

NANO REVIEW

Open Access



Current Strategies for Noble Metal Nanoparticle Synthesis

Giyauallah Habibullah, Jitka Viktorova* and Tomas Ruml

Abstract

Noble metals have played an integral part in human history for centuries; however, their integration with recent advances in nanotechnology and material sciences have provided new research opportunities in both academia and industry, which has resulted in a new array of advanced applications, including medical ones. Noble metal nanoparticles (NMNPs) have been of great importance in the field of biomedicine over the past few decades due to their importance in personalized healthcare and diagnostics. In particular, platinum, gold and silver nanoparticles have achieved the most dominant spot in the list, thanks to a very diverse range of industrial applications, including biomedical ones such as antimicrobial and antiviral agents, diagnostics, drug carriers and imaging probes. In particular, their superior resistance to extreme conditions of corrosion and oxidation is highly appreciated. Notably, in the past two decades there has been a tremendous advancement in the development of new strategies of more cost-effective and robust NMNP synthesis methods that provide materials with highly tunable physicochemical, optical and thermal properties, and biochemical functionalities. As a result, new advanced hybrid NMNPs with polymer, graphene, carbon nanotubes, quantum dots and core-shell systems have been developed with even more enhanced physicochemical characteristics that has led to exceptional diagnostic and therapeutic applications. In this review, we aim to summarize current advances in the synthesis of NMNPs (Au, Ag and Pt).

Keywords: Noble metal nanoparticles, Personal healthcare, Therapeutics, Diagnostics, Biomedical applications

Introduction

Noble metals have been in use for a very long time, dating back to the first Egyptian civilization, and have always been viewed as a sign of superior power and wealth. As a result, they can be seen in history in the form of expensive artworks, coins, jewels, etc. [1]. These metals generally tend to be more expensive than others because of their availability in the Earth's crust [2, 3]. Due to their robust nature, resistance to extreme conditions of corrosion and oxidation, they have been widely used in the aerospace, automotive, chemical, energy, electrical and electronics industry and more importantly healthcare (from surgical equipment to contrast enhancers in imaging) [4, 5].

Over the past two decades, nanotechnology has proven to be the most promising future technology, offering countless possibilities. Multidisciplinary support from academic and industrial sectors has made it the most rapidly expanding field, with highly promising outcomes [6–8]. Currently, the technological leap in synthesizing and controlling metals at the nanoscale level has provided immense research opportunities to progress in personalized healthcare, diagnostics and therapies [9–11]. Metal nanoparticles (MNPs) have turned out to be the most commonly and broadly studied because of their impressive physicochemical properties and large surface-to-volume ratio compared to their bulk material (metal). As for biomedical applications, NMNPs became a natural pick due to their resistance to harsh environments. They have been applied in highly sensitive diagnostic assays, as thermal ablation enhancers in radiotherapy, and as drug and gene delivery vehicles [3, 12, 13].

*Correspondence: prokesoj@vscht.cz

Department of Biochemistry and Microbiology, University of Chemistry and Technology Prague, Technická 5, 166 28 Prague, Czech Republic

The recent merging of nanotechnology with material sciences has resulted in the development of new nanocomposite materials with highly enhanced thermal, catalytic, electrical, optical and mechanical properties compared to the individual components. Notably, composites made of NMNPs have gained a great deal of research interest because of their impressive physicochemical properties that play a vital role in modifying the nanoscale building blocks and result in wide applications in catalysis (mainly electrocatalysis), optics, nanomedicine and environmental protection [14–17]. Noble metals in the colloidal state have been the subject of intensive studies, mainly due to their effectiveness in therapeutics and diagnostics [2, 18]. Similarly, improvements in the synthesis of materials such as graphene oxide and reduced graphene oxide [14, 19, 20], quantum dots [21–23] and carbon nanotubes [24–26] has contributed to more feasible and effective methods for the formation of NMNCs.

Due to the small size of Au and PtNPs and NMNPs, their large surface area-to-volume ratio and ability to assist in high electron transfer processes, they are ideal candidates for applications as electrochemical sensors [27–29]. The optical properties of NMNPs have served as a topic for many studies, especially Ag and AuNPs. These NPs are able to respond differently to different wavelengths of light (extensive scattering from the visible region to the near infrared region with Au), and so they are applied as signal enhancers in surface-enhanced Raman spectroscopy (SERS), localized surface plasmon resonance and other resonance scattering spectroscopy [30–33]. Due to the extensively tunable optical properties and biocompatibility of AuNPs, they have been applied in the photothermal therapy and in vivo imaging (photoacoustic imaging) of tumors [34–36]. Recently, AgNPs have also exhibited their potential in photothermal therapy, where they are generally applied as Ag core-shell systems or composites (with reduced graphene oxide/ carbon nanotubes) [37–39]. The biocompatibility of NMNPs with cells and tissues has opened up broad applicability in diagnostics [14]. Biosensors of NMNPs and NMNCs (especially graphene) have played a key role in enhancements of accuracy and specificity that provide an advantage over existing biomolecular diagnostics methods [40, 41]. Generally, Au and PtNPs are employed in the development of novel biosensors and probes due to their ability to adsorb to the biomolecules along with their supreme conductivity and stability [42–45]. As a result, NMNPs themselves or in the form of NMNCs are applied as immunosensors [46], biomolecules for detection [47] and nanoprobe (for in vivo cell imaging, tracking and studying the pathogenesis of disease progression)

[2, 6, 48]. Despite all these advantages of NMNPs and NMNCs, there have still been many questions and debates concerning their safety profile in the human body [49–51].

In this review, we provide a survey on the synthesis methodologies of NMNPs (Ag, Au and Pt) and NMNCs (with Ag, Au and Pt) along with their current developments in biomedical applications as therapeutics and diagnostics, including the synergism exhibited by NMNCs with NMNPs in terms of improved performance, which is a current hot topic in materials research.

Current Trends in NMNPs Synthesis

Synthesis Methods of NMNPs

The preparation of NPs basically follows two different approaches, (1) top-down (destructive method) and (2) bottom-up (constructive method) (Fig. 1).

Top-down processes involve breaking bulk materials into smaller particles of nano-dimensions using various physical and chemical methods. In contrast, in the bottom-up approach, NPs are produced by the self-assembly of the atoms, the molecules or the clusters. Top-down approaches involve externally controlled processes of cutting, milling and shaping the materials into the desired order and shape. Several physical methods, such as pyrolysis [61, 62], nanolithography [63, 64], thermolysis [65] and radiation-induced methods [66–68] belong in this category. However, this approach comes with a major limitation, which is the imperfect surface structure of the resulting MNPs, which substantially affects their physical and chemical properties [1]. Moreover, this method requires an enormous amount of energy to maintain the high-pressure and high-temperature conditions during the synthetic procedure, making the process expensive.

In bottom-up methods, NPs are assembled from the corresponding atoms, clusters and molecules using chemical as well as biological procedures. The bottom-up approach has turned out to be advantageous, as it provides a far better control over the final product formation with more homogeneous size, shape (physical parameters) and chemical composition. Moreover, this approach in general is less expensive. The bottom-up approach is commonly a wet-chemical synthesis procedure, such as chemical [69, 70], electrochemical [71–73], sonochemical [74, 75] and green synthesis [76, 77]. In the bottom-up approach, the purification of the synthesized particles from their reaction mixture (toxic chemicals, organic solvents and reagents) is a major challenge that casts doubt on their biomedical applications except for green synthesis methods.

