrogen atoms to neutralize DPPH. It was a dose-dependent activity as the inhibition percent increased with the increment of Pt concentration. The degree of antioxidant activity of 1000 µg/mL nanoparticles were ordered from lowest to highest was MN23 < ADR19< KT2440 < KC19 < B-11177 < CCV1 < FZC6 < ZC15 (Figure 16) (Eramabadi et al. 2020).

5.4 Pd nanoparticles (Pd NPs)

Palladium is a very precious metal and is endowed with significant thermal and chemical stability, optical and electronic properties, with ease of biofunctionalization for enhancing their medical applications (Fahmy et al. 2020).

5.4.1 Synthesis and properties
Biogenic Pd NPs fabricated using green alga, *Botryococcus braunii* revealed the formation of 4.89 nm-sized and truncated triangular, spherical, cubical shaped nanoparticles which were synthesized by stirring the solution of algal extract (20 mL) and an aqueous solution of Pd (OAc)$_2$ (80 mL of 1 mM) for 3 hours at 60°C while maintaining pH in the range 6-7. A positive (with alga extract and Pd (OAc)$_2$) and negative control (without alga extract) were maintained for the comparison. The solution bearing Pd NPs was centrifuged for 30 minutes and washed for the removal of impurities. For better separation of nanoparticles, the process was repeated 3 times and nanoparticles were dried at 70°C in a hot air oven, the entire process of Pd NPs synthesis is depicted in Figure 17 (Anju et al. 2020).

Genetically modified *Pichia pastoris* fungus was found as the factory for producing Pd NPs. Parental and modified species were cultivated in YPD media (Yeast, Peptone, and Dextrose in 1,2,2% w/v) and inoculated with the covering of the flask by cheese cloth (two-folded) for oxygen transfer; 0.5% methanol was daily added to the flasks for AOX1 promoter induction. To reach optical cell density up to 0.1, the cells were cultivated in a shaker incubator at 30°C at 250 rpm. Subsequently, PdCl$_2$ was added to the flask to attain 60 mM final concentration and after the time intervals of 0-, 6-, 12-, 24-, 36-, 48-, 60- and 72-hour, 10 mL of aliquots were collected for recording the absorbance value at 600 nm. The nanoparticles were collected by centrifugation at 5000×g for 10 min and washed thoroughly. The maximum absorption in recombinant yeast was found at 79.79%. The best equation of Pd NPs was found $y = 177.78 \times \ln(t) - 233.23$ and $y = 6.87 \times \ln(t) + 49.91$, for the Pd biosorption capacity (mg/g) and formation yield (%) (Elahian et al. 2020).

### 5.4.2 Applications

Pd NPs are generally used as a homogenous and heterogeneous catalyst in many of the organic reactions such as Suzuki coupling reactions and Suzuki-Miyaura cross-coupling reactions (Liu et al. 2021; Sun et al. 2021), medical diagnosis (Zhuge et al. 2019), cancer treatments (Kang et al. 2018), drug delivery (Zhang et al. 2019), antimicrobial activities (Nasrollahzadeh et al. 2020a), antioxidants (Fahmy et al. 2020), and as nanocatalysts for dye degradation in effluents from textile industries among other biomedical applications (Gil et al. 2018; Pandey et al. 2021). *Escherichia coli* assisted obtained Pd NPs showed better catalytic activity to chemical counterparts at low temperature and in the air for the oxidation of benzyl alcohol; catalysis was performed with 180 mg of nanocatalyst and 50 mL of benzyl alcohol and the reactor was set to reach 90°C. These biogenic Pd NPs were compared with the chemically prepared catalyst in O$_2$ and noticed that at lower loadings of catalyst (6 × 10$^{-5}$ mol l$^{-1}$), it displayed higher activities (Deplanche et al. 2012). Fahmy *et al.* (Fahmy et al. 2020) reviewed the Pd NPs synthesized adopting biological routes for their unique physiological properties and biomedical applications.

### 5.5 Cu nanoparticles (Cu NPs)

There are numerous types of copper (Cu) nanoparticles such as Cu, CuO, Cu$_2$O nanoparticles (Ighalo et al. 2021; Kumar et al. 2021; Medvedeva et al. 2021); they are widely known for their magnetic, optical, electric, and catalytic properties which are applicable in optoelectronics, photocatalysis, sensors, and biomedical fields such as antifungal, antibacterial, antioxidant, anticancer, antiviral, and drug delivery systems (Al-Hakkani 2020; Marouzi et al. 2021). Their synthesis, properties, and applications are discussed in this section.

#### 5.5.1 Synthesis and properties

The bacterial strains used for the nanoparticle’s synthesis were inoculated in Luria–Bertani medium followed by incubation on a rotatory shaker at 200 rpm at 22°C. After 24 hours, the final concentration of 1 mM was attained with the addition of CuSO$_4$·5H$_2$O. Then the incubation of the reaction mixture was performed further on a rotatory shaker at 150 rpm for 24-48 hours at 22°C. For control, heat-killed bacterial strains or without bacterial strains Luria–Bertani
medium with 1mM CuSO$_4$ was maintained. The color of the mixture changed to dark green from cyan blue suggesting the formation of Cu nanoparticles. When white-rot fungus *Stereum hirsutum* (Cuevas et al. 2015) and *Morganella* sp. (Lalitha et al. 2020) were used as reducing and capping agents, the same color change was observed affirming the formation of nanoparticles. The solution was further centrifuged at 5000 rpm for 20 minutes at 4°C and collected for washing with double distilled water. Short duration (15 seconds) ultrasonic wave irradiation was imparted for the recovery of nanoparticles from cell pellet and centrifuged for 20 minutes at 5000 rpm followed by recovery of the nanoparticles which were dried in an oven at 80°C; ovoidal or spherical and monodispersed nanoparticles ensued with 10-70 nm particle size and with an average size of 40 nm (John et al. 2021).

For the synthesis of Cu NPs using *Escherichia sp.*, the cultivation and incubation were accomplished in nutrient broth for 24 hours at 150 rpm followed by the addition of CuSO$_4$ (5 mM) and incubation again. The color change was noticed from bluish-green to dense green and it was phenotypic confirmation for the synthesis of Cu nanoparticles; in the UV region, it showed a peak at 325.89 affirming the synthesis of nanoparticles (Figure 18) (Noman et al. 2020). *Shewanella loihica* PV-4 mediated Cu NPs were synthesized by extracellular bioreduction of Cu (II) and the size of nanoparticles was found to be 10–16 nm by TEM analysis while a strong Cu signal was observed by EDX (Energy-dispersive X-ray spectroscopy) analysis to confirm the synthesis (Lv et al. 2018).

### 5.4.2 Applications

*Penicillium chrysogenum* assisted spherical CuO NPs unveiled antibiolm, antifungal, and antibacterial activity. The highest effect was shown by CuO NPs against *Staphylococcus aureus* at a concentration under MIC values. These nanoparticles could reduce the formation of biofilm by 68.8, 85.9, 94.4, 94.1 and 95% at concentrations 0.01, 0.03, 0.07, 0.15, and 0.3 mg/mL, respectively without any effect on bacterial growth (Figure 19a). However, they showed no effect on biofilm formation by *Pseudomonas aeruginosa* (Figure 19b). These nanoparticles showed antibacterial activity against Gram-positive and Gram-negative bacteria but the more effective diameter of clear zone was found against Gram-positive than Gram-negative bacteria. The formed clear zone diameters were 11.66 ± 0.33, 11.93 ± 0.52, 13.6 ± 0.4, 16.26 ± 0.63 and 22 ± 0.57 mm for *Salmonella typhimurium, Escherichia coli, Pseudomonas aeruginosa, Bacillus subtilis,* and *Staphylococcus aureus,* respectively at 5 mg/mL of CuO nanoparticles, the same process was repeated with the ZnO NPs synthesized using the same bacteria which revealed that CuO NPs exhibited better inhibitory effects against all bacteria in comparison of ZnO NPs probably due to their interaction with bacterial protein via the SH groups thus inactivating the growth of bacteria (Figure 19c) (Mohamed et al. 2021).

The textile wastewater has a high percentage of contaminants such as hardness, high turbidity, pH, TSS (total suspended solids), TDS (total dissolved solids), COD (chemical oxygen demand), sulphates, chlorides, and many other impurities which causes the death to aquatic organisms. The treatment with biogenic Cu NPs obtained using *Escherichia sp.* by Noman *et al.* (Noman et al. 2020) revealed their potential to decolorize the azo dyes (25 mg L$^{-1}$) up to 83.61% ± 1.93, 88.42% ± 2.80, 90.55% ± 2.06 and 97.07% ± 1.22, and for RB-5, DB-1, MG, and CR in 5 hours of sunlight exposure (Figure 18d). *Streptomyces sp.* (Endophytic actinomycetes) mediated CuO NPs showed their potential in biotechnological applications (Hassan et al. 2019). *Aspergillus niger* strain STA9 assisted Cu NPs displayed antibacterial, antidiabetic, and anticancer activities (Noor et al. 2020).

### 5.6 TiO$_2$ nanoparticles (TiO$_2$ NPs)

TiO$_2$ nanoparticles have been mostly studied and used for their brilliant antioxidant nature and superior photocatalytic properties. They are frequently used in implant biomaterials, photocatalysis, sunscreen products, toothpaste, self-cleaning sanitary ceramics, cement, sugar, paper, rubber, biomedical ceramic, printing ink, paints, antimicrobial plastic
packaging, films, etc. (Khataee and Mansoori 2011). Green synthesis of TiO$_2$ NPs by microorganisms has been studied and summarized in this section.

### 5.6.1 Synthesis and properties

Synthesis of TiO$_2$ NPs using *Streptomyces sp.* HC$_1$ was studied by Ağçeli and coworkers when they cultured the bacterial colony in sterile nutrient broth (50 mL) and incubated it for 24 hours in a shaker with 150 rpm at 37°C. This bacterial culture was used after the appearance of turbidity and added to TiO(OH)$_2$ solution (20 mL, 0.025 M), followed by incubation in a steam bath for 30 minutes at 60°C. After incubation, white clusters were noticed at the bottom of the flask which was collected by centrifugation, and the precipitate was washed with distilled water to maintain neutral pH (Ağçeli et al. 2020). *Bacillus sp.* bacteria was used for the synthesis of 50 nm-sized spherical shapes TiO$_2$ NPs. The synthesis of these bacteria-mediated nanoparticles was performed using the Taguchi method (which increases the reliability of production by optimizing the process parameters) and obtained nanoparticles revealed their highly dense spherical shape which was confirmed by TEM and SEM micrographs. The TGA studies suggested the weight loss up to 670°C in which the evaporation of water was responsible for first weight loss at below 150°C temperature while in second weight loss, TiO$_2$ nanoparticles and organic compounds were decomposed in the range of 250 to 670°C (Figure 20) (Moradpoor et al. 2021).

### 5.5.2 Applications

TiO$_2$ NPs exhibit outstanding contributions in photoelectrochemical energy production, and their biocompatible and non-toxic properties, render them a suitable candidate for biomedical applications and pharmaceutical industries. (Zhao et al. 2007; Weir et al. 2012; Ahn et al. 2018) The TiO$_2$ NPs synthesized using *Aspergillus flavus* showed their effect on the bacterial sp, *K. pneumoniae* (18 mm), *B. subtilis* (22 mm), *S. aureus* (25 mm), *P. aeruginosa* (27 mm), and *E. coli* (35 mm); for the control, tetracycline antibiotics was used and for the zone of inhibition, they deployed the cell diffusion method and MIC. The zone of inhibition was shown against both Gram-positive and Gram-negative bacteria. The MIC values were found to be 40 µg mL$^{-1}$ for *E. coli* (MTCC-1721), 40 µg mL$^{-1}$ for *S. aureus* (MTCC-3160), 45 µg mL$^{-1}$ for *B. subtilis* (MTCC-1427), 70 µg mL$^{-1}$ for *K. pneumoniae* (MTCC-4030), and 80 µg mL$^{-1}$ for *P. aeruginosa* (MTCC-1034) suggested best results against *E. coli*, Figure 21 (Rajakumar et al. 2012) TiO$_2$ has also unveiled antibacterial activity against *Bacillus megaterium* (Karunakaran et al. 2013) and *E. Coli*. (Amin et al. 2009; Hong et al. 2017) using environmental light.

### 5.7 ZnO nanoparticles (ZnO NPs)

ZnO nanoparticles have been widely used as antibacterial, anti-fungal with some other biomedical applications, and as active photocatalysts for the degradation of dyes and other organic contaminants (Ong et al. 2018).

#### 5.6.1 Synthesis and properties

Barani *et al.* (Barani et al. 2021) used two bacterial strains (*Vibrio* sp. VLA strains and Marinobacter sp. 2C8) for the synthesis of ZnO NPs. The ensuing precipitate after bacterial exposure was separated by centrifuged, washed, and dried by a freeze dryer. The peak in the UV was found at 250 nm ZnO-VLA while 266 nm for ZnO-2C8 nanoparticles. The shape of nanoparticles was found spherical within the range of 10.23 ± 2.48 nm size. The change in color to golden brown with some precipitate indicated the formation of nanoparticles which was centrifuged for 10 minutes at 10,000 g to separate the precipitate; their formation was determined by UV Visible spectroscopy which suggested the absorption maxima at 360 nm (characteristic peak for ZnO) and quantum size effect was analyzed with a blue shift
which is responsible for the diminution of size and wavelength due to widening of the bandgap. The 34.98 nm-sized and spherical-shaped nanoparticles were affirmed by TEM analysis while SAED analysis suggested crystals of 7 nm average size (Rafeeq et al. 2021).