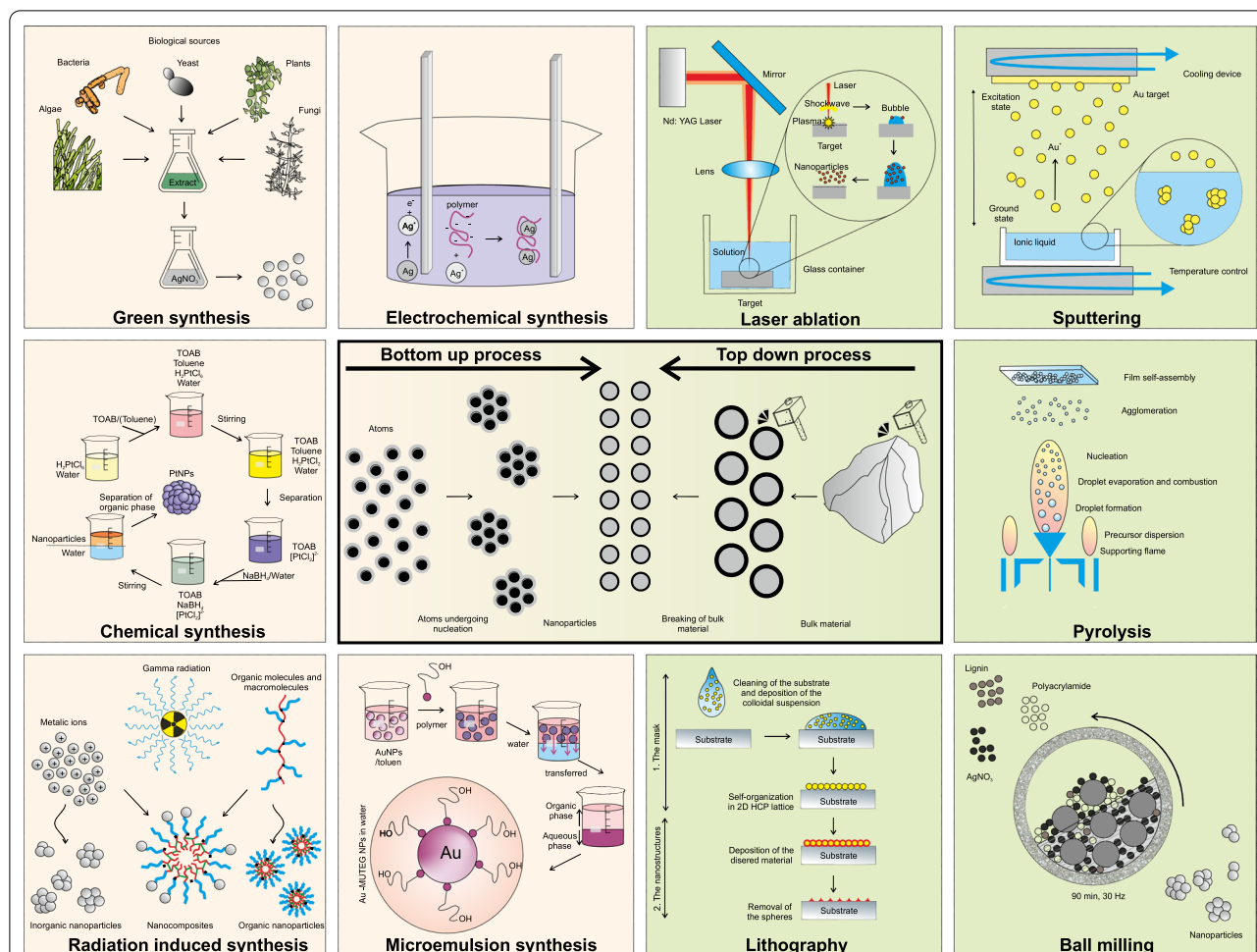


Fig. 1 Schematic representation of the top-down (images with the green background) and bottom-up (images with pale yellow background) approaches of nanoparticle synthesis, the image was adapted and redrawn from [52–60]

Top-Down Approaches

Sputtering

Sputtering is one of the most commonly used synthesis protocols that includes the deposition of NPs as a thin layer generated by the collision of ions over the substrate and followed by annealing. This method is also referred as the physical vapor deposition (PVD) method [78, 79]. The efficiency of this method mainly depends on factors such as layer thickness, substrate type, annealing duration and temperature, which directly influence the size and shape of the NPs [55, 80, 81].

Micropatterning

Micropatterning, a popular technique employed in biosensors, microarrays, tissue engineering and cellular studies [82], is also used in the synthesis of MNPs. In general, this technique is equivalent to a printing process in which a material is cut or formed into the required shape and size either with a light or electron beam for

the synthesis of nanostructured arrays from an appropriate precursor. This is a low-temperature, non-vacuum method that uses photolithography for the synthesis of MNPs, employing the laser sintering of MNP ink [83, 84]. Apart from photolithography, numerous lithography techniques have been developed such as scanning, soft nanoimprinting, colloidal, nanosphere and E-beam lithography [2, 57, 85, 86].

Milling

Milling is generally represented as the public face of top-down processes, as it involves the direct breaking of bulk materials into micro/nanostructures. In mechanical milling, the kinetic energy of the rollers/balls is transferred to the bulk material, which results in the reduction in grain size [87]. Parameters such as the type of mill, milling atmosphere, milling media, intensity, time and temperature play a crucial role in controlling the shape and size of the NPs [88, 89]. Different techniques have

been developed in order to overcome these constraints, including shaker mills, tumbler mills, vibratory mills, attrition mills and planetary mills.

Laser Ablation

Laser ablation is one of the methods that is considered to be a suitable replacement for conventional chemical methods due to its fast processing times, providing better control over the size and shape of the particles and high yields with better long-term stability [78, 90–92]. In a laser ablation process, a solid surface (generally a plate of pure metal) is irradiated with a laser beam, leading to a low-flux plasma plume, which is finally evaporated or sublimated to form NPs [93]. At a higher flux, the materials are converted to plasma. The lack of requirement to remove excess reagents as well as the possibility of metal nanoparticle synthesis in both aqueous and organic solvents has enabled the implementation of the laser ablation method in biomedical applications such as the in situ conjugation of biomolecules with MNPs, which has been proved to be more effective than standard techniques [54, 94, 95].

Pyrolysis

Thermal decomposition is another important technique commonly used separately or in combination with other physical methods for MNP synthesis [78]. It is an endothermic chemical decomposition process that uses heat to break the compound's chemical bonds, resulting in decomposition of the precursor, forcing it into a chemical reaction producing NPs along with other by-products in the form of ash. Through further processing of the obtained solid ash, NPs are recovered. Pyrolysis is frequently used for the preparation of noble MNPs [56, 96, 97]. Excessive energy consumption is one of the most important drawbacks of this method.

Chemical Vapor Deposition

This method is also known as the vacuum deposition method, where the gaseous reactant is deposited as a thin film onto a substrate along with a combination of other gas molecules that promote superheating of the substrate. During the reaction, the substrate comes in contact with the combined gases, leading to reduction of the ions [78]. The product of this reaction is usually in the form of a film which the NPs need to be scraped out from. The method produces highly pure, uniform and nonporous nanoparticles; as a result, this method has become highly important in the electronics and semiconductor industry. Despite these huge advantages, this method suffers from some major disadvantages: The requirement for special equipment for making the films and chambers for the

reaction, and the fact that the gaseous by-products of this reaction are extremely toxic [98].

Bottom-Up Approaches

Reduction of Metal Ions in Solution

This approach involves the reduction of metal ions from their ionic salts by using various chemical reducing agents in the presence of a stabilizing agent under favorable reaction parameters (pH, temperature, etc.). This procedure is the most common and reliable method of all the bottom-up approaches due to its sheer simplicity [2, 99]. An extensive list of a number of reducing agents is available for this process that includes commonly used sodium citrate [10, 100], tannic acid [99], sodium borohydride [101], hydrazine, hydrogen, lithium aluminum hydride, and alcohols can also be used [2, 60]. Similarly, when it comes to stabilizing agents there are many options, and they generally fall into two categories (1) low-molecular-weight (e.g., citrate, SDS, chitosan, etc.) and (2) high-molecular-weight ones (e.g., starch, tween, PVP, PEG, DISPERBYK, etc.). The low-molecular-weight stabilizers (generally charged detergents) have the tendency to alter the surface charge of the synthesized particles and maintain the repulsive force between them, preventing aggregation; this type of stabilizer generally does not protect well against environmental stress factors (especially changes in storage temperature and light exposure). High-molecular-weight stabilizers generally engulf the particles and protect them from environmental stresses. They have been shown to be more efficient than the low-molecular-weight stabilizers. Despite their advantages, their biological applications and catalytic properties are questionable due to the thick layer of stabilizing agent over the particles that prevents their dissolution [102, 103]. In terms of homogeneity in particle size and shape, the clear winner is the chemical-based reduction. This is because reduction can be easily regulated by changing the reaction parameters (pH and the ratio between the reducing and the stabilizing agent). Tyagi and his team produced AuNPs [104] using the citrate reduction method at room temperature, at pH 3 with 2:1 and 5:1 molar ratios of citrate to AuCl₃ of, yielding particles with an average size of 28 and 25 nm, respectively. At this pH, the reaction was much faster than at other pH values. They also showed that AuNPs of different shapes such as prisms, rods and spheres were formed at pH values ranging from 3 to 6 (with a 2:1 molar ratio of citrate to AuCl₃). In another study by Agnihotri and coworkers [105], who applied a similar citrate reduction method for the synthesis of AgNPs, obtained particles with an average size of 5 nm at the highest concentration of sodium citrate (4.28×10^{-3} mol dm⁻³). Their size increased at elevated concentrations of citrate (to 100 nm

at 1.77×10^{-2} mol dm⁻³). Another study by Hou et al. [106] described the synthesis of highly stable and mono-dispersed Pt nanoparticles in the form of hydrosols for electrocatalytic applications.