Periconium sp. was used for ZnO NPs synthesis by applying the sol-gel process via dissolution of Zn (NO$_3$)$_2$ (20 g) in deionized water (100 mL) at 90°C with constant stirring. The addition of fungal extract (25 mL) was done at this stage and could form a sol by evaporation while the pH was maintained at 5. The sol was kept for more than 24 hours in a hot air oven at 45°C for evaporation of water resulting in the gel formation and even dispersal of Zn$^{2+}$ ions. After drying for 12 more hours at 125°C, the color of gel changed to brittle yellow and porous ZnO NPs ensued after calcination for 4 hours at 700°C under the aerobic condition in a muffle furnace. The process of synthesis and morphology (studied by TEM micrographs) of ZnO NPs are depicted in Figure 22 (i) and (ii) (a-e), suggesting quasi-spherical (size~16 and 78 nm), polydisperse (polydispersity index ~ 1.48), and less agglomerated. The SAED patterns revealed a circular peripheral layer related to the planes suggested by XRD patterns (Ganesan et al. 2020).

In another process, a freshly grown cell-free supernatant of Bacillus megaterium was used with 1mM aqueous ZnNO$_3$.5H$_2$O and kept on a shaker incubator for 48 hours at 37° C. The white clusters were obtained at the bottom of the flask after 12-48 hours of incubation which was centrifuged and washed several times to obtain pure white crystals of ZnO NPs; characteristic surface plasmon resonance peak at 346 nm in the UV-Vis spectrum confirmed their synthesis. XRD pattern supported the crystalline nature of synthesized nanoparticles with sizes in between 45 and 95 nm possessing cubic shape (Figure 23) (Saravanan et al. 2018).

5.6.2 Applications

The antioxidant activity of ZnO NPs synthesized via Marinobacter sp.2C8 and Vibrio sp. bacteria was evaluated by DPPH scavenging radicals. When the ZnO NPs react with DPPH radicals, pale yellow color ensues from the deep purple which showed the existence of 1,1-diphenyl-2-picrylhydrazine as a result of receiving electrons. The two sets, ZnO-2C8 and ZnO VLA, of nanoparticles, showed different activity from 31.2 µg/mL to 2500 µg/mL concentration; at increasing concentration of ZnO concentration, the DPPH radical scavenging activity percent also increased, suggesting a dose-dependent antioxidant activity. The maximum antioxidant activity was observed at 2500 µg/mL was 89% for ZnO-2C8 NPs and 86% for ZnO-VLA NPs; EC$_{50}$ values for both being at 600 µg/mL, Figure 24 (Barani et al. 2021).

ZnO NPs fabricated from cyanobacterium Nostoc sp. EA03 showed its potential in biological functions in terms of antibacterial, antimicrobial, and toxicity activities. With these nanoparticles, MBC and IC$_{50}$ values were determined to be 2500, 2500, and 128 µg mL$^{-1}$, and 2000, 2000, and 64 µg mL$^{-1}$, respectively which bodes well for their biomedical appliances (Khatami et al. 2018; Ebadi et al. 2019).

5.8 Fe$_2$O$_3$ nanoparticles (Fe$_2$O$_3$ NPs)

Iron oxide nanoparticles (IONP) predominantly exist in two forms which are magnetite (Fe$_3$O$_4$) and the oxidized form called maghemite (γ-Fe$_2$O$_3$) (Markova et al. 2014; Plachtová et al. 2018). The Fe$_2$O$_3$ NPs attracted much attention due to their unique properties of super magnetism, and their appliances in various areas including terabit magnetic storage, catalysis, gene, and drug delivery, and other therapeutic applications (Can et al. 2012). When the high surface energy possessing Fe$_2$O$_3$ NPs react with the biomolecules, it results in the enhancement of dispersion and less aggregation due to the presence of polysaccharides which offer a brilliant biocompatible shell (Ghosh et al. 2021).

5.8.1 Synthesis and properties
For the synthesis of Fe$_2$O$_3$ NPs by three strains of fungus, i.e., *Fusarium incarnatum*, *Phialemoniopsis ocularis*, and *Trichoderma asperellum*, initially, fungal cell filtrate (10 mL) of fungal strains were mixed with the salt solution of FeCl$_3$ and FeCl$_2$ (2:1 mM). The mixture was allowed to agitate at room temperature for 5 minutes when the change in color of the reaction mixture, indicated the formation of nanoparticles with selected fungal strain. Later, the synthesized Fe$_2$O$_3$ NPs were centrifuged for 20 minutes at 12,000 rpm and washed thoroughly with deionized water; the entire process was described by Mahanty *et al.* (Mahanty *et al.* 2019) in the flowchart (Figure 25). Aqueous extract of *Aegle marmelos* (5g) was used for the synthesis of Fe$_2$O$_3$ NPs with 100 mL distilled water and stirred with heating for 1 hour followed by the filtration of the extract using Whatman filter paper. 10 mL of this extract was mixed with 90 mL of ferric nitrate and stirred for 1 hour and then kept in a hot air oven while the temperature was maintained at 150°C. Later, the powder was calcinated for 5 hours at 400°C to generate Fe$_2$O$_3$ NPs (Sriramulu *et al.* 2021).

### 5.8.2 Applications

The Fe$_2$O$_3$ NPs synthesized using *Aegle marmelos* extracts inhibited the bacterial growth of *E. coli* and *S. aureus* more than the control antibiotic. The gram-negative bacteria (*Escherichia coli*) interacted more with nanoparticles at a higher and lower concentration as compared to gram-positive bacteria (*Staphylococcus aureus*) due to the difference in cell membrane thickness. The nanoparticles kill the bacterial cell by entering the membrane and inhibiting the bacterial growth and inactivated the enzymes with the increase of the cytoplasmic membrane leakage (Figure 26a); nanoparticles at concentration 32.25 µg/mL showed 7 ± 0.12 mm inhibition for *E. coli* (Khalil *et al.* 2017). Against *S. aureus*, 30 ± 0.387 mm and 28 ± 0.654 mm (30 µg/mL) zone inhibition was observed while 21 ± 0.432 and 19 ± 0.547 (15 µg/mL) was seen for *E. coli*, suggesting more inhibition of *E. coli* (Figure 26b). These Fe$_2$O$_3$ NPs exhibited superb photocatalytic activity for the degradation of BG dye with 95.89% degradation in 90 minutes under UV light; degradation efficiency and degradation kinetics suggested the pseudo-first-order kinetic model with the constant (K) value of 0.04058 min$^{-1}$ (Figure 26 (c-e)) (Sriramulu *et al.* 2021).

### 5.9 Se nanoparticles (Se NPs)

Se nanoparticles are attractive due to their low toxicity, good biocompatibility, excellent biological activities, and being essential for mammalian's life; as a trace element, they exhibit preventive properties for disease and exhibit good antitumor activity (Sun *et al.* 2014). It plays a key role in fighting against oxidative stress by participating in the antioxidant defense system of the liver. (Kondaparthi *et al.* 2019) On the other hand, selenium sulfide is an antifungal medicine and bioactive chemical. However, its biosynthesis is always an issue of controversy when one discusses nanoparticle forms.

#### 5.9.1 Synthesis and properties

Hashem *et al.* (Hashem *et al.* 2021) synthesized Se NPs using *Bacillus megaterium* bacteria wherein the bacteria were cultured and incubated at 37°C for 48 h with shaking aerobically followed by the removal of bacterial cells and macromolecules by filtration through 0.44 µm PVDF filter and centrifugation at 10,000 rpm. Later, selenious acid suspension (1 mM) was mixed with cell-free supernatant and stirred at 25°C. The synthesis of Se NPs by reduction was indicated by a color change from colorless to reddish color when they were centrifuged for more than 30 minutes at 12,000 rpm. DLS and TEM studies suggested the synthesis of 41.2 nm-sized monodispersed spheres. The fungus, *Saccharomyces cerevisiae* was used to fabricate the SeS nanoparticles via the addition of selenium salts in 1 mM concentration into the 24 hours culture of *Saccharomyces cerevisiae* and incubation for 4.5 hours at 35°C with 180 rpm shaking using a shaking incubator. Next, the medium changed the color from yellow to brownish red for
(synthesized using sodium selenosulfide salt) in 18 hours while for \( S_2 \) (using selenous acid/sodium sulfite) in 4.5 hours. The presence of nanoparticles was confirmed by optical microscopy and these results were supported by TEM and SEM analysis which revealed 6.0 nm size for \( S_1 \) and 153 nm size for \( S_2 \) nanoparticles. The characteristic peaks of SeS nanoparticles were confirmed by XRD spectra as well as mass spectroscopy. The process of SeS NPs fabrication has been given in Figure 27 (Asghari-Paskiabi et al. 2019).

Afzal et al. (Afzal et al. 2021) used cyanobacteria for Se NPs synthesis as affirmed by the synthesis of spherical and amorphous nanoparticles of 10.8 nm size. Freshly, \( Stenotrophomonas bentonitica \) BII-R7 bacterial strain was used to reduce Se(IV) to Se(0) NPs by biotransformation of amorphous nanospheres of Se(IV) to trigonal Se (0) NPs (Pinel-Cabello et al. 2021).

5.9.2 Applications

Sirsat et al. (Shirsat et al. 2015) reviewed the microbial-assisted synthesis of Se NPs and their applications with their appliances in various diverse fields such as medicine, sensors, electronics, energy, and space industries; assorted therapeutic applications of Se NPs are depicted in Figure 28.

These nanoparticles could inhibit the growth of \( Alternaria, Candida, Aspergillus \), and the dermatophytes genera pathogenic fungi and MTT assay revealed their non-toxic nature (Asghari-Paskiabi et al. 2019). Se NPs produced using cyanobacteria showed biocompatibility and antioxidant, antimicrobial, anticancer activity when compared to chemically synthesized or commercially available Se NPs. The antioxidant activity was performed against ABTS, FRAP, DPPH, SOR assays, and ascorbic acid was used as the positive control. IC\(_{50}\) values for ascorbic acid, B-SeNPs (biogenically synthesized), and C-SeNPs (chemically synthesized) were found 84.71 ± 0.68, 92.58 ± 1.28 and 239.11 ± 0.34 µg/ mL in ABTS assays while 59.53 ± 0.53, 155.02 ± 0.93 and 178.89 ± 1.84 µg/ mL respectively found in FRAP assay. In DPPH assays, IC\(_{50}\) values for ascorbic acid, B-SeNPs, and C-SeNPs were 56.36 ± 1.52, 83.89 ± 2.11 and 174.79 ± 0.29 µg/ mL, respectively and for SOR assay, these values were 74.95 ± 0.95, 80.55 ± 1.14 and 176.84 ± 0.12 µg/ mL for ascorbic acid, B-SeNPs, and C-SeNPs, respectively, Figure 29 (Afzal et al. 2021).

\( Lactobacillus casei \) ATCC 393 assisted prepared Se NPs inhibited the colon cancer cell growth which was studied in BALB/c mice's CT26 syngeneic colorectal cancer model. The nanoparticles showed \textit{in vitro} antiproliferative activity, induced apoptosis, and raised ROS levels in cancer cells (Spyridopoulou et al. 2021).

6. Advantages And Disadvantages Of The Nanoparticle’s Synthesis Using Microorganisms

Several microorganisms have been used for the sustainable synthesis of nanoparticles such as metals, quantum dots, semiconductors, etc. having different sizes and shapes (Narayanan and Sakthivel 2010). In comparison to conventional synthesis, green synthesis is cheaper, eco-friendly, and non-toxic (Mahmoud 2020). Adopting the microbial route has numerous advantages such as the microbes having a high growth rate and being inexpensive to cultivate (Prasad et al. 2016). They are easy to handle and can be genetically manipulated or modified without much difficulty (Bhattacharya and Gupta 2005). The process for the synthesis of nanoparticles using microbes is very simple, stable, and robust that leading to higher production rates (Nikolaidis 2020). In addition, the nanoparticles synthesized using microbes revealed high surface area, as well as these, were monodispersed (Singaravelu et al. 2007).

Although the microbial synthesis route showed several advantages yet some disadvantages needed to be noticed such as low repeatability and the process for getting the clear filtrates from colloidal broths involving the use of
sophisticated equipment. However, genetic manipulation is in demand but for the fungal platform is still challenging (Grasso et al. 2020). Moreover, pure nanoparticles are hard to obtain that are lack biomolecules and capping agents. Also, there is a need for thorough research for large-scale production and applications. (Prasad et al. 2016)

7. Conclusion And Future Perspective

In recent years, sustainable or green synthesis has received considerable attention due to its economic importance as it provides a clean, facile, effectual, non-toxic, and eco-friendly route for the synthesis of nanoparticles. Microbes-assisted metal or metal oxide nanoparticles with extremely ordered structures demonstrated their potential for numerous applications in waste treatment, biological and therapeutic fields due to their biocompatibility, controlled morphology, and other useful endowed properties in nano form. Some unique features of microbial cells that promote their use in the synthesis of nanoparticles as reducing and capping agents comprise easy maintenance, fast growth, and safer use. The greener synthesis addresses the bottlenecks for the synthetic methods due to the coating of nanoparticles with the biomolecule or lipid layer which endows physiological solubility, processibility, and stability to the nanoparticles as it enables surface functionalization for applications in biomedical fields.