Microemulsion

The fabrication of metal NPs based on microemulsions is becoming a topic of great interest, and it has also emerged as an effective method that provides better control over the physical aspects of the synthesized nanoparticles such as size and shape. In general, microemulsions are simply mixtures of two immiscible liquids in the presence of a surfactant. These systems generally have ultralow interfacial tension, a large interfacial area and thermodynamic stability [107]. The first microemulsion-based synthesis of NMNPs was described by the team of Muñoz-Flores et al. [58, 108, 109] who synthesized platinum, palladium and rhodium NPs. In the microemulsion-based NPs synthesis, two separate microemulsions are prepared, one containing the ionic salt and another containing the reducing agent produced in an amphiphilic environment. The collision between the emulsions leads to the mixing of the reactants and reduces the ions from the salt to neutral atoms, which then form nanoparticles [2]. Water-in-oil systems are generally employed for the synthesis of metal nanoparticles, and as the nanoparticles produced by this method are derived in the form of emulsions, they are generally thermodynamically stable. Depending on the need, this process could be also tailored to synthesize a specific type of nanoparticle by altering the ratio of the surfactant to oil. This makes it possible enables to control the size and shape of the particles [110].

Electrochemical Methods

Electrochemical processes are commonly employed for the synthesis of NMNPs and nanocomposites, which are mostly used for their catalytic properties and have recently been used in biomedical applications as biosensors [111]. The electrochemical method was first introduced in 1994 by Reetz and Helbig, who dissolved a pure metal sheet from the anode to achieve the deposition of metal salt on the cathode of an electrochemical cell in the presence of an electrolyte to produce nanoparticles [2, 112]. The effectiveness of this method depends on various parameters such as the nature of the reducing agent, the purity of the metal and the stabilizer, choice of the electrolyte, concentration ratio and temperature, which directly impact the physical parameters of the NPs [53]. At present, the synthesis of nanocomposites (especially those with graphene) using electrochemical methods is preferred to the synthesis of NPs [113].

Radiation-Induced Synthesis Methods

This method employs ionizing radiation (especially gamma radiation and includes X-rays and UV-light) for the synthesis of metal nanoparticles. It has been proved to be highly efficient compared to the conventional methods of NP synthesis, as it provides fully reduced, highly pure (by-product free) metal nanoparticles. The topic has been nicely covered in several reviews [59, 66, 114, 115]. In this process, an aqueous solution of reducing and stabilizing agent is exposed to radiation-mediated radiolysis, which leads to the formation of NPs. During the radiation exposure, the water molecules break up, yielding transient products that act as strong oxidizing or reducing agents and reduce metal ions to neutral metal atoms, which further nucleate to form NPs. The synchrotron X-ray techniques enabled monitoring of the growth trajectories of colloidal NPs in real time [116]. The physical parameters critical for the synthesis of NPs include the radiation dose, pH of the system and the type of solvent used in the synthesis [117]. Recently, radiation-induced synthesis was used for the production of tween 80 stabilized AgNPs for antibacterial applications [118].

Microwave-Induced Green Synthesis Methods

Generally, microwave-assisted synthesis is also known as one-pot synthesis and involves the synthesis of NPs from salts and surfactant solutions. It is a highly reliable, fast and easy method that supports control over the morphology of the synthesized NPs [2]. This method works on the principle of dipole interaction (molecules tend to align themselves and oscillate in step with the oscillating electrical field of the microwaves, collision and friction between them causes heat) and ionic conduction (The electric field generates ionic motion as the molecules try to orient themselves to the rapidly changing field, causing instantaneous super heating) producing a heating effect that results in the reduction of metal ions to NPs [119, 120]. The microwave irradiation time and the concentration of the reactant mainly determine the morphological parameters of the NPs. Recently, physical properties such as monodispersity and grain size of superparamagnetic magnetite NPs prepared by microwave-assisted synthesis were controlled by the injection of humate-polyanion at different stages of the synthesis [121]. Microwave-induced electric discharge was used also for the synthesis of Cu, Ni, und Zn nanoparticles from metal particles in the absence of solvents or surfactants [122].

Green Synthesis Methods

The excessive use of chemicals in chemical synthesis has almost jeopardized the future of biological applications of NMNPs. This resulted in the exploration

of other, ecological methods with a minimal use of chemicals. Green synthetic methods employing plant extracts, microorganisms and biopolymers have proven to be potent candidates for replacing chemical methods of NP synthesis (Fig. 2) [123]. Thanks to simpler and greener methodologies, there has been an exponential

increase in publications in the past two decades [52, 124, 125].

Biosystem Synthesis of NMNPS

The quest for the development of economically and environmentally benevolent methods has led to the

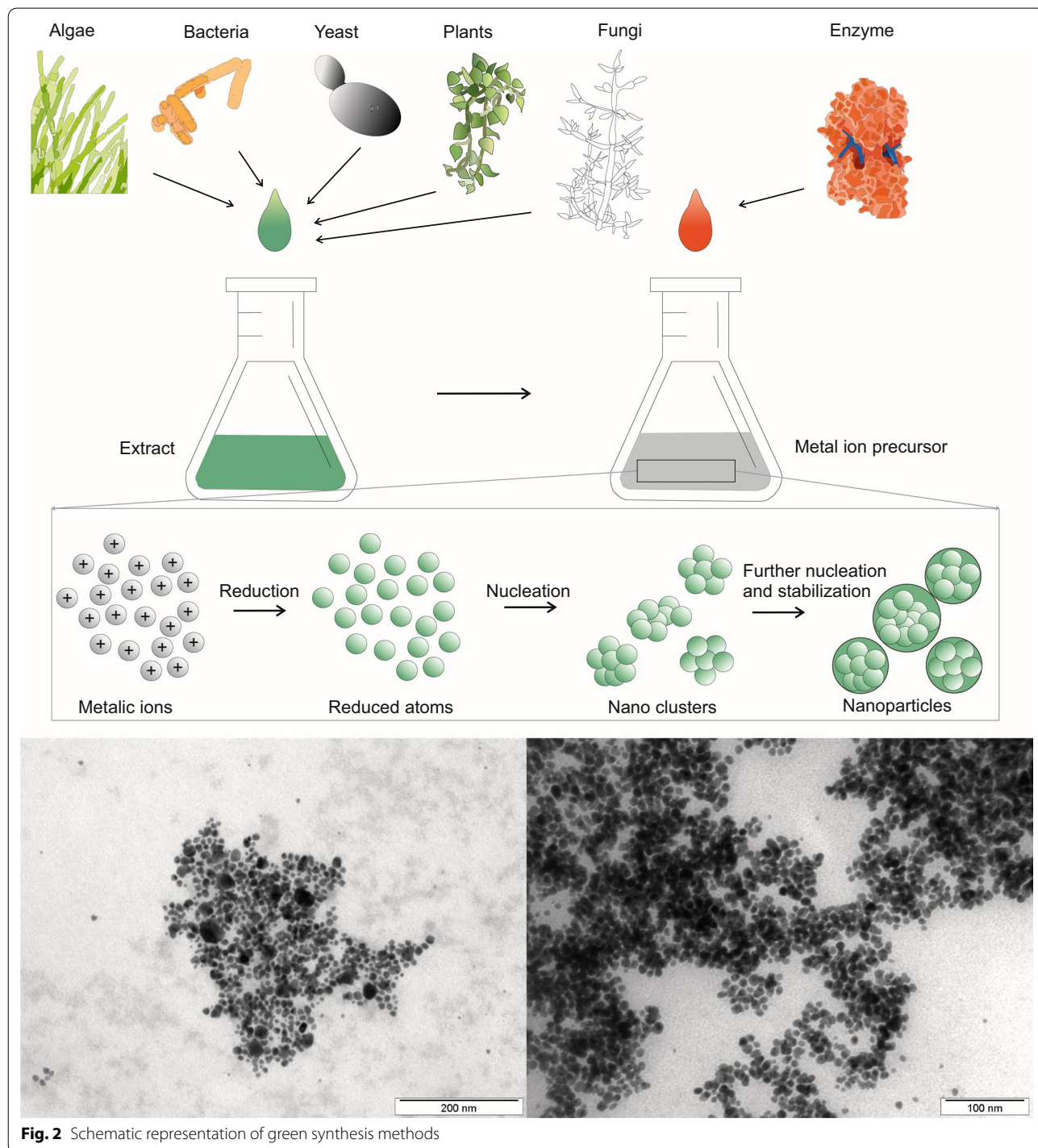


Fig. 2 Schematic representation of green synthesis methods

exploration of microorganisms as a potential candidate for the synthesis of nanoparticles [126, 127]. Biological systems are excellent examples of hierarchical organizations of atoms and molecules, which attract researchers to use microorganisms as potential cell factories for nanomaterial preparation. Both prokaryotic (bacteria) and eukaryotic (algae, fungi and plants) species are used for the green synthesis of NPs [123].