However, the nanoparticles synthesized adopting the green route face some challenges which need to be addressed namely the slow rates of synthesis and stability of nanoparticles. The problems can be circumvented by augmenting the methods of cultivation of microbes and techniques of extraction and optimization via numerous combinatorial approaches, for example, photobiological methods. The other challenge is the production rate which is quite low in the case of biosynthesis (1/3 in comparison of chemical synthesis) which needs to be surmounted for their applications in real-world systems for large-scale applications. In addition, the lack of monodispersity, variations from batch to batch, and time-consuming process also limit their use in the commercial world. All the underlying mechanisms for the synthesis of nanoparticles including biochemical, cellular, and molecular mechanisms should be researched in detail for enhancing the properties, rate of synthesis, and applications of these nanoparticles. Biological protocols should be kept in mind before the synthesis of such nanoparticles namely the type and inheritable properties of organisms, ideal conditions for enzyme activity and cell growth as well as the reaction conditions. Although researchers are focusing on the therapeutic effect of nanoparticles yet the other important aspect is their toxic side effects. In the absence of biodegradation, delayed elimination trailed by the intercellular reactive oxygen species generation, damage to DNA, apoptotic cell death, and long-term toxicity can be caused by nanoparticles. Till now, most of the microbes-assisted nanoparticles have been examined in in-vitro studies for biomedical use and clinical trials on large scale to assess their safety is an important aspect for their effects in in-vivo. Hence, some factors such as reduction or removal of toxicity, doses, and response to host immune system throughout treatment are some aspects that still need to be addressed before the commercialization of these nanoparticles. The “green chemistry” concept combined with the “white biotechnology” approach can lead to a major achievement in many sustainable industrial developments with the use of genetically modified organisms by understanding the mechanistic aspects and related metabolic pathway culminating in the enhancement of efficiency for the synthesis of nanoparticles with reduced toxicity (Iravani and Varma 2019). Hopefully, with further thorough investigations, the microbes-assisted nanoparticles will attain their immense potential in various sectors of nanotechnology using genetically engineered organisms.

Abbreviations

4-AP - 4-amino phenol

BET - Brunauer-Emmett-Teller

BG - Brilliant green
Declarations

Conflict of interest:
The authors declare no conflict of interest.

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References

1. Abd El Aty AA, Zohair MM (2020) Green-synthesis and optimization of an eco-friendly nanobiofungicide from Bacillus amyloliquefaciens MH046937 with antimicrobial potential against phytopathogens. Environ Nanotechnology, Monit Manag 14:100309. https://doi.org/https://doi.org/10.1016/j.enmm.2020.100309
2. Abdulwahid KE, Dwaish AS, Dakhil OA (2019) Green synthesis and characterization of zinc oxide nanoparticles from cladophora glomerata and its antifungal activity against some fungal isolates. Plant Arch 19:3527–3532
3. Acay H (2021) Utilization of Morchella esculenta-mediated green synthesis golden nanoparticles in biomedicine applications. Prep Biochem Biotechnol 51:127–136. https://doi.org/10.1080/10826068.2020.1799390
4. Afzal B, Yasin D, Naaz H, et al (2021) Biomedical potential of Anabaena variabilis NCCU-441 based Selenium nanoparticles and their comparison with commercial nanoparticles. Sci Rep 11:13507. https://doi.org/10.1038/s41598-021-91738-7
5. Ağçeli GK, Hammachi H, Kodal SP, et al (2020) A Novel Approach to Synthesize TiO2 Nanoparticles: Biosynthesis by Using Streptomyces sp. HC1. J Inorg Organomet Polym Mater 30:3221–3229. https://doi.org/10.1007/s10904-020-01486-w
6. Ahamad I, Aziz N, Zaki A, Fatma T (2021) Synthesis and characterization of silver nanoparticles using Anabaena variabilis as a potential antimicrobial agent. J Appl Phycol 33:829–841. https://doi.org/10.1007/s10811-020-02323-w
7. Ahmad A, Senapati S, Khan MI, et al (2003a) Extracellular biosynthesis of monodisperse gold nanoparticles by a novel extremophilic actinomycete, Thermomonospora sp. Langmuir 19:3550–3553
8. Ahmad A, Senapati S, Khan MI, et al (2003b) Intracellular synthesis of gold nanoparticles by a novel alkalotolerant actinomycete, Rhodococcus species. Nanotechnology 14:824
9. Ahmed T, Ren H, Noman M, et al (2021) Green synthesis and characterization of zirconium oxide nanoparticles by using a native Enterobacter sp. and its antifungal activity against bayberry twig blight disease pathogen Pestalotiopsis versicolor. Nanoinfluence 21:100281. https://doi.org/https://doi.org/10.1016/j.impact.2020.100281
10. Ahn T-K, Lee DH, Kim T, et al (2018) Modification of titanium implant and titanium dioxide for bone tissue engineering. Nov Biomater Regen Med 355–368
11. Ajayi RF, Nqunqa S, Mgwili Y, et al (2021) Green-Synthesized Nanoparticles as Potential Sensors for Health Hazardous Compounds. In: Green Synthesis in Nanomedicine and Human Health. CRC Press, pp 291–314
12. Akintelu SA, Olugbeko SC, Folorunso AS, et al (2021) Potentials of phytosynthesized silver nanoparticles in biomedical fields: a review. Int Nano Lett 1–21
13. Al-Bahrani R, Raman J, Lakshmanan H, et al (2017) Green synthesis of silver nanoparticles using tree oyster mushroom Pleurotus ostreatus and its inhibitory activity against pathogenic bacteria. Mater Lett 186:21–25. https://doi.org/https://doi.org/10.1016/j.matlet.2016.09.069
14. Al-Hakkani MF (2020) Biogenic copper nanoparticles and their applications: A review. SN Appl Sci 2:1–20
15. Alamri SAM, Hashem M, Nafady NA, et al (2018) Controllable biogenic synthesis of intracellular Silver/Silver Chloride Nanoparticles by Meyerozyma guilliermondii KX008616. J Microbiol Biotechnol 28:917–930

16. AlNadhari S, Al-Enazi NM, Alshehrei F, Ameen F (2021) A review on biogenic synthesis of metal nanoparticles using marine algae and its applications. Environ Res 194:110672. https://doi.org/https://doi.org/10.1016/j.envres.2020.110672

17. Alsamhary KI (2020) Eco-friendly synthesis of silver nanoparticles by Bacillus subtilis and their antibacterial activity. Saudi J Biol Sci 27:2185–2191

18. Amin SA, Pazouki M, Hosseinnia A (2009) Synthesis of TiO2–Ag nanocomposite with sol–gel method and investigation of its antibacterial activity against E. coli. Powder Technol 196:241–245

19. Aminabad NS, Farshbaf M, Akbarzadeh A (2019) Recent advances of gold nanoparticles in biomedical applications: state of the art. Cell Biochem Biophys 77:123–137

20. Ammar HA, El Aty AAA, El Awdan SA (2021) Extracellular myco-synthesis of nano-silver using the fermentable yeasts Pichia kudriavzeviiHA-NY2 and Saccharomyces uvarumHA-NY3, and their effective biomedical applications. Bioprocess Biosyst Eng 44:841–854. https://doi.org/10.1007/s00449-020-02494-3

21. Ananthi V, Siva Prakash G, Mohan Rasu K, et al (2018) Comparison of integrated sustainable biodiesel and antibacterial nano silver production by microalgal and yeast isolates. J Photochem Photobiol B Biol 186:232–242. https://doi.org/https://doi.org/10.1016/j.jphotobiol.2018.07.021

22. Anju A, Gupta K, Chundawat TS (2020) In Vitro Antimicrobial and Antioxidant Activity of Biogenically Synthesized Palladium and Platinum Nanoparticles Using Botryococcus braunii. Turkish J Pharm Sci 17:299

23. Araya-Castro K, Chao T-C, Durán-Vinet B, et al (2021) Green Synthesis of Copper Oxide Nanoparticles Using Protein Fractions from an Aqueous Extract of Brown Algae Macrocystis pyrifera. Process. 9

24. Arsiya F, Sayadi MH, Sobhani S (2017) Green synthesis of palladium nanoparticles using Chlorella vulgaris. Mater. Lett.

25. Arya A, Gupta K, Chundawat TS (2020) In Vitro Antimicrobial and Antioxidant Activity of Biogenically Synthesized Palladium and Platinum Nanoparticles Using Botryococcus braunii. Turkish J Pharm Sci 17:299–306. https://doi.org/10.4274/tjps.galenos.2019.94103

26. Arya A, Gupta K, Chundawat TS, Vaya D (2018) Biogenic Synthesis of Copper and Silver Nanoparticles Using Green Alga Botryococcus braunii and Its Antimicrobial Activity. Bioinorg Chem Appl 2018:7879403. https://doi.org/10.1155/2018/7879403

27. Arya A, Mishra V, Chundawat TS (2019) Green synthesis of silver nanoparticles from green algae (Botryococcus braunii) and its catalytic behavior for the synthesis of benzimidazoles. Chem Data Collect 20:100190

28. Asghari-Paskiabi F, Imani M, Rafii-Tabar H, Razzaghi-Abyaneh M (2019) Physicochemical properties, antifungal activity and cytotoxicity of selenium sulfide nanoparticles green synthesized by Saccharomyces cerevisiae. Biochem Biophys Res Commun 516:1078–1084. https://doi.org/https://doi.org/10.1016/j.bbrc.2019.07.007

29. Ashraf N, Ahmad F, Jing Jie C, et al (2020) Optimization of Enterobacter cloacae mediated synthesis of extracellular silver nanoparticles by response surface methodology and their characterization. Part Sci Technol 38:931–943. https://doi.org/10.1008/02726351.2019.1636915

30. Aswathy R, Gabylis B, Anwesha S, Bhaskara Rao K (2017) Green synthesis and characterization of marine yeast-mediated silver and zinc oxide nanoparticles and assessment of their antioxidant activity. Asian J Pharm Clin Res 10:235–240

31. Aygün A, Özdemir S, Gülcan M, et al (2020) Synthesis and characterization of Reishi mushroom-mediated green synthesis of silver nanoparticles for the biochemical applications. J Pharm Biomed Anal 178:112970.
32. Banerjee A, Das D, Andler R, Bandopadhyay R (2021) Green Synthesis of Silver Nanoparticles Using Exopolysaccharides Produced by Bacillus anthracis PFAB2 and its Biocidal Property. J Polym Environ 29:2701–2709. https://doi.org/10.1007/s10924-021-02051-3

33. Barani M, Masoudi M, Mashreghi M, et al (2021) Cell-free extract assisted synthesis of ZnO nanoparticles using aquatic bacterial strains: biological activities and toxicological evaluation. Int J Pharm 120878. https://doi.org/10.1016/j.ijpharm.2021.120878

34. Bartosiak M, Giersz J, Jankowski K (2019) Analytical monitoring of selenium nanoparticles green synthesis using photochemical vapor generation coupled with MIP-OES and UV–Vis spectrophotometry. Microchem J 145:1169–1175. https://doi.org/10.1016/j.microc.2018.12.024

35. Basavaraja S, Balaji SD, Lagashetty A, et al (2008) Extracellular biosynthesis of silver nanoparticles using the fungus Fusarium semitectum. Mater Res Bull 43:1164–1170. https://doi.org/10.1016/j.materresbull.2007.06.020

36. Bedovicová Z, Salayová A (2017) Green-Synthesized Silver Nanoparticles and Their Potential for Antibacterial Applications. Bact Pathog Antibact Control

37. Ben Tahar I, Fickers P, Dziedzic A, et al (2019) Green pyomelanin-mediated synthesis of gold nanoparticles: modelling and design, physico-chemical and biological characteristics. Microb Cell Fact 18:210. https://doi.org/10.1186/s12934-019-1254-2

38. Beveridge TJ, Murray RGE (1980) Sites of metal deposition in the cell wall of Bacillus subtilis. J Bacteriol 141:876–887. https://doi.org/10.1128/jb.141.2.876-887.1980

39. Bharathi S, Kumaran S, Suresh G, et al (2020) Extracellular synthesis of nanoselenium from fresh water bacteria Bacillus sp., and its validation of antibacterial and cytotoxic potential. Biocatal Agric Biotechnol 27:101655. https://doi.org/10.1016/j.biocatagricbiotechnol.2020.101655

40. Bhattacharya D, Gupta RK (2005) Nanotechnology and potential of microorganisms. Crit Rev Biotechnol 25:199–204

41. Bhattacharya P, Chatterjee K, Swarnakar S, Banerjee S (2020) Green Synthesis of Zinc Oxide Nanoparticles via Algal Route and its Action on Cancerous Cells and Pathogenic Microbes. Adv Nano Res 3:15–27

42. Bloch K, Pardesi K, Satriano C, Ghosh S (2021) Bacteriogenic Platinum Nanoparticles for Application in Nanomedicine. Front. Chem. 9:32

43. Borah D, Das N, Das N, et al (2020) Alga-mediated facile green synthesis of silver nanoparticles: Photophysical, catalytic and antibacterial activity. Appl Organomet Chem 34:e5597. https://doi.org/10.1002/aoc.5597

44. Boroumand Moghaddam A, Namvar F, Moniri M, et al (2015) Nanoparticles biosynthesized by fungi and yeast: a review of their preparation, properties, and medical applications. Molecules 20:16540–16565

45. Botteon CEA, Silva LB, Ccana-Ccapatinta G V, et al (2021) Biosynthesis and characterization of gold nanoparticles using Brazilian red propolis and evaluation of its antimicrobial and anticancer activities. Sci Rep 11:1974. https://doi.org/10.1038/s41598-021-81281-w

46. Brock TD, Gustafson J (1976) Ferric iron reduction by sulfur-and iron-oxidizing bacteria. Appl Environ Microbiol 32:567–571

47. Can MM, Coşkun M, Firat T (2012) A comparative study of nanosized iron oxide particles; magnetite (Fe3O4), maghemite (γ-Fe2O3) and hematite (α-Fe2O3), using ferromagnetic resonance. J Alloys Compd 542:241–247
48. Castro-Longoria E, Moreno-Velasquez SD, Vilchis-Nestor AR, et al (2012) Production of platinum nanoparticles and nanoaggregates using Neurospora crassa. J Microbiol Biotechnol 22:1000–1004
49. Chandrappa CP, Govindappa M, Chandrasekar N, et al (2016) Endophytic synthesis of silver chloride nanoparticles from Penicillium sp. of Calophyllum apetalum. Adv Nat Sci Nanosci Nanotechnol 7:25016
50. Chen TL, Kim H, Pan S-Y, et al (2020) Implementation of green chemistry principles in circular economy system towards sustainable development goals: Challenges and perspectives. Sci Total Environ 716:136998
51. Chen X, Li H, Qiao X, et al (2021) Agarose oligosaccharide-silver nanoparticle-antimicrobial peptide-composite for wound dressing. Carbohydr Polym 269:118258. https://doi.org/https://doi.org/10.1016/j.carbpol.2021.118258
52. Chokshi K, Pancha I, Ghosh T, et al (2016) Green synthesis, characterization and antioxidant potential of silver nanoparticles biosynthesized from de-oiled biomass of thermotolerant oleaginous microalgae Acutodesmus dimorphus. RSC Adv 6:72269–72274
53. Clarance P, Luvankar B, Sales J, et al (2020) Green synthesis and characterization of gold nanoparticles using endophytic fungi Fusarium solani and its in-vitro anticancer and biomedical applications. Saudi J Biol Sci 27:706–712. https://doi.org/https://doi.org/10.1016/j.sjbs.2019.12.026
54. Consolo VF, Torres-Nicolini A, Alvarez VA (2020) Mycosynthetized Ag, CuO and ZnO nanoparticles from a promising Trichoderma harzianum strain and their antifungal potential against important phytopathogens. Sci Rep 10:20499. https://doi.org/10.1038/s41598-020-77294-6
55. Costa JSD, Hoskisson PA, Paterlini P, et al (2020) Whole genome sequence of the multi-resistant plant growth-promoting bacteria Streptomyces sp. Z38 with potential application in agroindustry and bio-nanotechnology. Genomics 112:4684–4689
56. Cuevas R, Durán N, Diez MC, et al (2015) Extracellular biosynthesis of copper and copper oxide nanoparticles by Stereum hirsutum, a native white-rot fungus from chilean forests. J Nanomater 2015:
57. Daphne J, Francis A, Mohanty R, et al (2018) Green synthesis of antibacterial silver nanoparticles using yeast isolates and its characterization. Res J Pharm Technol 11:83–92
58. De Silva C, Noor AAM, Abd Karim MM, et al (2020) The green synthesis and characterisation of silver nanoparticles from Serratia spp. Rev Mex Ing Química 19:1327–1339
59. Deepak P, Amutha V, Birundha R, et al (2018) Facile green synthesis of nanoparticles from brown seaweed Sargassum wightii and its biological application potential. Adv Nat Sci Nanosci Nanotechnol 9:35019. https://doi.org/10.1088/2043-6254/aadc4a
60. Deplanche K, Merroun ML, Casadesus M, et al (2012) Microbial synthesis of core/shell gold/palladium nanoparticles for applications in green chemistry. J R Soc Interface 9:1705–1712
61. Dhillon GS, Brar SK, Kaur S, Verma M (2012) Green approach for nanoparticle biosynthesis by fungi: current trends and applications. Crit Rev Biotechnol 32:49–73
62. Duran N, Seabra AB (2018) Biogenic synthesized Ag/Au nanoparticles: production, characterization, and applications. Curr Nanosci 14:82–94
63. Ebadi M, Zolfaghari MR, Aghaie SS, et al (2019) A bio-inspired strategy for the synthesis of zinc oxide nanoparticles (ZnO NPs) using the cell extract of cyanobacterium Nostoc sp. EA03: from biological function to toxicity evaluation. RSC Adv 9:23508–23525
64. El-Sayyad GS, Mosallam FM, El-Batal AI (2018) One-pot green synthesis of magnesium oxide nanoparticles using Penicillium chrysogenum melamin pigment and gamma rays with antimicrobial activity against multidrug-resistant microbes. Adv Powder Technol 29:2616–2625. https://doi.org/https://doi.org/10.1016/j.apt.2018.07.009
65. Elahian F, Heidari R, Charghan VR, et al (2020) Genetically modified Pichia pastoris, a powerful resistant factory for gold and palladium bioleaching and nanostructure heavy metal biosynthesis. Artif Cells, Nanomedicine, Biotechnol 48:259–265. https://doi.org/10.1080/21691401.2019.1699832

66. Elahian F, Reiisi S, Shahidi A, Mirzaei SA (2017) High-throughput bioaccumulation, biotransformation, and production of silver and selenium nanoparticles using genetically engineered Pichia pastoris. Nanomedicine Nanotechnology, Biol Med 13:853–861. https://doi.org/https://doi.org/10.1016/j.nano.2016.10.009

67. Elgamouz A, Idriss H, Nassab C, et al (2020) Green Synthesis, Characterization, Antimicrobial, Anti-Cancer, and Optimization of Colorimetric Sensing of Hydrogen Peroxide of Algae Extract Capped Silver Nanoparticles. Nanomater. 10

68. Elnagar SE, Tayel AA, Elguindy NM, et al (2021) Innovative biosynthesis of silver nanoparticles using yeast glucan nanopolymer and their potentiality as antibacterial composite. J Basic Microbiol n/a: https://doi.org/https://doi.org/10.1002/jobm.202100195

69. Eramabadi P, Masoudi M, Makhdoumi A, Mashreghi M (2020) Microbial cell lysate supernatant (CLS) alteration impact on platinum nanoparticles fabrication, characterization, antioxidant and antibacterial activity. Mater Sci Eng C 117:111292. https://doi.org/https://doi.org/10.1016/j.msec.2020.111292

70. Facile green synthesis of gold nanoparticles from marine algae Gelidiella acerosa and evaluation of its biological PotentialSenthilkumar P, Surendran L, Sudhagar B, Ranjith Santhosh Kumar DS (2019) Facile green synthesis of gold nanoparticles from marine algae Gelidiella acerosa and evaluation of its biological Potential. SN Appl Sci 1:284. https://doi.org/10.1007/s42452-019-0284-z

71. Fahmy SA, Preis E, Bakowsky U, Azzazy HME-S (2020) Palladium Nanoparticles Fabricated by Green Chemistry: Promising Chemotherapeutic, Antioxidant and Antimicrobial Agents. Materials (Basel) 13:3661

72. Farag S, Amr A, El-Shafei A, et al (2021) Green synthesis of titanium dioxide nanoparticles via bacterial cellulose (BC) produced from agricultural wastes. Cellulose. https://doi.org/10.1007/s10570-021-04011-5

73. Fariq A, Khan T, Yasmin A (2017) Microbial synthesis of nanoparticles and their potential applications in biomedicine. J Appl Biomed 15:241–248. https://doi.org/https://doi.org/10.1016/j.jab.2017.03.004

74. Fatima R, Priya M, Indurthi L, et al (2020) Biosynthesis of silver nanoparticles using red algae Peroncia homennii and its antibacterial activity against fish pathogens. Microb Pathog 138:103780

75. Gade A, Gaikwad S, Duran N, Rai M (2014) Green synthesis of silver nanoparticles by Phoma glomerata. Micron 59:52–59. https://doi.org/https://doi.org/10.1016/j.micron.2013.12.005

76. Gahlawat G, Choudhury AR (2019) A review on the biosynthesis of metal and metal salt nanoparticles by microbes. RSC Adv 9:12944–12967. https://doi.org/10.1039/C8RA10483B

77. Gaidhani S V, Yeshvekar RK, Shedbalkar UU, et al (2014) Bio-reduction of hexachloroplatinic acid to platinum nanoparticles employing Acinetobacter calcoaceticus. Process Biochem 49:2313–2319. https://doi.org/https://doi.org/10.1016/j.procbio.2014.10.002

78. Ganesan V, Hariram M, Vivekanandan S, Muthuramkumar S (2020) Peroncia sp. (endophytic fungi) extract mediated sol-gel synthesis of ZnO nanoparticles for antimicrobial and antioxidant applications. Mater Sci Semicond Process 105:104739. https://doi.org/https://doi.org/10.1016/j.mssp.2019.104739

79. Ganesh KN, Zhang D, Miller SJ, et al (2021) Green Chemistry: A Framework for a Sustainable Future

80. Gawande MB, Shelke SN, Zboril R, Varma RS (2014) Microwave-assisted chemistry: synthetic applications for rapid assembly of nanomaterials and Organics. Acc Chem Res 47:1338–1348

81. Gayda GZ, Demkiv OM, Stasyuk NY, et al (2019) Metallic Nanoparticles Obtained via “Green” Synthesis as a Platform for Biosensor Construction. Appl. Sci. 9
82. Gevorgyan S, Schubert R, Yeranosyan M, et al. (2021) Antibacterial activity of royal jelly-mediated green synthesized silver nanoparticles. AMB Express 11:51. https://doi.org/10.1186/s13568-021-01213-9
83. Ghiuta I, Croitoru C, Kost J, et al. (2021) Bacteria-Mediated Synthesis of Silver and Silver Chloride Nanoparticles and Their Antimicrobial Activity. Appl. Sci. 11
84. Ghosh S, Ahmad R, Zeyaulal M, Khare SK. (2021) Microbial Nano-Factories: Synthesis and Biomedical Applications. Front. Chem. 9:194
85. Gil Y-G, Kang S, Chae A, et al. (2018) Synthesis of porous Pd nanoparticles by therapeutic chaga extract for highly efficient tri-modal cancer treatment. Nanoscale 10:19810–19817
86. Giovagnoli S, Marenzoni ML, Nocchetti M, et al. (2014) Synthesis, characterization and in vitro extracellular and intracellular activity against Mycobacterium tuberculosis infection of new second-line antitubercular drug-palladium complexes. J Pharm Pharmacol 66:106–121. https://doi.org/https://doi.org/10.1111/jphp.12162
87. Goel N, Ahmad R, Singh R, et al. (2021) Biological synthesized silver nanoparticles by Streptomyces sp. EMB 24 extracts used against the drug resistant bacteria. Bioresour Technol Reports 100753
88. Golińska P. (2020) Synthesis of Nanoparticles by Actinomycetes: Mechanism and Applications. In: Microbial Nanotechnology. CRC Press, pp 1–19
89. González-Ballesteros N, Prado-López S, Rodríguez-González JB, et al. (2017) Green synthesis of gold nanoparticles using brown algae Cystoseira baccata: Its activity in colon cancer cells. Colloids Surfaces B BioInterfaces 153:190–198. https://doi.org/https://doi.org/10.1016/j.colsurfb.2017.02.020
90. Gopu M, Kumar P, Selvankumar T, et al. (2021) Green biomimetic silver nanoparticles utilizing the red algae Amphirhoa rigida and its potent antibacterial, cytotoxicity and larvicidal efficiency. Bioprocess Biosyst Eng 44:217–223. https://doi.org/10.1007/s00449-020-02426-1
91. Govender Y, Riddin T, Gericke M, Whiteley CG. (2009) Bioreduction of platinum salts into nanoparticles: a mechanistic perspective. Biotechnol Lett 31:95–100. https://doi.org/10.1007/s10529-008-9825-z
92. Grasso G, Zane D, Dragone R (2020) Microbial nanotechnology: challenges and prospects for green biocatalytic synthesis of nanoscale materials for sensoristic and biomedical applications. Nanomaterials 10:11
93. Guilger-Casagrande M, Germano-Costa T, Bilesky-José N, et al. (2021) Influence of the capping of biogenic silver nanoparticles on their toxicity and mechanism of action towards Sclerotinia sclerotiorum. J Nanobiotechnology 19:53. https://doi.org/10.1186/s12951-021-00797-5
94. Gupta K, Chundawat TS. (2020) Zinc oxide nanoparticles synthesized using Fusarium oxysporum to enhance bioethanol production from rice-straw. Biomass and Bioenergy 143:105840. https://doi.org/https://doi.org/10.1016/j.biombioe.2020.105840
95. Gupta RK, Kumar V, Gundampati RK, et al. (2017) Biosynthesis of silver nanoparticles from the novel strain of Streptomyces Sp. BHUMBU-80 with highly efficient electroanalytical detection of hydrogen peroxide and antibacterial activity. J Environ Chem Eng 5:5624–5635. https://doi.org/https://doi.org/10.1016/j.jece.2017.09.029
96. Hamed AA, Kabary H, Khedr M, Emam AN (2020) Antibiofilm, antimicrobial and cytotoxic activity of extracellular green-synthesized silver nanoparticles by two marine-derived actinomycete. RSC Adv 10:10361–10367
97. Hansda A, Kumar V, Anshumali (2016) A comparative review towards potential of microbial cells for heavy metal removal with emphasis on biosorption and bioaccumulation. World J Microbiol Biotechnol 32:170. https://doi.org/10.1007/s11274-016-2117-1
98. Hashem AH, Abdelaziz AM, Askar AA, et al. (2021) Bacillus megaterium-Mediated Synthesis of Selenium Nanoparticles and Their Antifungal Activity against Rhizoctonia solani in Faba Bean Plants. J Fungi 7:195
99. Hassan KT, Ibraheem IJ, Hassan OM, et al (2021a) Facile green synthesis of Ag/AgCl nanoparticles derived from Chara algae extract and evaluating their antibacterial activity and synergistic effect with antibiotics. J Environ Chem Eng 9:105359. https://doi.org/https://doi.org/10.1016/j.jece.2021.105359