Bacteria-Based Synthesis of Nanoparticles Bacteria that have been repeatedly exposed to metal-rich environments have often developed resistance to these extreme conditions [128]. Thus, prokaryotes have become a natural choice for producing nanomaterials. *Pseudomonas stutzeri* AG259, a metal-accumulating bacterium isolated from a silver mine, was utilized by Klaus et al. [129] to create intracellular nanocrystals of metallic silver of up to 200 nm in size. The extracellular synthesis of NPs was first reported by Shahverdi and co-workers [130], where AgNPs were produced by the reduction of aqueous Ag^+ ions through various culture supernatants of Gram-negative bacteria, i.e., *Enterobacter cloacae*, *Escherichia coli* and *Klebsiella pneumoniae*. The synthesis rate was much faster than the intracellular synthesis, which resulted in Ag-NPs synthesis within 5 min of the Ag^+ ions encountering the cell filtrate. Extracellular reductase enzymes produced by the microorganisms, namely *Bacillus licheniformis* and *Bacillus clausii*, reduce the silver ions to neutral silver, resulting in nanosized particles. Protein assay of these microorganisms revealed that the NADH-dependent reductase enzyme plays a vital role in the bioreduction of silver ions to silver nanoparticles. The reductase enzyme gets its electrons from NADH oxidation to NAD^+ . During the oxidation, the enzyme also gets oxidized at the same time, resulting in the reduction of silver ions to AgNPs. In some cases, it has been observed that the nitrate-dependent reductase can also participate in the bio reduction [131–133]. In addition, several bacterial strains (gram-negative as well as gram-positive), namely *A. calcoaceticus*, *B. amyloliquefaciens*, *B. flexus*, *B. megaterium* and *S. aureus*, have also been used for both the extra- and intracellular biosynthesis of AgNPs [123]. Similarly, AuNPs and PtNPs are also prepared by the accumulation and reduction of gold and platinum salts by bacteria. *B. licheniformis*, *B. megaterium*, *Delftia sp* KCM-006., *Shewanella sp.*, *Stenotrophomonas maltophilia* and *Lactobacillus sp.* are some examples of bacteria which have been used to produce gold nanomaterials [134, 135]. In addition, the bacteria *Shewanella sp.* and *Acinetobacter calcoaceticus* PUCM 1011 were utilized for the preparation of PtNPs [136, 137]. Although bacteria-mediated synthesis is promis-

ing in terms of its green nature and control over the particle shape and size (mostly in extracellular synthesis), it suffers from disadvantages such as handling difficulties and low yields.

Fungus-Based Synthesis In recent years, NMNP synthesis with eukaryotic microorganisms has emerged as a better alternative to prokaryotes due to their high intracellular metal uptake capability, ability to synthesize NPs with different chemical compositions, ability to produce a large amount of enzymes per unit biomass and easy biomass handling at laboratory scale [131].

In general, fungi have the potential to synthesize metallic NPs due to their metal bioaccumulation capacity, their tolerance, high binding capacity and intracellular uptake like bacteria [127]. Fungi use both intracellular and extracellular methods for the synthesis of NPs, and extracellular synthesis is the most commonly reported synthesis mechanism due to their ability to produce large quantity of extracellular enzymes that convert Ag^+ ions to nanoscale silver particles [138–140]. In intracellular synthesis, Ag^+ ions are adsorbed to the cell surface by the electrostatic interaction between negatively charged carboxylate groups in enzymes and positively charged Ag^+ ions. Ag^+ ions are later reduced by the enzymes present in the cell wall to form AgNPs, in this process NPs are formed on the surface of mycelia, not in solution. In 2001, the intracellular preparation of AuNPs using *Verticillium sp* was first reported by Mukherjee et al. [141], where Au^{3+} ions from tetrachloroaurate were reduced within the fungal cells, resulting in the formation of particles within the size range of 20 nm. Vahabi and coworkers [142] employed *Trichoderma reesei* for AgNPs synthesis, where the media with biomass was inoculated with AgNO_3 and incubated over a period of 72 h, resulting in the formation of AgNPs in the size range of 5–50 nm. Similarly, another study by the team of Vigneshwaran et al. [138] demonstrated the intracellular synthesis of AgNPs from *Aspergillus flavus* and reported that enzymes in the cell wall were mainly responsible for the reduction, and the proteins were responsible for stabilization. Despite all these advantages such as faster synthesis, and better control over the size and shape of the synthesized particles, intracellular processes suffer from a huge disadvantage in terms of product recovery that makes the process hard and expensive, since NPs bind to the cell. As a result, extracellular synthesis is preferred. In extracellular synthesis, cell-free broth/suspension is used in the synthesis process that turns out to be more environmentally friendly and cost-effective. In 2016, the team of Balakumaran et al. [143] used a cell-free suspension of *Aspergillus terreus* for the synthesis of both Au and AgNPs, resulting in spherical nanoparticles in the

size range of 8–20 nm and 10–50 nm for Ag and AuNPs, respectively. FTIR evaluation of the particles confirmed the binding of proteins with the NPs.

Algae-Based Synthesis The algae-mediated synthesis of NPs utilizes four different methods: (1) whole algal cells are harvested from their culture media at a given phase of growth using centrifugation and then dispersed directly into an aqueous solution of the metallic salt; (2) cell-free aqueous extract made from freshly harvested or lyophilized cells; (3) an aqueous extract filtrate or supernatant of ground, fresh or dried algae; and (4) an aqueous filtrate of an algal broth. Extract-mediated synthesis is the most commonly reported algae-based synthesis mechanism [131, 144]. The accumulation of elemental gold in the form of AuNPs (9–20 nm) was noted with a dried cell suspension of *Chlorella vulgaris* by Hosea et al., who also reported an increase in the concentration of gold with time, proving the ability of the algal cells to uptake and reduce the gold ions from tetrachloroauric acid [145]. Velgosova and coworkers [146] reported on the synthesis of highly stable AgNPs from *Parachlorella kessleri*, a green algae aqueous extract, where the synthesized particles were in the size range of about 20 nm and exhibited excellent stability over a year. Other Algal sp, such as *Pithophora oedogonia*, *Sargassum wightii* and *Plectonema boryanum*, have been used successfully to construct Ag, Au and PtNPs, respectively [147–149].

Plant-Based Synthesis Plant- and plant extract-mediated synthesis has been the most commonly reported synthesis methodology [123, 135, 150]. This type of synthesis is designated phytosynthesis. The major advantage of this synthesis method is easy product recovery. In 2003, the team of Gardea-Torresdey et al. was the first to illustrate the synthesis of metal nanoparticles (AgNPs) using a living plant system with alfalfa sprouts (*Medicago sativa*) in an agar medium. The roots possess the tendency to absorb the Ag from the medium and transport it along the shoot of the system in the same oxidation state, in the shoot the Ag atoms are further arranged to form AgNPs. Similarly, another study employed the alfalfa plant secretome to reduce Au^+ to Au^0 , which also followed a similar procedure to produce AuNPs [151]. Plant-extract-mediated synthesis uses a plant component (leaves, stems, roots, shoots, flowers, barks and seeds) extract for the synthesis of NPs, the major advantage of this method is the ability of the extract to serve as both the reducing and stabilizing agent [152]. This method has been proved to be the most cost efficient and user friendly method to produce nanoparticles with long-term stability. In 2016, the team of Balashanmugam et al. demonstrated the phytogenic synthesis of AgNPs from *Cassia roxburghii* aqueous leaf

extract. The synthesized AgNPs were in the size range of about 35 nm and exhibited excellent stability over a year. This method also facilitated the synthesis of both individual and bimetallic particles. Neem (*Azadirachta indica*) leaf extract was successfully used by Shankar et al. [153] to prepare silver, gold and bimetallic Au/Ag core-shell NPs. Similar plant extracts (bark, leaf, fruit and gum) have been used by several researchers to produce a variety of NMNPs [153–155]. Currently, light-induced nanoparticles are in the spotlight, as this procedure facilitates faster synthesis during the exposure of the mixture to sunlight. Kumar et al. [156] used *Erigeron Bonariensis* aqueous leaf extract for the synthesis of silver nanoparticles that yielded spherical and oval-shaped AgNPs with a size range of 13 nm (TEM size). The crucial parameters to be considered in this synthesis are the light exposure time and the concentration of the plant extract in the reaction system.