100. Hassan SE-D, Fouda A, Radwan AA, et al (2019) Endophytic actinomycetes Streptomyces spp mediated biosynthesis of copper oxide nanoparticles as a promising tool for biotechnological applications. JBIC J Biol Inorg Chem 24:377–393. https://doi.org/10.1007/s00775-019-01654-5

101. Hassan SE, Fouda A, Saied E, et al (2021b) Rhizopus oryzae-Mediated Green Synthesis of Magnesium Oxide Nanoparticles (MgO-NPs): A Promising Tool for Antimicrobial, Mosquitocidal Action, and Tanning Effluent Treatment. J. Fungi 7

102. He S, Guo Z, Zhang Y, et al (2007) Biosynthesis of gold nanoparticles using the bacteria Rhodopseudomonas capsulata. Mater Lett 61:3984–3987. https://doi.org/10.1016/j.matlet.2007.01.018

103. Hemashekhar B, Chandrappa CP, Govindappa M, et al (2017) Green synthesis of silver nanoparticles from Endophytic fungus Aspergillus niger isolated from Simarouba glauca leaf and its Antibacterial and Antioxidant activity. Inter J Eng Res Appl 7:17–24

104. Hong X, Zhou Y, Ye Z, et al (2017) Enhanced hydrophilicity and antibacterial activity of PVDF ultrafiltration membrane using Ag3PO4/TiO2 nanocomposite against E. coli. Desalin Water Treat 75:26–33

105. Hossain A, Hong X, Ibrahim E, et al (2019) Green Synthesis of Silver Nanoparticles with Culture Supernatant of a Bacterium Pseudomonas rhodesiae and Their Antibacterial Activity against Soft Rot Pathogen Dickeya dadantii. Mol. 24

106. Hu J, Xianyu Y (2021) When nano meets plants: A review on the interplay between nanoparticles and plants. Nano Today 38:101143. https://doi.org/https://doi.org/10.1016/j.nantod.2021.101143

107. Huq M (2020a) Biogenic Silver Nanoparticles Synthesized by Lysinibacillus xylanilyticus MAHUQ-40 to Control Antibiotic-Resistant Human Pathogens Vibrio paraaemolyticus and Salmonella Typhimurium. Front Bioeng Biotechnol 8:1407

108. Huq MA (2020b) Green Synthesis of Silver Nanoparticles Using Pseudoduganella eburnea MAHUQ-39 and Their Antimicrobial Mechanisms Investigation against Drug Resistant Human Pathogens. Int. J. Mol. Sci. 21

109. Huq MA, Akter S (2021) Bacterial Mediated Rapid and Facile Synthesis of Silver Nanoparticles and Their Antimicrobial Efficacy against Pathogenic Microorganisms. Mater. 14

110. Ighalo JO, Sagboye PA, Umenweke G, et al (2021) CuO Nanoparticles (CuO NPs) for Water Treatment: A Review of Recent Advances. Environ Nanotechnology, Monit Manag 100443

111. Iravani S, Varma RS (2020) Sustainable synthesis of cobalt and cobalt oxide nanoparticles and their catalytic and biomedical applications. Green Chem 22:2643–2661

112. Iravani S, Varma RS (2019) Biofactories: engineered nanoparticles via genetically engineered organisms. Green Chem 21:4583–4603

113. Ito R, Kuroda K, Hashimoto H, Ueda M (2016) Recovery of platinum(0) through the reduction of platinum ions by hydrogenase-displaying yeast. AMB Express 6:88. https://doi.org/10.1186/s13568-016-0262-4

114. Jadoun S, Arif R, Jangid NK, Meena RK (2021) Green synthesis of nanoparticles using plant extracts: a review. Environ Chem Lett 19:355–374. https://doi.org/10.1007/s10311-020-01074-x

115. Jadoun S, Difi KFA (2021) Silver Nanoparticles with Natural Polymers. Polym Nanocomposites Based Silver Nanoparticles Synth Charact Appl 139–157

116. Jha AK, Prasad K (2010) Biosynthesis of metal and oxide nanoparticles using Lactobacilli from yoghurt and probiotic spore tablets. Biotechnol J 5:285–291
117. Jiwani CK, Com AM, Ph MP, et al (2018) “Green Marketing - Challenges and Opportunities for Greener Today and Tomorrow” Being Green and Clean Is Not Just an Aspiration but an Action. -Christine Pelosi. 87–93

118. John MS, Nagoth JA, Zannotti M, et al (2021) Biogenic Synthesis of Copper Nanoparticles Using Bacterial Strains Isolated from an Antarctic Consortium Associated to a Psychrophilic Marine Ciliate: Characterization and Potential Application as Antimicrobial Agents. Mar. Drugs 19

119. Kalimuthu K, Suresh Babu R, Venkataraman D, et al (2008) Biosynthesis of silver nanocrystals by Bacillus licheniformis. Colloids Surfaces B Biointerfaces 65:150–153. https://doi.org/https://doi.org/10.1016/j.colsurfb.2008.02.018

120. Kalyani P, Lakshmi BKM, Dinesh RG, Hemalatha KPJ (2018) Green synthesis of silver nanoparticles by using aspergillus fumigatus and their antibacterial activity. Int J Curr Res in Life Sci 7:788–791

121. Kang S, Shin W, Kang K, et al (2018) Revisiting of Pd nanoparticles in cancer treatment: all-round excellence of porous Pd nanoparticles in gene-thermo combinational therapy. ACS Appl Mater Interfaces 10:13819–13828

122. Kaplan Ö, Gökşen Tosun N, Ö zgür A, et al (2021) Microwave-assisted green synthesis of silver nanoparticles using crude extracts of Boletus edulis and Coriolus versicolor: Characterization, anticancer, antimicrobial and wound healing activities. J Drug Deliv Sci Technol 64:102641. https://doi.org/https://doi.org/10.1016/j.jddst.2021.102641

123. Karunakaran G, Suriyaprabha R, Manivasakan P, et al (2013) Impact of nano and bulk ZrO2, TiO2 particles on soil nutrient contents and PGPR. J Nanosci Nanotechnol 13:678–685

124. Kashyap M, Samadhiya K, Ghosh A, et al (2021) Synthesis, characterization and application of intracellular Ag/AgCl nanohybrids biosynthesized in Scenedesmus sp. as neutral lipid inducer and antibacterial agent. Environ Res 201:111499. https://doi.org/https://doi.org/10.1016/j.envres.2021.111499

125. Kathiresan K, Manivannan S, Nabeel MA, Dhivya B (2009) Studies on silver nanoparticles synthesized by a marine fungus, Penicillium fellutanum isolated from coastal mangrove sediment. Colloids surfaces B Biointerfaces 71:133–137

126. Khalil AT, Ovais M, Ullah I, et al (2017) Biosynthesis of iron oxide (Fe2O3) nanoparticles via aqueous extracts of Sageretia thea (Osbeck.) and their pharmacognostic properties. Green Chem Lett Rev 10:186–201. https://doi.org/10.1080/17518253.2017.1339831

127. Khan AU, Malik N, Khan M, et al (2018) Fungi-assisted silver nanoparticle synthesis and their applications. Bioprocess Biosyst Eng 41:1–20

128. Khataee A, Mansoori GA (2011) Nanostructured titanium dioxide materials: Properties, preparation and applications. World scientific

129. Khatami M, Varma RS, Zafarina N, et al (2018) Applications of green synthesized Ag, ZnO and Ag/ZnO nanoparticles for making clinical antimicrobial wound-healing bandages. Sustain Chem Pharm 10:9–15

130. Kim D-Y, Saratale RG, Shinde S, et al (2018) Green synthesis of silver nanoparticles using Laminaria japonica extract: Characterization and seeding growth assessment. J Clean Prod 172:2910–2918. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.11.123

131. Konappa N, Udayashankar AC, Dhamodaran N, et al (2021) Ameliorated Antibacterial and Antioxidant Properties by Trichoderma harzianum Mediated Green Synthesis of Silver Nanoparticles. Biomol. 11

132. Kondaparthi P, Flora SJS, Naqvi S (2019) Selenium nanoparticles: an insight on its Pro-oxidant and antioxidant properties. Front Nanosci Nanotechnol

133. Kou J, Varma RS (2013) Expeditious organic-free assembly: morphologically controlled synthesis of iron oxides using microwaves. Nanoscale 5:8675–8679
134. Krishnan S, Chadha A (2020) Microbial Synthesis of Gold Nanoparticles and Their Applications as Catalysts. Handb Nanomater Nanocomposites Energy Environ Appl 1–28

135. Krishnan S, Patel PN, Balasubramanian KK, Chadha A (2021) Yeast supported gold nanoparticles: an efficient catalyst for the synthesis of commercially important aryl amines. New J Chem 45:1915–1923. https://doi.org/10.1039/D0NJ04542J

136. Kumar N, Parui SS, Limbu S, et al (2021) Structural and optical properties of sol–gel derived CuO and Cu2O nanoparticles. Mater Today Proc 41:237–241

137. Lalitha K, Kalaimurgan D, Nithya K, et al (2020) Antibacterial, Antifungal and Mosquitocidal Efficacy of Copper Nanoparticles Synthesized from Entomopathogenic Nematode: Insect–Host Relationship of Bacteria in Secondary Metabolites of Morganella morganii sp. (PMA1). Arab J Sci Eng 45:4489–4501. https://doi.org/10.1007/s13369-020-04487-6

138. Laxmi Sharma J, Dhayal V, Kumar Sharma R (2021) Antibacterial effect of glycerol assisted ZnO nanoparticles synthesized by white rot fungus Phanerochaete chrysosporium. Mater Today Proc 43:2855–2860. https://doi.org/https://doi.org/10.1016/j.matpr.2021.01.075

139. Lian S, Diko CS, Yan Y, et al (2019) Characterization of biogenic selenium nanoparticles derived from cell-free extracts of a novel yeast Magnusiomyces ingens. 3 Biotech 9:221. https://doi.org/10.1007/s13205-019-1748-y

140. Liu J, Qiao SZ, Hu QH, Lu GQ (2011) Magnetic nanocomposites with mesoporous structures: synthesis and applications. small 7:425–443

141. Liu J, Zhan H, Wang N, et al (2021) Palladium Nanoparticles on Covalent Organic Framework Supports as Catalysts for Suzuki–Miyaura Cross-Coupling Reactions. ACS Appl Nano Mater

142. Lu Y, Ozcan S (2015) Green nanomaterials: On track for a sustainable future. Nano Today 10:417–420. https://doi.org/https://doi.org/10.1016/j.nantod.2015.04.010

143. Lv Q, Zhang B, Xing X, et al (2018) Biosynthesis of copper nanoparticles using Shewanella loihica PV-4 with antibacterial activity: Novel approach and mechanisms investigation. J Hazard Mater 347:141–149. https://doi.org/https://doi.org/10.1016/j.jhazmat.2017.12.070

144. MHM, Joshi CG, Danagoudar A, et al (2017) Biogenic synthesis of gold nanoparticles by marine endophytic fungus-Cladosporium cladosporioides isolated from seaweed and evaluation of their antioxidant and antimicrobial properties. Process Biochem 63:137–144. https://doi.org/https://doi.org/10.1016/j.procbio.2017.09.008

145. Maceda AF, Ouano JJS, Que MCO, et al (2018) Controlling the absorption of gold nanoparticles via green synthesis using Sargassum crassifolium extract. In: Key Engineering Materials. Trans Tech Publ, pp 44–48

146. MacKellar JJ, Constable DJC, Kirchhoff MM, et al (2020) Toward a green and sustainable chemistry education road map. J Chem Educ 97:2104–2113

147. Mahajan A, Arya A, Chundawat TS (2019) Green synthesis of silver nanoparticles using green alga (Chlorella vulgaris) and its application for synthesis of quinolines derivatives. Synth Commun 49:1926–1937. https://doi.org/10.1080/00397911.2019.1610776

148. Mahanty S, Bakshi M, Ghosh S, et al (2019) Green Synthesis of Iron Oxide Nanoparticles Mediated by Filamentous Fungi Isolated from Sundarban Mangrove Ecosystem, India. Bionanoscience 9:637–651. https://doi.org/10.1007/s12668-019-00644-w

149. Mahmoud AED (2020) Nanomaterials: Green synthesis for water applications. Handb Nanomater Nanocomposites Energy Environ Appl 1–21
150. Mandal D, Bolander ME, Mukhopadhyay D, et al (2006) The use of microorganisms for the formation of metal nanoparticles and their application. Appl Microbiol Biotechnol 69:485–492

151. Manjunath Hulikere M, Joshi CG (2019) Characterization, antioxidant and antimicrobial activity of silver nanoparticles synthesized using marine endophytic fungus- Cladosporium cladosporioides. Process Biochem 82:199–204. https://doi.org/https://doi.org/10.1016/j.procbio.2019.04.011

152. Markova Z, Novak P, Kaslik J, et al (2014) Iron (II, III)–polyphenol complex nanoparticles derived from green tea with remarkable ecotoxicological impact. ACS Sustain Chem Eng 2:1674–1680

153. Marouzi S, Sabouri Z, Darroudi M (2021) Greener Synthesis and Medical Applications of Metal Oxide Nanoparticles. Ceram Int

154. Massironi A, Morelli A, Grassi L, et al (2019) Ulvan as novel reducing and stabilizing agent from renewable algal biomass: Application to green synthesis of silver nanoparticles. Carbohydr Polym 203:310–321. https://doi.org/https://doi.org/10.1016/j.carbpol.2018.09.066

155. Medvedeva X V, Li F, Maokhamphiou A, et al (2021) Shape control in seed-mediated synthesis of non-elongated Cu nanoparticles and their optical properties. Nanoscale

156. Menon S, Agarwal H, Shanmugam VK (2021) Catalytical degradation of industrial dyes using biosynthesized selenium nanoparticles and evaluating its antimicrobial activities. Sustain Environ Res 31:2. https://doi.org/10.1186/s42834-020-00072-6

157. Messaoudi O, Bendahou M (2020) Biological synthesis of nanoparticles using endophytic microorganisms: Current development. Nanotechnol Environ

158. Mmola M, Roes-Hill M Le, Durrell K, et al (2016) Enhanced antimicrobial and anticancer activity of silver and gold nanoparticles synthesised using Sargassum incisifolium aqueous extracts. Molecules 21:1633

159. Moghaddam AB, Moniri M, Azizi S, et al (2017) Biosynthesis of ZnO Nanoparticles by a New Pichia kudriavzevii Yeast Strain and Evaluation of Their Antimicrobial and Antioxidant Activities. Mol. 22

160. Moghaddam K (2010) An introduction to microbial metal nanoparticle preparation method. J Young Investig 19:

161. Mohamed AA, Abu-Elghait M, Ahmed NE, Salem SS (2021) Eco-friendly Mycogenic Synthesis of ZnO and CuO Nanoparticles for In Vitro Antibacterial, Antifongal, and Antifungal Applications. Biol Trace Elem Res 199:2788–2799. https://doi.org/10.1007/s12011-020-02369-4

162. Mohammadinejad R, Shavandi A, Raie DS, et al (2019) Plant molecular farming: production of metallic nanoparticles and therapeutic proteins using green factories. Green Chem 21:1845–1865

163. Mohd Yusof H, Mohamad R, Zaidan UH, Abdul Rahman NA (2019) Microbial synthesis of zinc oxide nanoparticles and their potential application as an antimicrobial agent and a feed supplement in animal industry: a review. J Anim Sci Biotechnol 10:57. https://doi.org/10.1186/s40104-019-0368-z

164. Monga Y, Kumar P, Sharma RK, et al (2020) Sustainable synthesis of nanoscale zeraivalent iron particles for environmental remediation. ChemSusChem 13:3288–3305

165. Moradpoor H, Safaei M, Golshah A, et al (2021) Green synthesis and antifungal effect of titanium dioxide nanoparticles on oral Candida albicans pathogen. Inorg Chem Commun 130:108748. https://doi.org/https://doi.org/10.1016/j.inoche.2021.108748

166. Mukherjee P, Senapati S, Mandal D, et al (2002) Extracellular Synthesis of Gold Nanoparticles by the Fungus Fusarium oxysporum. ChemBioChem 3:461–463. https://doi.org/https://doi.org/10.1002/1439-7633(20020503)3:5<461::AID-CBIC461>3.0.CO;2-X

167. Murugesan S, Bhuvaneswari S, Sivamurugan V (2017) Green synthesis, characterization of silver nanoparticles of a marine red alga Spyridia fusiformis and their antibacterial activity
168. Musa SF, Yeat TS, Kamal LZM, et al (2018) Pleurotus sajor-caju can be used to synthesize silver nanoparticles with antifungal activity against Candida albicans. J Sci Food Agric 98:1197–1207. https://doi.org/https://doi.org/10.1002/jsfa.8573

169. Naimi-Shamel N, Pourali P, Dolatabadi S (2019) Green synthesis of gold nanoparticles using Fusarium oxysporum and antibacterial activity of its tetracycline conjugant. J Mycol Med 29:7–13. https://doi.org/https://doi.org/10.1016/j.mycmed.2019.01.005

170. Nanda A, Saravanan M (2009) Biosynthesis of silver nanoparticles from Staphylococcus aureus and its antimicrobial activity against MRSA and MRSE. Nanomedicine Nanotechnology, Biol Med 5:452–456. https://doi.org/https://doi.org/10.1016/j.nano.2009.01.012

171. Narayanan KB, Sakthivel N (2010) Biological synthesis of metal nanoparticles by microbes. Adv. Colloid Interface Sci. 156:1–13

172. Naseer QA, Xue X, Wang X, et al (2021) Synthesis of silver nanoparticles using Lactobacillus bulgaricus and assessment of their antibacterial potential. Brazilian J Biol 82:

173. Nasrollahzadeh M, Sajjadi M, Dadashi J, Ghafari H (2020a) Pd-based nanoparticles: Plant-assisted biosynthesis, characterization, mechanism, stability, catalytic and antimicrobial activities. Adv Colloid Interface Sci 276:102103

174. Nasrollahzadeh M, Sajjadi M, Iravani S, Varma RS (2021) Green-synthesized nanocatalysts and nanomaterials for water treatment: Current challenges and future perspectives. J Hazard Mater 401:123401

175. Nasrollahzadeh M, Shafiei N, Eslamipanah M, et al (2020b) Preparation of Au nanoparticles by Q switched laser ablation and their application in 4-nitrophenol reduction. Clean Technol Environ Policy 22:1715–1724

176. Nazari N, Jookar Kashi F (2021) A novel microbial synthesis of silver nanoparticles: Its bioactivity, Ag/Ca-Alg beads as an effective catalyst for decolorization Disperse Blue 183 from textile industry effluent. Sep Purif Technol 259:118117. https://doi.org/https://doi.org/10.1016/j.seppur.2020.118117

177. Nejati K, Dadashpour M, Gharibi T, et al (2021) Biomedical Applications of Functionalized Gold Nanoparticles: A Review. J Clust Sci 1–16

178. Nikolaidis P (2020) Analysis of Green methods to synthesize nanomaterials. Green Synth Nanomater bioenergy Appl 125–144

179. Niño-Martínez N, Salas Orozco MF, Martínez-Castañón G-A, et al (2019) Molecular Mechanisms of Bacterial Resistance to Metal and Metal Oxide Nanoparticles. Int. J. Mol. Sci. 20

180. Noman M, Shahid M, Ahmed T, et al (2020) Use of biogenic copper nanoparticles synthesized from a native Escherichia sp. as photocatalysts for azo dye degradation and treatment of textile effluents. Environ Pollut 257:113514. https://doi.org/https://doi.org/10.1016/j.envpol.2019.113514

181. Noor S, Shah Z, Javed A, et al (2020) A fungal based synthesis method for copper nanoparticles with the determination of anticancer, antidiabetic and antibacterial activities. J Microbiol Methods 174:105966. https://doi.org/https://doi.org/10.1016/j.mimet.2020.105966

182. Ogi T, Honda R, Tamaoki K, et al (2011) Direct room-temperature synthesis of a highly dispersed Pd nanoparticle catalyst and its electrical properties in a fuel cell. Powder Technol 205:143–148. https://doi.org/https://doi.org/10.1016/j.powtec.2010.09.004

183. Omomowo IO, Adenigba VO, Ogunsena SB, et al (2020) Antimicrobial and antioxidant activities of algal-mediated silver and gold nanoparticles. IOP Conf Ser Mater Sci Eng 805:12010. https://doi.org/10.1088/1757-899x/805/1/012010

184. Ong CB, Ng LY, Mohammad AW (2018) A review of ZnO nanoparticles as solar photocatalysts: synthesis, mechanisms and applications. Renew Sustain Energy Rev 81:536–551
185. Osorio-Echavarría J, Osorio-Echavarría J, Ossa-Orozco CP, Gómez-Vanegas NA (2021) Synthesis of silver nanoparticles using white-rot fungus Anamorphous Bjerkandera sp. R1: influence of silver nitrate concentration and fungus growth time. Sci Rep 11:3842. https://doi.org/10.1038/s41598-021-82514-8

186. Otari S V, Patil RM, Ghosh SJ, et al (2015) Intracellular synthesis of silver nanoparticle by actinobacteria and its antimicrobial activity. Spectrochim Acta Part A Mol Biomol Spectrosc 136:1175–1180. https://doi.org/10.1016/j.saa.2014.10.003

187. Owaid MN (2019) Green synthesis of silver nanoparticles by Pleurotus (oyster mushroom) and their bioactivity: Review. Environ Nanotechnology, Monit Manag 12:100256. https://doi.org/10.1016/j.enmm.2019.100256

188. Pandey PC, Mitra MD, Tiwari AK, Singh S (2021) Synthetic incorporation of palladium-nickel bimetallic nanoparticles within mesoporous silica/silica nanoparticles as efficient and cheaper catalyst for both cationic and anionic dyes degradation. J Environ Sci Heal Part A 56:460–472

189. Patil MP, Kim G-D (2018) Marine microorganisms for synthesis of metallic nanoparticles and their biomedical applications. Colloids Surfaces B Biointerfaces 172:487–495. https://doi.org/10.1016/j.colsurfb.2018.09.007

190. Pedone D, Mogliarietti M, De Luca E, et al (2017) Platinum nanoparticles in nanobiomedicine. Chem Soc Rev 46:4951–4975

191. Pei X, Qu Y, Shen W, et al (2017) Green synthesis of gold nanoparticles using fungus Mariannaea sp. HJ and their catalysis in reduction of 4-nitrophenol. Environ Sci Pollut Res 24:21649–21659. https://doi.org/10.1007/s11356-017-9684-z

192. Peiris MMK, Guansekera T, Jayaweera PM, Fernando SSN (2018) TiO 2 Nanoparticles from Baker's Yeast: A Potent Antimicrobial. J Microbiol Biotechnol 28:1664–1670

193. Pinel-Cabello M, Chapon V, Ruiz-Fresneda MA, et al (2021) Delineation of cellular stages and identification of key proteins for reduction and biotransformation of Se(IV) by Stenotrophomonas bontenitica BII-R7. J Hazard Mater 418:126150. https://doi.org/https://doi.org/10.1016/j.jhazmat.2021.126150

194. Plachtová P, Medrikova Z, Zboril R, et al (2018) Iron and iron oxide nanoparticles synthesized with green tea extract: differences in ecotoxicological profile and ability to degrade malachite green. ACS Sustain Chem Eng 6:8679–8687

195. Prasad R, Pandey R, Barman I (2016) Engineering tailored nanoparticles with microbes: quo vadis? Wiley Interdiscip Rev Nanomedicine Nanobiotechnology 8:316–330

196. Puja P, Kumar P (2019) A perspective on biogenic synthesis of platinum nanoparticles and their biomedical applications. Spectrochim Acta Part A Mol Biomol Spectrosc 211:94–99. https://doi.org/10.1016/j.saa.2018.11.047

197. Purohit J, Chattopadhyay A, Singh NK (2019) Green synthesis of microbial nanoparticle: Approaches to application. In: Microbial Nanobionics. Springer, pp 35–60

198. Qu Y, Li X, Lian S, et al (2019) Biosynthesis of gold nanoparticles using fungus Trichoderma sp. WL-Go and their catalysis in degradation of aromatic pollutants. IET Nanobiotechnology 13:12–17. https://doi.org/10.1049/iet-nbt.2018.5177

199. Qu Y, Pei X, Shen W, et al (2017a) Biosynthesis of gold nanoparticles by Aspergillum sp. WL-Au for degradation of aromatic pollutants. Phys E Low-dimensional Syst Nanostructures 88:133–141. https://doi.org/https://doi.org/10.1016/j.physe.2017.01.010

200. Qu Y, Shen W, Pei X, et al (2017b) Biosynthesis of gold nanoparticles by Trichoderma sp. WL-Go for azo dyes decolorization. J Environ Sci 56:79–86. https://doi.org/https://doi.org/10.1016/j.jes.2016.09.007
201. Qu Y, You S, Zhang X, et al (2018) Biosynthesis of gold nanoparticles using cell-free extracts of Magnusiomyces ingens LH-F1 for nitrophenols reduction. Bioprocess Biosyst Eng 41:359–367. https://doi.org/10.1007/s00449-017-1869-9

202. Rabiee N, Khatami M, Jamalipour Sou G, et al (2021) Diatoms with Invaluable Applications in Nanotechnology, Biotechnology, and Biomedicine: Recent Advances. ACS Biomater Sci Eng

203. Rafeeq CM, Paul E, Vidya Saagar E, Manzur Ali PP (2021) Mycosynthesis of zinc oxide nanoparticles using Pleurotus floriananus and optimization of process parameters. Ceram Int 47:12375–12380. https://doi.org/https://doi.org/10.1016/j.ceramint.2021.01.091