Conclusion

Several physical, chemical as well as biological methods have been developed for the synthesis of NPs. All these processes are widely used based on the utility and applicability of the nanoproducts. However, each of the existing protocols suffers from certain drawbacks and also most of these processes cannot be scaled up for large-scale production. Thus, the development of alternative processes to fabricate NPs with controlled and tunable properties is still an open challenge.

Abbreviations

NM: Noble metals; NPs: Nanoparticles; NMNPs: Noble metal nanoparticles; AuNPs: Gold nanoparticles; AgNPs: Silver nanoparticles; PtNPs: Platinum nanoparticles; NMNCs: Noble metal composites; PVD: Physical vapor deposition; SDS: Sodium dodecyl sulfate; PVP: Polyvinylpyrrolidone; PEG: Polyethylene glycol; AuCl_3 : Gold chloride; NADH: Nicotinamide adenine dinucleotide; TEM: Transmission electron microscopy.

Acknowledgements

The authors thank Ben Watson-Jones, MEng., for providing language corrections.

Authors' contributions

All contributed to study design; GH contributed to manuscript writing, JV and TR to editing; JV contributed to figures preparation. All authors read and approved the manuscript.

Funding

The work was supported by the Czech National Program of Sustainability NPU I (LO) (MSMT-43760/2015). We declare no role of the funding body in the design of the study and collection, analysis, and interpretation of data and in writing the manuscript.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no conflicts of interest.

Received: 1 July 2020 Accepted: 11 January 2021
Published online: 15 March 2021

References

- Medici S, Peana M, Nurchi VM, Lachowicz JI, Crisponi G, Zoroddu MA (2015) Noble metals in medicine: latest advances. *Coord Chem Rev* 284:329–350
- Azharuddin M et al (2019) A repertoire of biomedical applications of noble metal nanoparticles. *Chem Commun* 55(49):6964–6996
- Conde J, Doria G, Baptista P (2012) Noble metal nanoparticles applications in cancer. *J Drug Deliv* 2012:1–12
- Balcerzak M (2015) Noble metals, analytical chemistry of. In: *Encyclopedia of analytical chemistry*. American Cancer Society, pp 1–29
- Zhang Z, Wang H, Chen Z, Wang X, Choo J, Chen L (2018) Plasmonic colorimetric sensors based on etching and growth of noble metal nanoparticles: Strategies and applications. *Biosens Bioelectron* 114:52–65
- Bhattacharyya S, Kudgus RA, Bhattacharya R, Mukherjee P (2011) Inorganic nanoparticles in cancer therapy. *Pharm Res* 28(2):237–259
- Nie S, Xing Y, Kim GJ, Simons JW (2007) Nanotechnology applications in cancer. *Annu Rev Biomed Eng* 9(1):257–288
- Du R, Jin X, Hübner R, Fan X, Hu Y, Eychmüller A (2020) Engineering self-supported noble metal foams toward electrocatalysis and beyond. *Adv Energy Mater* 10(11):1901945
- Sanvicens N, Marco MP (2008) Multifunctional nanoparticles—properties and prospects for their use in human medicine. *Trends Biotechnol* 6:425–433
- Slepička P, Slepičková Kasálková N, Siegel J, Kolská Z, Švorčík V (2019) Methods of gold and silver nanoparticles preparation. *Materials (Basel)* 13(1):1
- Rosarin FS, Mirunalini S (2011) Nobel metallic nanoparticles with novel biomedical properties. *J Bioanal Biomed* 03(04):85–91
- Huang X, Jain PK, El-Sayed IH, El-Sayed MA (2007) Gold nanoparticles: interesting optical properties and recent applications in cancer diagnostics and therapy. *Nanomedicine* 2(5):681–693
- Dauthal P, Mukhopadhyay M (2016) Noble metal nanoparticles: plant-mediated synthesis, mechanistic aspects of synthesis, and applications. *Ind Eng Chem Res* 55(36):9557–9577
- Darabdhara G, Das MR, Singh SP, Rengan AK, Szunerits S, Boukherroub R (2019) Ag and Au nanoparticles/reduced graphene oxide composite materials: synthesis and application in diagnostics and therapeutics. *Adv Colloid Interface Sci* 271:101991
- Sharma G et al (2018) Applications of nanocomposite hydrogels for biomedical engineering and environmental protection. *Environ Chem Lett* 16(1):113–146
- Lee J, Kim J, Kim S, Min D-H (2016) Biosensors based on graphene oxide and its biomedical application. *Adv Drug Deliv Rev* 105:275–287
- Zare Y, Shabani I (2016) Polymer/metal nanocomposites for biomedical applications. *Mater Sci Eng C* 60:195–203
- Rai M, Ingle AP, Birla S, Yadav A, Dos Santos CA (2016) Strategic role of selected noble metal nanoparticles in medicine. *Crit Rev Microbiol* 42(5):696–719
- Lee HC et al (2017) Review of the synthesis, transfer, characterization and growth mechanisms of single and multilayer graphene. *RSC Adv* 7(26):15644–15693
- Wu Y, Wang S, Komvopoulos K (2020) A review of graphene synthesis by indirect and direct deposition methods. *J Mater Res* 35(1):76–89
- Iravani S, Varma RS (2020) Green synthesis, biomedical and biotechnological applications of carbon and graphene quantum dots. A review. *Environ Chem Lett* 18(3):703–727
- Wang T, Nie C, Ao Z, Wang S, An T (2020) Recent progress in g-C₃N₄ quantum dots: synthesis, properties and applications in photocatalytic degradation of organic pollutants. *J Mater Chem A* 8(2):485–502
- Manikandan A, Chen Y-Z, Shen C-C, Sher C-W, Kuo H-C, Chueh Y-L (2019) A critical review on two-dimensional quantum dots (2D QDs): from synthesis toward applications in energy and optoelectronics. *Prog Quantum Electron* 68:100226
- Negri V, Pacheco-Torres J, Calle D, López-Larrubia P (2020) Carbon nanotubes in biomedicine. *Top Curr Chem* 378(1):15
- Sajid MI, Jamshaid U, Jamshaid T, Zafar N, Fessi H, Elaissari A (2016) Carbon nanotubes from synthesis to in vivo biomedical applications. *Int J Pharm* 501(1):278–299
- Simon J, Flahaut E, Golzio M (2019) Overview of carbon nanotubes for biomedical applications. *Mater (Basel, Switzerland)* 12(4):624
- Ruiz-Carmuega AI et al (2019) Electrochemical sensors modified with combinations of sulfur containing phthalocyanines and capped gold nanoparticles: a study of the influence of the nature of the interaction between sensing materials. *Nanomaterials* 9(11):1506
- Lian W et al (2012) Electrochemical sensor based on gold nanoparticles fabricated molecularly imprinted polymer film at chitosan–platinum nanoparticles/graphene–gold nanoparticles double nanocomposites modified electrode for detection of erythromycin. *Biosens Bioelectron* 38(1):163–169
- Luo X, Morrin A, Killard AJ, Smyth MR (2006) Application of nanoparticles in electrochemical sensors and biosensors. *Electroanalysis* 18(4):319–326
- Yang W, Liang H, Ma S, Wang D, Huang J (2019) Gold nanoparticle based photothermal therapy: development and application for effective cancer treatment. *Sustain Mater Technol* 22:e00109
- Kamran M, Haroon M, Popoola SA, Almohammadi AR, Al-Saadi AA, Saleh TA (2019) Characterization of valeric acid using substrate of silver nanoparticles with SERS. *J Mol Liq* 273:536–542
- Zhang A et al (2019) Spontaneous implantation of gold nanoparticles on graphene oxide for salivary SERS sensing. *Anal Methods* 11(40):5089–5097
- Zhang C, Gao Y, Yang N, You T, Chen H, Yin P (2018) Direct determination of the tumor marker AFP via silver nanoparticle enhanced SERS and AFP-modified gold nanoparticles as capturing substrate. *Microchim Acta* 185(2):90
- Cheng X, Sun R, Yin L, Chai Z, Shi H, Gao M (2017) Light-triggered assembly of gold nanoparticles for photothermal therapy and photoacoustic imaging of tumors in vivo. *Adv Mater* 29(6):1604894
- Sun M et al (2016) Salt-induced aggregation of gold nanoparticles for photoacoustic imaging and photothermal therapy of cancer. *Nanoscale* 8(8):4452–4457
- Kim HS, Lee DY (2017) Photothermal therapy with gold nanoparticles as an anticancer medication. *J Pharm Investig* 47(1):19–26
- Behnam MA et al (2018) Novel combination of silver nanoparticles and carbon nanotubes for plasmonic photothermal therapy in melanoma cancer model. *Adv Pharm Bull* 8(1):49–55
- Poudel BK et al (2018) In situ fabrication of mesoporous silica-coated silver-gold hollow nanoshell for remotely controllable chemo-photothermal therapy via phase-change molecule as gatekeepers. *Int J Pharm* 548(1):92–103
- Manivannan K, Cheng C-C, Anbazhagan R, Tsai H-C, Chen J-K (2019) Fabrication of silver seeds and nanoparticle on core-shell Ag@SiO₂ nanohybrids for combined photothermal therapy and bioimaging. *J Colloid Interface Sci* 537:604–614
- Zhao W, Karp JM, Ferrari M, Serda R (2011) Bioengineering nanotechnology: towards the clinic. *Nanotechnology* 22(49):10–12
- Conde J, Rosa J, Lima JC, Baptista PV (2012) Nanophotonics for molecular diagnostics and therapy applications. *Int J Photoenergy* 2012:1–12
- Pannico M, Calarco A, Peluso G, Musto P (2018) Functionalized gold nanoparticles as biosensors for monitoring cellular uptake and localization in normal and tumor prostatic cells. *Biosensors* 8(4):87
- Rasheed PA, Sandhyarani N (2017) Electrochemical DNA sensors based on the use of gold nanoparticles: a review on recent developments. *Microchim Acta* 184(4):981–1000
- Chen H, Qiu Q, Sharif S, Ying S, Wang Y, Ying Y (2018) Solution-phase synthesis of platinum nanoparticle-decorated metal-organic framework hybrid nanomaterials as biomimetic nanoenzymes for biosensing applications. *ACS Appl Mater Interfaces* 10(28):24108–24115
- Borisova B et al (2016) Reduced graphene oxide-carboxymethyl-cellulose layered with platinum nanoparticles/PAMAM dendrimer/magnetic nanoparticles hybrids. Application to the preparation of enzyme electrochemical biosensors. *Sensors Actuators B Chem* 232:84–90
- Doria G et al (2012) Noble metal nanoparticles for biosensing applications. *Sensors* 12(2):1657–1687