204. Rafique M, Sadaf I, Rafique MS, Tahir MB (2017) A review on green synthesis of silver nanoparticles and their applications. Artif Cells, Nanomedicine, Biotechnol 45:1272–1291. https://doi.org/10.1080/21691401.2016.1241792

205. Rajakumar G, Rahuman AA, Roopan SM, et al (2012) Fungus-mediated biosynthesis and characterization of TiO2 nanoparticles and their activity against pathogenic bacteria. Spectrochim Acta Part A Mol Biomol Spectrosc 91:23–29. https://doi.org/https://doi.org/10.1016/j.saa.2012.01.011

206. Rana A, Yadav K, Jagadevan S (2020) A comprehensive review on green synthesis of nature-inspired metal nanoparticles: Mechanism, application and toxicity. J Clean Prod 122880

207. Rani R, Sharma D, Chaturvedi M, Yadav JP (2017) Green synthesis, characterization and antibacterial activity of silver nanoparticles of endophytic fungi Aspergillus terreus. J Nanomed Nanotechnol 8:

208. Ranjitha VR, Rai VR (2017) Actinomycetes mediated synthesis of gold nanoparticles from the culture supernatant of Streptomyces griseoruber with special reference to catalytic activity. 3 Biotech 7:299. https://doi.org/10.1007/s13205-017-0930-3

209. Rao MD, Pennathur G (2017) Green synthesis and characterization of cadmium sulphide nanoparticles from Chlamydomonas reinhardtii and their application as photocatalysts. Mater Res Bull 85:64–73. https://doi.org/https://doi.org/10.1016/j.materesbull.2016.08.049

210. Rayaman P, Ocsoy I, Gurer US (2018) Green synthesis and characterization of silver nanoparticles using the fungus A. niger and bioactive potential against microorganisms and cancer cells. Lat Am J Pharm 37:979–986

211. Rehman S, Jermy BR, Akhtar S, et al (2019) Isolation and characterization of a novel thermophile; Bacillus haynesii, applied for the green synthesis of ZnO nanoparticles. Artif Cells, Nanomedicine, Biotechnol 47:2072–2082. https://doi.org/10.1080/21691401.2019.1620254

212. Rónavári A, Igaz N, Gopisetty MK, et al (2018) Biosynthesized silver and gold nanoparticles are potent antimycotics against opportunistic pathogenic yeasts and dermatophytes. Int J Nanomedicine 13:695

213. Saitawadekar A, Kakde UB (2020) Green synthesis of copper nanoparticles using aspergillus flavus. J Crit Rev 7:1083–1090

214. Saleh GM (2020) Green Synthesis Concept of Nanoparticles From Environmental Bacteria and Their Effects on Pathogenic Bacteria. Iraqi J Sci 1289–1297

215. Salvadori MR, Ando RA, Nascimento CAO, Corrêa B (2017) Dead biomass of Amazon yeast: A new insight into bioremediation and recovery of silver by intracellular synthesis of nanoparticles. J Environ Sci Heal Part A 52:1112–1120. https://doi.org/10.1080/10934529.2017.1340754

216. Sanaeimehr Z, Javadi I, Namvar F (2018) Antiangiogenic and antiapoptotic effects of green-synthesized zinc oxide nanoparticles using Sargassum muticum algae extraction. Cancer Nanotechnol 9:3. https://doi.org/10.1186/s12645-018-0037-5
217. Santos TS, Passos EM dos, Seabra MG de J, et al (2021) Entomopathogenic Fungi Biomass Production and Excesscellular Biosynthesis of Silver Nanoparticles for Bioinsecticide Action. Appl. Sci. 11

218. Saravanan M, Gopinath V, Chaurasia MK, et al (2018) Green synthesis of anisotropic zinc oxide nanoparticles with antibacterial and cytotoxic properties. Microb Pathog 115:57–63.
https://doi.org/https://doi.org/10.1016/j.micpath.2017.12.039

219. Sarfraz N, Khan I (2021) Plasmonic Gold Nanoparticles (AuNPs): Properties, Synthesis and their Advanced Energy, Environmental and Biomedical Applications. Chem Asian J 16:720–742

220. Scala A, Piperno A, Hada A, et al (2019) Marine Bacterial Exopolymers-Mediated Green Synthesis of Noble Metal Nanoparticles with Antimicrobial Properties. Polym. 11

221. Senthilkumar P, Suresh K, Sudhagar B, Ranjith Santhosh Kumar DS (2019) Facile green synthesis of gold nanoparticles from marine alga Gelidiella acerosa and evaluation of its biological Potential. SN Appl Sci 1:284.
https://doi.org/10.1007/s42452-019-0284-z

222. Seydi N, Saneel S, Jalalvand AR, et al (2019) Synthesis of titanium nanoparticles using Allium eriophyllum Boiss aqueous extract by green synthesis method and evaluation of their remedial properties. Appl Organomet Chem 33:e5191. https://doi.org/https://doi.org/10.1002/aoc.5191

223. Shaligram NS, Bule M, Bhamure R, et al (2009) Biosynthesis of silver nanoparticles using aqueous extract from the compactin producing fungal strain. Process Biochem 44:939–943.
https://doi.org/https://doi.org/10.1016/j.procbio.2009.04.009

224. Sharma JL, Dhayal V, Sharma RK (2021) White-rot fungus mediated green synthesis of zinc oxide nanoparticles and their impregnation on cellulose to develop environmental friendly antimicrobial fibers. 3 Biotech 11:269.
https://doi.org/10.1007/s13205-021-02840-6

225. Shi G, Li Y, Xi G, et al (2017) Rapid green synthesis of gold nanocatalyst for high-efficiency degradation of quinclorac. J Hazard Mater 335:170–177. https://doi.org/https://doi.org/10.1016/j.jhazmat.2017.04.042

226. Shirsat S, Kadam A, Naushad M, Mane RS (2015) Selenium nanostructures: microbial synthesis and applications. RSC Adv 5:92799–92811.
https://doi.org/10.1039/C5RA17921A

227. Shu M, He F, Li Z, et al (2020) Biosynthesis and Antibacterial Activity of Silver Nanoparticles Using Yeast Extract as Reducing and Capping Agents. Nanoscale Res Lett 15:14.
https://doi.org/10.1186/s11671-019-3244-z

228. Shunmugam R, Renukadevi Balusamy S, Kumar V, et al (2021) Biosynthesis of gold nanoparticles using marine microbe (Vibrio alginolyticus) and its anticancer and antioxidant analysis. J King Saud Univ - Sci 33:101260.
https://doi.org/https://doi.org/10.1016/j.jksus.2020.101260

229. Siddiqi KS, Husen A (2016) Green Synthesis, Characterization and Uses of Palladium/Platinum Nanoparticles. Nanoscale Res Lett 11:482.
https://doi.org/10.1186/s11671-016-1695-z

230. Silva-Vinhote NM, Caballero NED, de Amorim Silva T, et al (2017) Extracellular biogenic synthesis of silver nanoparticles by Actinomycetes from ammonic biomass and its antimicrobial efficiency. African J Biotechnol 16:2072–2082

231. Silva LP, da Rocha Vaz GM, Pupe JM, et al (2020) Green nanoparticles for biomedical and bioengineering applications. Nanoparticles their Biomed Appl 225–262

232. Silva TA, Andrade PF, Segala K, et al (2017) Silver nanoparticles biosynthesis and impregnation in cellulose acetate membrane for anti-yeast therapy. African J Biotechnol 16:1490–1500

233. Singaravelu G, Arockiamary JS, Kumar VG, Govindaraju K (2007) A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, Sargassum wightii Greville. Colloids Surfaces B Biointerfaces 57:97–101.
https://doi.org/https://doi.org/10.1016/j.colsurfb.2007.01.010
234. Singh I (2019) Biosynthesis of silver nanoparticle from fungi, algae and bacteria. Eur J Biol Res 9:45–56
235. Singh P, Kim YJ, Zhang D, Yang DC (2016) Biological Synthesis of Nanoparticles from Plants and Microorganisms. Trends Biotechnol. 34:588–599
236. Singh P, Pandit S, Jers C, et al (2021) Silver nanoparticles produced from Cedecea sp. exhibit antbiofilm activity and remarkable stability. Sci Rep 11:12619. https://doi.org/10.1038/s41598-021-92006-4
237. Sivaraj A, Kumar V, Sunder R, et al (2020) Commercial Yeast Extracts Mediated Green Synthesis of Silver Chloride Nanoparticles and their Anti-mycobacterial Activity. J Clust Sci 31:287–291. https://doi.org/10.1007/s10876-019-01626-4
238. Skalickova S, Baron M, Sochor J (2017) Nanoparticles biosynthesized by yeast: a review of their application. Kvas Prum 63:290–292
239. Soliman H, Elsayed A, Dyaa A (2018) Antimicrobial activity of silver nanoparticles biosynthesised by Rhodotorula sp. strain ATL72. Egypt J Basic Appl Sci 5:228–233. https://doi.org/10.1016/j.ejbas.2018.05.005
240. Sonbol H, Ameen F, AlYahya S, et al (2021) Padina boryana mediated green synthesis of crystalline palladium nanoparticles as potential nanodrug against multidrug resistant bacteria and cancer cells. Sci Rep 11:5444. https://doi.org/10.1038/s41598-021-84794-6
241. Soni N, Prakash S (2012) Synthesis of gold nanoparticles by the fungus Aspergillus niger and its efficacy against mosquito larvae. Reports Parasitol 2:1–7
242. Sowbarnika R, Anhuradha S, Preetha B (2018) Enhanced Antimicrobial Effect of Yeast Mediated Silver Nanoparticles Synthesized From Baker’s Yeast. Int J Nanosci Nanotechnol 14:33–42
243. Spyridopoulou K, Tryfonopoulou E, Aindelis G, et al (2021) Biogenic selenium nanoparticles produced by Lactobacillus casei ATCC 393 inhibit colon cancer cell growth in vitro and in vivo. Nanoscale Adv 3:2516–2528
244. Sriramulu M, Balaji, Sumathi S (2021) Photo Catalytic, Antimicrobial and Antifungal Activity of Biogenic Iron Oxide Nanoparticles Synthesised Using Aegle marmelos Extracts. J Inorg Organomet Polym Mater 31:1738–1744. https://doi.org/10.1007/s10904-020-01812-2
245. Subramaniyan SA, Sheet S, Vinothkannan M, et al (2018) One-pot facile synthesis of Pt nanoparticles using cultural filtrate of microgravity simulated grown P. chrysogenum and their activity on bacteria and cancer cells. J Nanosci Nanotechnol 18:3110–3125
246. Sun D, Liu Y, Yu Q, et al (2014) Inhibition of tumor growth and vasculature and fluorescence imaging using functionalized ruthenium-thiol protected selenium nanoparticles. Biomaterials 35:1572–1583. https://doi.org/10.1016/j.biomaterials.2013.11.007
247. Sun X, Li S, Cao J, et al (2021) A Hierarchical-Structured Impeller with Engineered Pd Nanoparticles Catalyzing Suzuki Coupling Reactions for High-Purity Biphenyl. ACS Appl Mater Interfaces 13:17429–17438
248. Suryavanshi P, Pandit R, Gade A, et al (2017) Colletotrichum sp.- mediated synthesis of sulphur and aluminium oxide nanoparticles and its in vitro activity against selected food-borne pathogens. LWT - Food Sci Technol 81:188–194. https://doi.org/https://doi.org/10.1016/j.lwt.2017.03.038
249. Syed A, Ahmad A (2012) Extracellular biosynthesis of platinum nanoparticles using the fungus Fusarium oxysporum. Colloids Surfaces B Biointerfaces 97:27–31. https://doi.org/https://doi.org/10.1016/j.colsurfb.2012.03.026
250. Sytu MRC, Camacho DH (2018) Green Synthesis of Silver Nanoparticles (AgNPs) from Lenzites betulina and the Potential Synergistic Effect of AgNP and Capping Biomolecules in Enhancing Antioxidant Activity. Bionanoscience 8:835–844. https://doi.org/10.1007/s12668-018-0548-x
251. Thirumoorthy GS, Balasubramaniam O, Kumaresan P, et al (2021) Tetraselmis indica Mediated Green Synthesis of Zinc Oxide (ZnO) Nanoparticles and Evaluating Its Antibacterial, Antioxidant, and Hemolytic Activity. Bionanoscience 11:172–181. https://doi.org/10.1007/s12668-020-00817-y

252. Thomas PD (2017) Actinomycetes synthesized nanoparticles and their antibacterial activity. Res J Sci Technol 9:219–223

253. Uthaman A, Lal HM, Thomas S (2021) Fundamentals of Silver Nanoparticles and Their Toxicological Aspects BT - Polymer Nanocomposites Based on Silver Nanoparticles: Synthesis, Characterization and Applications. In: Lal HM, Thomas S, Li T, Maria HJ (eds). Springer International Publishing, Cham, pp 1–24

254. Vanlalveni C, Rajkumari K, Biswas A, et al (2018) Green Synthesis of Silver Nanoparticles Using Nostoc linckia and its Antimicrobial Activity: a Novel Biological Approach. Bionanoscience 8:624–631. https://doi.org/10.1007/s12668-018-0520-9

255. Varma RS (2016) Greener and sustainable trends in synthesis of organics and nanomaterials

256. VASANTHI BATHRINARAYANAN P, THANGAVELU D, MUTHUKUMARASAMY VK, et al (2013) Biological synthesis and characterization of intracellular gold nanoparticles using biomass of Aspergillus fumigatus. Bull Mater Sci 36:1201–1205. https://doi.org/10.1007/s12034-013-0599-0

257. Vaseghi Z, Nematollahzadeh A, Tavakoli O (2018) Green methods for the synthesis of metal nanoparticles using biogenic reducing agents: a review. Rev Chem Eng 34:529–559

258. Venil CK, Malathi M, Velmurugan P, Renuka Devi P (2021a) Green synthesis of silver nanoparticles using canthaxanthin from Dietzia maris AURCCBT01 and their cytotoxic properties against human keratinocyte cell line. J Appl Microbiol 130:1730–1744. https://doi.org/10.1111/jam.14889

259. Venil CK, Usha R, Devi PR (2021b) Green synthesis of nanoparticles from microbes and their prospective applications. In: Nanomaterials. Elsevier, pp 283–298

260. Venkatesan J, Kim S-K, Shim MS (2016) Antimicrobial, Antioxidant, and Anticancer Activities of Biosynthesized Silver Nanoparticles Using Marine Algae Ecklonia cava. Nanomater. 6

261. Venkatesan J, Manivasagan P, Kim S-K, et al (2014) Marine algae-mediated synthesis of gold nanoparticles using a novel Ecklonia cava. Bioprocess Biosyst Eng 37:1591–1597. https://doi.org/10.1007/s00449-014-1131-7

262. Vetchinkina E, Loshchinina E, Kupryashina M, et al (2019) Shape and Size Diversity of Gold, Silver, Selenium, and Silica Nanoparticles Prepared by Green Synthesis Using Fungi and Bacteria. Ind Eng Chem Res 58:17207–17218. https://doi.org/10.1021/acs.iecr.9b03345

263. Vetchinkina E, Loshchinina E, Kupryashina M, et al (2018) Green synthesis of nanoparticles with extracellular and intracellular extracts of basidiomycetes. PeerJ 6:e5237

264. Virkutyte J, Varma RS (2011) Green synthesis of metal nanoparticles: biodegradable polymers and enzymes in stabilization and surface functionalization. Chem Sci 2:837–846

265. Wang D, Xue B, Wang L, et al (2021) Fungus-mediated green synthesis of nano-silver using Aspergillus sydowii and its antifungal/antiproliferative activities. Sci Rep 11:10356. https://doi.org/10.1038/s41598-021-89854-5

266. Weir A, Westerhoff P, Fabricius L, et al (2012) Titanium dioxide nanoparticles in food and personal care products. Environ Sci Technol 46:2242–2250

267. Yadav A, Kon K, Kratosova G, et al (2015) Fungi as an efficient mycosystem for the synthesis of metal nanoparticles: progress and key aspects of research. Biotechnol Lett 37:2099–2120. https://doi.org/10.1007/s10529-015-1901-6

268. Yadav VK, Khan SH, Malik P, et al (2020) Microbial synthesis of nanoparticles and their applications for wastewater treatment. In: Microbial Biotechnology: Basic Research and Applications. Springer, pp 147–187
269. Yamada M, Foote M, Prow TW (2015) Therapeutic gold, silver, and platinum nanoparticles. Wiley Interdiscip Rev Nanomedicine Nanobiotechnology 7:428–445

270. Yantcheva NS, Karashanova DB, Georgieva BC, et al (2019) Characterization and application of spent brewer's yeast for silver nanoparticles synthesis. Bulg Chem Commun 173

271. Yu X, Li J, Mu D, et al (2021) Green synthesis and characterizations of silver nanoparticles with enhanced antibacterial properties by secondary metabolites of Bacillus subtilis (SDUM301120). Green Chem Lett Rev 14:190–203. https://doi.org/10.1080/17518253.2021.1894244

272. Zare EN, Padil VVT, Mokhtari B, et al (2020) Advances in biogenically synthesized shaped metal-and carbon-based nanoarchitectures and their medicinal applications. Adv Colloid Interface Sci 102236

273. Zawadzka K, Felczak A, Nowak M, et al (2021) Antimicrobial activity and toxicological risk assessment of silver nanoparticles synthesized using an eco-friendly method with Gloeophyllum striatum. J Hazard Mater 418:126316. https://doi.org/https://doi.org/10.1016/j.jhazmat.2021.126316

274. Zhang L, Zhao P, Yue C, et al (2019) Sustained release of bioactive hydrogen by Pd hydride nanoparticles overcomes Alzheimer's disease. Biomaterials 197:393–404

275. Zhang X, He X, Wang K, Yang X (2011) Different active biomolecules involved in biosynthesis of gold nanoparticles by three fungus species. J Biomed Nanotechnol 7:245–254

276. Zhao Y, Li C, Liu X, et al (2007) Synthesis and optical properties of TiO2 nanoparticles. Mater Lett 61:79–83

277. Zhuge W, Tan X, Zhang R, et al (2019) Fluorescent and colorimetric immunoassay of nuclear matrix protein 22 enhanced by porous Pd nanoparticles. Chinese Chem Lett 30:1307–1309

278. Zonooz NF, Salouti M, Shapouri R, Nasseryan J (2012) Biosynthesis of Gold Nanoparticles by Streptomyces sp. ERI-3 Supernatant and Process Optimization for Enhanced Production. J Clust Sci 23:375–382. https://doi.org/10.1007/s10876-012-0439-1

Figures

**Figure 1**

Assorted methods for the synthesis of nanoparticles (reproduced from Ref. (Jadoun et al. 2021) with permission)

**Figure 2**

The number of articles published on green synthesis of nanoparticles using algae, fungi, bacteria, yeast, and other microorganisms over the last decades (Data from the ISI Web of Knowledge database).

**Figure 3**

Flowchart of microbial synthesis of nanoparticles and their applications.
Figure 4

Schematic representation of scheme of green synthesis of nanoparticles (nanorods, nanowires, nanoconjugates, and nanotubes) via microbes (bacteria, fungi, algae, yeast, and virus) (Reproduced from Ref. (Gahlawat and Choudhury 2019) with permission)

Figure 5

Schematic representation of the intracellular synthesis of nanoparticles by microorganisms. (NP – nanoparticles, N – nucleus, +ve = ions, −ve = charges on the cell wall

Figure 6

Green synthesis of Ag/AgCl nanoparticles derived from Chara vulgaris algae extract and its antibacterial applications (Reproduced from Ref. (Hassan et al. 2021a) with permission)

Figure 7

Microwave-assisted green synthesis of Ag NPs using crude extracts of Boletus edulis and Coriolus versicolor. Characterization, anticancer, antimicrobial and wound healing activities (Kaplan et al. 2021)

Figure 8

Proposed scheme for green synthesis of silver (Ag) nanoparticles using yeast extract and antibacterial activity. (Reproduced from Ref. (Shu et al. 2020) with permission)

Figure 9

The schematic diagram for the synthesis of silver (Ag) by using (a) Bacteria (b) Fungi (c) Algae (Reproduced from Ref. (Rafique et al. 2017) and (Arya et al. 2019) with permission)

Figure 10

Green synthesis of Ag NPs using Enterobacter sp. (i) Observation of supernatant and UV-Visible spectra for the synthesis of Ag NPs (a) control supernatant of Enterobacter sp. (SMP1) (a1) Control 1.5 mM AgNO₃ solution (b) Development of brown color after the addition of supernatant to AgNO₃ solution indicated the formation of nanoparticles (c) the appearance of Ag NPs peak at 450 nm in UV-vis absorption spectrum is a characteristic peak of Ag NPs assigned to surface Plasmon resonance of the particles. (ii) (a1 and b) Spherical morphology of Ag NPs by
TEM images. X-ray elemental mapping of (a2) Ag (red), (a3) nitrogen (blue), (a4) carbon (green), (a5) oxygen (yellow), and (a6) sulfur (orange) in which the area covered by Ag NPs is shown with the pink dotted line and the presence of characteristic elements are shown by intense color for respective elements detected (c) the crystalline nature of Ag NPs is shown by X-ray diffraction pattern and (d) the presence of silver is shown by energy dispersive spectroscopy (EDS) spectrum (Reproduced from Ref. (Ashraf et al. 2020) with permission)

**Figure 11**

Applications of Ag NPs in different fields (a) catalytic behavior of Ag NPs in the synthesis of benzimidazoles (b) antibacterial activity of Ag NPs against standard and multi-drug resistance strains. (Reproduced from Ref. (Arya et al. 2019) and (Nazari and Jookar Kashi 2021) with permission)

**Figure 12**

Representation for the synthesis of Au NPs from alga *Gelidiella acerosa* and its alpha-glucosidase enzyme inhibition property (Reproduced from Ref. (Senthilkumar et al. 2019) with permission)

**Figure 13**

Green synthesis of Au nanocatalyst for (a) high-efficiency degradation of quinclorac (b) decolorization of azo dye (Reproduced from Ref. (Shi et al. 2017) and (Qu et al. 2017b) with permission)

**Figure 14**

Antiproliferative activity of Au NPs against colon cancer cell lines. (A) Observation of cytotoxicity of Au NPs comparison with a standard (B) Morphological observation of HCA-7 cell line by the treatment of Au NPs (Reproduced from Ref. (Shunmugam et al. 2021) with permission).

**Figure 15**

Green synthesis of Pt NPs (a) using microorganisms as reducing and capping agent, the change in color and its spherical morphology (b) two-cycle two-electron mechanism for bioreduction Pt NPs (c) Size distribution of *Neurospora crassa* assisted Pt NPs (Reproduced from Ref. (Govender et al. 2009; Castro-Longoria et al. 2012; Puja and Kumar 2019) with permission)

**Figure 16**
Antioxidant activity of Pt NPs synthesized using various microbial strains (ADR19 - *Pseudomonas kunmingensis*; FZC6 - *Psychrobacter faecalis*; B11177 - *Vibrio fischeri*; ZC15 - *Jeotgalicoccus coquinae*; KC19 - *Sporosarcina psychrophila*; MN23 - *Kocuria rosea*; KT2440 - *Pseudomonas putida*; CCV1 - *Rhodotorula mucilaginosa*) (Reproduced from Ref. (Eramabadi et al. 2020) with permission)

**Figure 17**

Green synthesis of Pd NPs using *Botryococcus braunii* algal extract (Reproduced from Ref. (Anju et al. 2020) with permission)

**Figure 18**

Biosynthesis of Cu NPs using *Escherichia sp.* (Reproduced from Ref. (Noman et al. 2020) with permission)

**Figure 19**

Anti-biofilm activity of the CuO NPs against Gram-positive and Gram-negative strains. (a) against *Staphylococcus aureus* (b) against *Pseudomonas aeruginosa* (c) Antibacterial activity for CuO NPs against different pathogenic bacteria at (5 mg/mL) (d) wastewater treatment by Cu NPs synthesized using *Escherichia sp.* (Reproduced from Ref. (Noman et al. 2020) and (Mohamed et al. 2021) with permission)

**Figure 20**

Microbial synthesis of TiO$_2$ NPs using Bacillus sp. (Reproduced from Ref. (Moradpoor et al. 2021) with permission)

**Figure 21**

Antimicrobial activity and zone of inhibition of TiO$_2$ NPs against (a) *Staphylococcus aureus*, (b) *Escherichia coli*, (c) *Pseudomonas aeruginosa*, (d) *Klebsiella pneumoniae*, and (e) *Bacillus subtilis*. (Reproduced from Ref. (Rajakumar et al. 2012) with permission)

**Figure 22**

Systematic diagram for the (i) Sol-gel synthesis of ZnO NPs using *Periconium sp.* extract (ii) TEM images (a–e) of the ZnO NPs attained at various magnification and (f) their respective SAED (selected area electron diffraction) pattern (reproduced from Ref. (Ganesan et al. 2020) with permission).
Figure 23
Green synthesis of anisotropic ZnO NPs using *Bacillus megaterium*, the characteristic peak appeared in UV and cubic shape particles by TEM (Reproduced from Ref. (Saravanan et al. 2018) with permission)

Figure 24
The antioxidant activity of biogenic ZnO NPs via *Marinobacter* sp. 2C8 and *Vibrio* sp at different concentrations where ascorbic acid was used as a standard (Reproduced from Ref. (Barani et al. 2021) with permission)

Figure 25
Flowchart for green synthesis of Fe$_2$O$_3$ NPs by fungi (Reproduced from Ref. (Mahanty et al. 2019) with permission)

Figure 26
Applications of Fe$_2$O$_3$ NPs in antibacterial and dye degradation (a) mechanism of antibacterial activity of *Aegel marmelos* mediated iron oxide NPs (b) antibacterial activity of iron oxide NPs against *Escherichia coli* and *Staphylococcus aureus* (c) UV–Visible analysis of brilliant blue dye degradation with time (d) % of degradation (e) kinetics study of brilliant blue dye degradation using iron oxide NPs (Reproduced from Ref. (Sriramulu et al. 2021) with permission)

Figure 27
Pictorial representation of the green synthesis of SeS NPs by Saccharomyces cerevisiae along with its properties, antifungal activity, and cytotoxicity (Reproduced from Ref. (Asghari-Paskiabi et al. 2019) with permission)

Figure 28
The numerous therapeutic and other benefits of Se NPs

Figure 29
Comparative anti-oxidant assays of ascorbic acid, B-SeNPs (biologically synthesized Se NPs), and C-SeNPs (chemically synthesized Se NPs) (a) DPPH scavenging assay (b) SOR scavenging assay (c) ABTS assay (d) FRAP assay (Reproduced from Ref. (Afzal et al. 2021) with permission)