47. Zhao X, Zhao H, Yan L, Li N, Shi J, Jiang C (2020) Recent developments in detection using noble metal nanoparticles. *Crit Rev Anal Chem* 50(2):97–110
48. Jain KK (2007) Applications of nanobiotechnology in clinical diagnostics. *Clin Chem* 53(11):2002–2009
49. Valsami-Jones E, Lynch I (2015) How safe are nanomaterials? *Science* (80-) 350(6259):388LP–389LP
50. Fabiano B, Reverberi AP, Varbanov PS (2019) Safety opportunities for the synthesis of metal nanoparticles and short-cut approach to workplace risk evaluation. *J Clean Prod* 209:297–308
51. da Costa GM, Hussain CM (2020) 17 - Safety risk, ELSI (ethical, legal, social issues), and economics of nanomaterials. In: Hussain CM (ed) *Handbook of Nanomaterials in Analytical Chemistry*. Elsevier, pp 435–446. <https://doi.org/10.1016/B978-0-12-816699-4.00017-7>
52. Roy A, Bulut O, Some S, Mandal AK, Yilmaz MD (2019) Green synthesis of silver nanoparticles: biomolecule-nanoparticle organizations targeting antimicrobial activity. *RSC Adv* 9(5):2673–2702
53. Kuntiyi OI et al (2019) Electrochemical synthesis of silver nanoparticles by reversible current in solutions of sodium polyacrylate. *Colloid Polym Sci* 297(5):689–695
54. Huang H, Lai J, Lu J, Li Z (2019) Pulsed laser ablation of bulk target and particle products in liquid for nanomaterial fabrication. *AIP Adv* 9(1):15307
55. Hatakeyama Y, Onishi K, Nishikawa K (2011) Effects of sputtering conditions on formation of gold nanoparticles in sputter deposition technique. *RSC Adv* 1(9):1815–1821
56. Nunes D et al (2019) 2—Synthesis, design, and morphology of metal oxide nanostructures. In: Nunes D, Pimentel A, Santos L, Barquinha P, Pereira L, Fortunato E, Martins R (eds) *Metal oxides*. Elsevier, New York, pp 21–57
57. Colson P, Henric C, Cloots R (2013) Nanosphere lithography: a powerful method for the controlled manufacturing of nanomaterials. *J Nanomater* 2013:948510
58. Salabat A, Mirhoseini F (2018) A novel and simple microemulsion method for synthesis of biocompatible functionalized gold nanoparticles. *J Mol Liq* 268:849–853
59. Flores-Rojas GG, López-Saucedo F, Bucio E (2020) Gamma-irradiation applied in the synthesis of metallic and organic nanoparticles: a short review. *Radiat Phys Chem* 169:107962
60. Jeyaraj M, Gurunathan S, Qasim M, Kang MH, Kim JH (2019) A comprehensive review on the synthesis, characterization, and biomedical application of platinum nanoparticles. *Nanomaterials* 9(12):1719
61. Jain KK (2008) Nanomedicine: application of nanobiotechnology in medical practice. *Med Princ Pract* 17(2):89–101
62. Košević MG et al (2019) Structural and electrochemical properties of nesting and core/shell Pt/TiO₂ spherical particles synthesized by ultrasonic spray pyrolysis. *Metals* (Basel) 10(1):11
63. Lusker KL, Li J-R, Garno JC (2011) Nanostructures of functionalized gold nanoparticles prepared by particle lithography with organosilanes. *Langmuir* 27(21):13269–13275
64. Yu X et al (2012) Direct patterning of engineered ionic gold nanoparticles via nanoimprint lithography. *Adv Mater* 24(47):6330–6334
65. Davies G-L, O'Brien J, Gun'ko YK (2017) Rare earth doped silica nanoparticles via thermolysis of a single source metallasilsesquioxane precursor. *Sci Rep* 7(1):45862
66. Abedini A, Daud AR, Abdul Hamid MA, Kamil Othman N, Saion E (2013) A review on radiation-induced nucleation and growth of colloidal metallic nanoparticles. *Nanoscale Res Lett* 8(1):474
67. Irvani S, Korbekandi H, Mirmohammadi SV, Zolfaghari B (2014) Synthesis of silver nanoparticles: chemical, physical and biological methods. *Res Pharm Sci* 9(6):385–406
68. Mirzaei A, Neri G (2016) Microwave-assisted synthesis of metal oxide nanostructures for gas sensing application: a review. *Sens Actuators B Chem* 237:749–775
69. Hasan S (2014) A review on nanoparticles: their synthesis and types. *Res J Recent Sci Res J Recent Sci Uttar Pradesh Lucknow Campus* 4:1–3
70. Sun S (2006) Recent advances in chemical synthesis, self-assembly, and applications of FePt nanoparticles. *Adv Mater* 18(4):393–403
71. Booth SG, Uehara A, Chang SY, Mosselmans JFW, Schroeder SLM, Dryfe RAW (2015) Gold deposition at a free-standing liquid/liquid interface: evidence for the formation of Au(I) by microfocus X-ray spectroscopy (μ XRF and μ XAFS) and cyclic voltammetry. *J Phys Chem C* 119(29):16785–16792
72. Starowicz M, Stypuła B (2008) Electrochemical synthesis of ZnO nanoparticles. *Eur J Inorg Chem* 2008(6):869–872
73. Ramimoghadam D, Bagheri S, Hamid SBA (2014) Progress in electrochemical synthesis of magnetic iron oxide nanoparticles. *J Magn Magn Mater* 368:207–229
74. Noman MT, Petru M, Militký J, Azeem M, Ashraf MA (2019) One-pot sonochemical synthesis of ZnO nanoparticles for photocatalytic applications, modelling and optimization. *Materials* (Basel) 13(1):14
75. Balachandramohan J, Sivasankar T, Sivakumar M (2020) Facile sonochemical synthesis of Ag₂O-guar gum nanocomposite as a visible light photocatalyst for the organic transformation reactions. *J Hazard Mater* 385:121621
76. Sharma D, Kanchi S, Bisetty K (2015) Biogenic synthesis of nanoparticles: a review. *Arab J Chem* 12:3576–3600
77. Ahmad S et al (2019) Green nanotechnology: a review on green synthesis of silver nanoparticles—an ecofriendly approach. *Int J Nanomed* 14:5087–5107
78. Ealias AM, Saravanakumar MP (2017) A review on the classification, characterisation, synthesis of nanoparticles and their application. *IOP Conf Ser Mater Sci Eng* 263(3):032019
79. Park S-I et al (2016) A review on fabrication processes for electrochromic devices. *Int J Precis Eng Manuf Technol* 3(4):397–421
80. Nguyen MT, Yonezawa T (2018) Sputtering onto a liquid: interesting physical preparation method for multi-metallic nanoparticles. *Sci Technol Adv Mater* 19(1):883–898
81. Wender H, Migowski P, Feil AF, Teixeira SR, Dupont J (2013) Sputtering deposition of nanoparticles onto liquid substrates: recent advances and future trends. *Coord Chem Rev* 257(17):2468–2483
82. Yap FL, Zhang Y (2007) Protein and cell micropatterning and its integration with micro/nanoparticles assembly. *Biosens Bioelectron* 22(6):775–788
83. Chen J, Mela P, Möller M, Lensen MC (2009) Microcontact deprinting: a technique to pattern gold nanoparticles. *ACS Nano* 3(6):1451–1456
84. Park S et al (2018) Micropatterning of metal nanoparticle ink by laser-induced thermocapillary flow. *Nanomaterials* 8(9):645
85. Walters G, Parkin IP (2009) The incorporation of noble metal nanoparticles into host matrix thin films: synthesis, characterisation and applications. *J Mater Chem* 19(5):574–590
86. Yesildag C, Ouyang Z, Zhang Z, Lensen MC (2019) Micro-patterning of PEG-based hydrogels with gold nanoparticles using a reactive micro-contact-printing approach. *Front Chem* 6:667
87. Xu C, De S, Balu AM, Ojeda M, Luque R (2015) Mechanochemical synthesis of advanced nanomaterials for catalytic applications. *Chem Commun* 51(31):6698–6713
88. Schreyer H, Eckert R, Immohr S, de Bellis J, Felderhoff M, Schüth F (2019) Milling down to nanometers: a general process for the direct dry synthesis of supported metal catalysts. *Angew Chemie Int Ed* 58(33):11262–11265
89. Blázquez JS et al (2017) Ball milling as a way to produce magnetic and magnetocaloric materials: a review. *J Mater Sci* 52(20):11834–11850
90. Korshed P, Li L, Ngo D (2018) Effect of storage conditions on the long-term stability of bactericidal effects for laser generated silver nanoparticles. *Nanomaterials* (Basel) 8(4):218
91. Korshed P, Li L, Liu Z, Wang T (2016) The molecular mechanisms of the antibacterial effect of picosecond laser generated silver nanoparticles and their toxicity to human cells. *PLoS ONE* 11(8):1–23
92. Semaltianos NG (2010) Nanoparticles by laser ablation. *Crit Rev Solid State Mater Sci* 35(2):105–124
93. Sportelli M et al (2018) The pros and cons of the use of laser ablation synthesis for the production of silver nano-antimicrobials. *Antibiotics* 7(3):67
94. Correard F et al (2014) Gold nanoparticles prepared by laser ablation in aqueous biocompatible solutions: assessment of safety and biological identity for nanomedicine applications. *Int J Nanomed* 9:5415–5430
95. Mutisya S, Franzel L, Barnstein BO, Faber TW, Ryan JJ, Bertino MF (2013) Comparison of in situ and ex situ bioconjugation of Au nanoparticles generated by laser ablation. *Appl Surf Sci* 264:27–30

96. Odularu AT (2018) Metal nanoparticles: thermal decomposition, biomedical applications to cancer treatment, and future perspectives. *Bioinorg Chem Appl* 2018:9354708
97. Dias DA, Urban S, Roessner U (2012) A Historical overview of natural products in drug discovery. *Metabolites* 2(2):303–336
98. Daruich De Souza C, Ribeiro Nogueira B, Rostelato MECM (2019) Review of the methodologies used in the synthesis gold nanoparticles by chemical reduction. *J. Alloys Compd.* 798:714–740
99. Ranozek-Soliwoda K et al (2017) The role of tannic acid and sodium citrate in the synthesis of silver nanoparticles. *J Nanopart Res* 19(8):273
100. Alqadi MK, Abo Noqta OA, Alzoubi FY, Alzoubi J, Aljarrah K (2014) PH effect on the aggregation of silver nanoparticles synthesized by chemical reduction. *Mater Sci Pol* 32(1):107–111
101. Rashid MU, Bhuiyan KH, Quayum ME (2013) Synthesis of silver nanoparticles (Ag-NPs) and their uses for quantitative analysis of vitamin C tablets. *J Pharm Sci* 12(1):29–35
102. Izak-Nau E et al (2015) Impact of storage conditions and storage time on silver nanoparticles' physicochemical properties and implications for their biological effects. *RSC Adv* 5(102):84172–84185
103. Kang H et al (2019) Stabilization of silver and gold nanoparticles: preservation and improvement of plasmonic functionalities. *Chem Rev* 119(1):664–699
104. Tyagi H, Kushwaha A, Kumar A, Aslam M (2016) A facile pH controlled citrate-based reduction method for gold nanoparticle synthesis at room temperature. *Nanoscale Res Lett* 11(1):362
105. Agnihotri S, Mukherji S, Mukherji S (2014) Size-controlled silver nanoparticles synthesized over the range 5–100 nm using the same protocol and their antibacterial efficacy. *RSC Adv* 4(8):3974–3983
106. Hou Z, Li M, Han M, Zeng J, Liao S (2014) Aqueous phase synthesis and characterizations of Pt nanoparticles by a modified citrate reduction method assisted by inorganic salt stabilization for PEMFCs. *Electrochim Acta* 134:187–192
107. Malik MA, Wani MY, Hashim MA (2012) Microemulsion method: a novel route to synthesize organic and inorganic nanomaterials: 1st nano update. *Arab J Chem* 5(4):397–417
108. Tojo C, Buceta D, López-Quintela MA (2018) Slowing down kinetics in microemulsions for nanosegregation control: a simulation study. *J Phys Chem C* 122(34):20006–20018
109. Muñoz-Flores BM, Kharisov BI, Jiménez-Pérez VM, Elizondo Martínez P, López ST (2011) Recent advances in the synthesis and main applications of metallic nanoalloys. *Ind Eng Chem Res* 50(13):7705–7721
110. Solanki JN, Murthy ZVP (2011) Controlled size silver nanoparticles synthesis with water-in-oil microemulsion method: a topical review. *Ind Eng Chem Res* 50(22):12311–12323
111. Yanilkinn VV, Nasretidinova GR, Kokorekin VA (2018) Mediated electrochemical synthesis of metal nanoparticles. *Russ Chem Rev* 87(11):1080–1110
112. Li C, Sato T, Yamauchi Y (2013) Electrochemical synthesis of one-dimensional mesoporous Pt nanorods using the assembly of surfactant micelles in confined space. *Angew Chem Int Ed* 52(31):8050–8053
113. Zou C et al (2017) Electrochemical synthesis of gold nanoparticles decorated flower-like graphene for high sensitivity detection of nitrite. *J Colloid Interface Sci* 488:135–141
114. Abedini A, Bakar AAA, Larki F, Menon PS, Islam MS, Shaari S (2016) Recent advances in shape-controlled synthesis of noble metal nanoparticles by radiolysis route. *Nanoscale Res Lett* 11(1):287
115. Freitas de Freitas L, Varca GHC, Dos Santos Batista JG, Benévolo Lugão A (2018) An overview of the synthesis of gold nanoparticles using radiation technologies. *Nanomater (Basel, Switzerland)* 8(11):939
116. Wu S, Li M, Sun Y (2019) In situ synchrotron X-ray characterization shining light on the nucleation and growth kinetics of colloidal nanoparticles. *Angew Chemie Int Ed* 58(27):8987–8995
117. Čubová K, Čuba V (2020) Synthesis of inorganic nanoparticles by ionizing radiation—a review. *Radiat Phys Chem* 169:108774
118. Bekhit M, Abu el-naga MN, Sokary R, Fahim RA, El-Sawy NM (2020) Radiation-induced synthesis of tween 80 stabilized silver nanoparticles for antibacterial applications. *J Environ Sci Health Part A* 55(10):1210–1217
119. Kokel A, Schäfer C, Török B (2018) Microwave-assisted reactions in green chemistry. In: Meyers RA (ed) *Encyclopedia of sustainability science and technology*. Springer, New York, pp 1–40
120. Gangrade D, Sd L, Al M (2015) Overview on microwave synthesis—Important tool for green Chemistry. *Int J Res Pharm Sci* 5(2):37–42
121. Kostyukhin EM, Nissenbaum VD, Abkhalimov EV, Kustov AL, Ershov BG, Kustov LM (2020) Microwave-assisted synthesis of water-dispersible humate-coated magnetite nanoparticles: relation of coating process parameters to the properties of nanoparticles. *Nanomater (Basel, Switzerland)* 10(8):1558
122. Tripathi V, Kumar H, Agarwal A, Panchakarla LS (2020) Microwave-induced electric discharges on metal particles for the synthesis of inorganic nanomaterials under solvent-free conditions. *Beilstein J Nanotechnol* 11:1019–1025
123. Siddiqi KS, Husen A, Rao RAK (2018) A review on biosynthesis of silver nanoparticles and their biocidal properties. *J Nanobiotechnol* 16:14
124. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P (2018) 'Green' synthesis of metals and their oxide nanoparticles: applications for environmental remediation. *J Nanobiotechnology* 16(1):1–24
125. Syafuddin A, Salmiati S, Salim MR, Beng Hong Kueh A, Hadibarata T, Nur H (2017) A review of silver nanoparticles: research trends, global consumption, synthesis, properties, and future challenges. *J Chin Chem Soc* 64(7):732–756
126. Jain N, Bhargava A, Majumdar S, Tarafdar JC, Panwar J (2011) Extracellular biosynthesis and characterization of silver nanoparticles using *Aspergillus flavus* NJP08: a mechanism perspective. *Nanoscale* 3(2):635–641
127. Rafique M, Sadaf I, Rafique MS, Tahir MB (2017) A review on green synthesis of silver nanoparticles and their applications. *Artif Cells Nanomed Biotechnol* 45(7):1272–1291
128. Panáček A et al (2018) Bacterial resistance to silver nanoparticles and how to overcome it. *Nat Nanotechnol* 13(1):65–71
129. Klaus T, Joerger R, Olsson E, Granqvist C-G (1999) Silver-based crystalline nanoparticles, microbially fabricated. *Proc Natl Acad Sci* 96(24):13611–13614
130. Shahverdi AR, Fakhimi A, Shahverdi HR, Minaian S (2007) "Synthesis and effect of silver nanoparticles on the antibacterial activity of different antibiotics against *Staphylococcus aureus* and *Escherichia coli*". *Nanomed Nanotechnol Biol Med* 3(2):168–171
131. Hulkoti NI, Taranath TC (2014) Biosynthesis of nanoparticles using microbes—a review. *Colloids Surf B Biointerfaces* 121:474–483
132. Mukherjee K, Gupta R, Kumar G, Kumari S, Biswas S, Padmanabhan P (2018) Synthesis of silver nanoparticles by *Bacillus clausii* and computational profiling of nitrate reductase enzyme involved in production. *J Genet Eng Biotechnol* 16(2):527–536
133. Shanthi S, David Jayaseelan B, Velusamy P, Vijayakumar S, Chih CT, Vaseeharan B (2016) Biosynthesis of silver nanoparticles using a probiotic *Bacillus licheniformis* Dabhb1 and their antibiofilm activity and toxicity effects in *Ceriodaphnia cornuta*. *Microb. Pathog.* 93:70–77
134. Abdel-Raouf N, Al-Enazi NM, Ibraheem IBM (2017) Green biosynthesis of gold nanoparticles using *Galaxaura elongata* and characterization of their antibacterial activity. *Arab J Chem* 10:53029–53039
135. Lee KX et al (2020) Recent developments in the facile bio-synthesis of gold nanoparticles (AuNPs) and their biomedical applications. *Int J Nanomed* 15:275–300
136. Konishi Y et al (2007) Bioreductive deposition of platinum nanoparticles on the bacterium *Shewanella* algae. *J Biotechnol* 128(3):648–653
137. Wadhvani SA, Shedbalkar UU, Singh R, Vashisth P, Pruthi V, Chopade BA (2016) Kinetics of synthesis of gold nanoparticles by *Acinetobacter* sp. SW30 isolated from environment. *Indian J Microbiol* 56(4):439–444
138. Vigneshwaran N, Ashtaputre NM, Varadarajan PV, Nachane RP, Paralikar KM, Balasubramanya RH (2007) Biological synthesis of silver nanoparticles using the fungus *Aspergillus flavus*. *Mater Lett* 61(6):1413–1418
139. Balakumaran MD, Ramachandran R, Kalaichelvan PT (2015) Exploitation of endophytic fungus, *Guignardia mangiferae* for extracellular synthesis of silver nanoparticles and their in vitro biological activities. *Microbiol Res* 178:9–17
140. Rauwel P, Küünal S, Ferdov S, Rauwel E (2015) A review on the green synthesis of silver nanoparticles and their morphologies studied via TEM. *Adv Mater Sci Eng* 2015:682749
141. Mukherjee P et al (2001) Bioreduction of AuCl₄—ions by the Fungus, *Verticillium* sp. and surface trapping of the gold nanoparticles formed. *Angew Chemie Int Ed* 40(19):3585–3588

142. Vahabi K, Mansoori GA, Karimi S (2011) Biosynthesis of silver nanoparticles by Fungus *Trichoderma Reesei* (a route for large-scale production of AgNPs). *Insciencas J* 1(1):65–79
143. Balakumaran MD, Ramachandran R, Balashanmugam P, Mukeshkumar DJ, Kalaichelvan PT (2016) Mycosynthesis of silver and gold nanoparticles: optimization, characterization and antimicrobial activity against human pathogens. *Microbiol Res* 182:8–20
144. Dahoumane SA et al (2017) Algae-mediated biosynthesis of inorganic nanomaterials as a promising route in nanobiotechnology – a review. *Green Chem* 19(3):552–587
145. Hosea M, Greene B, Mcpherson R, Henzl M, Dale Alexander M, Darnall DW (1986) Accumulation of elemental gold on the alga *Chlorella vulgaris*. *Inorganica Chim Acta* 123(3):161–165
146. Velgosova O, Čižmárová E, Málek J, Kavuličova J (2017) Effect of storage conditions on long-term stability of Ag nanoparticles formed via green synthesis. *Int J Miner Metall Mater* 24(10):1177–1182
147. Stranska-Zachariasova M et al (2017) Bioprospecting of turbinaria macroalgae as a potential source of health protective compounds. *Chem Biodivers* 14(2):e1600192
148. Mason C, Vivekanandhan S, Misra M, Mohanty AK (2012) Switchgrass (*Panicum virgatum*) extract mediated green synthesis of silver nanoparticles. *World J Nano Sci Eng* 2(June):47–52
149. Lengke MF, Fleet ME, Southam G (2006) Synthesis of platinum nanoparticles by reaction of filamentous cyanobacteria with platinum(IV)-chloride complex. *Langmuir* 22(17):7318–7323
150. Gopinath V et al (2015) Biogenic synthesis, characterization of antibacterial silver nanoparticles and its cell cytotoxicity. *Arab J Chem* 1:10
151. Keshavarzi M, Davoodi D, Pourseyedi S, Taghizadeh S (2018) The effects of three types of alfalfa plants (*Medicago sativa*) on the biosynthesis of gold nanoparticles: an insight into phytomining. *Gold Bull* 51(3):99–110
152. Balashanmugam P, Kalaichelvan PT (2015) Biosynthesis characterization of silver nanoparticles using *Cassia roxburghii* DC. aqueous extract, and coated on cotton cloth for effective antibacterial activity. *Int J Nanomed* 10:87–97
153. Shankar SS, Rai A, Ahmad A, Sastry M (2004) Rapid synthesis of Au, Ag, and bimetallic Au core-Ag shell nanoparticles using Neem (*Azadirachta indica*) leaf broth. *J Colloid Interface Sci* 275(2):496–502
154. Banerjee P, Satapathy M, Mukhopahayay A, Das P (2014) Leaf extract mediated green synthesis of silver nanoparticles from widely available Indian plants: synthesis, characterization, antimicrobial property and toxicity analysis. *Bioresour Bioprocess* 1(1):3
155. Tripathy A, Raichur AM, Chandrasekaran N, Prathna TC, Mukherjee A (2010) Process variables in biomimetic synthesis of silver nanoparticles by aqueous extract of *Azadirachta indica* (Neem) leaves. *J Nanoparticle Res* 12(1):237–246
156. Kumar V, Singh DK, Mohan S, Hasan SH (2016) Photo-induced biosynthesis of silver nanoparticles using aqueous extract of *Erigeron bonariensis* and its catalytic activity against Acridine Orange. *J Photochem Photobiol B Biol* 155:39–50

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen® journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at ► [springeropen.com](https://www.springeropen.com)
