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Photosynthesized Nanoparticles: Mechanistic Insights into Synthesis Characterization, and Emerging Application: A Review

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Abstract
Green synthesis of nanoparticles using photosynthetic processes is gaining prominence as an environmentally friendly substitute to conventional methods. This study focuses on understanding the mechanisms involved in the formation of nanoparticles using plant extracts under light exposure. It highlights the role of natural phytochemicals and light energy in initiating and controlling nanoparticle synthesis. Various analytical techniques—including UV-Vis, FTIR, XRD, SEM, and TEM—were used to assess particle characteristics. Parameters such as light intensity, pH, precursor concentration, and reaction time were examined for their impact on synthesis. The nanoparticles produced were further evaluated for applications in medicine, catalysis, and environmental treatment. This work contributes to the field by offering a deeper insight into the process and potential of photosynthesized nanoparticles.

Introduction:
Nanotechnology deals with materials and structures that are measured in nanometers. Living beings are composed of one or more cells. These cellular structures are essentially nanometer in size. Nanotechnology is fundamental concerned with designing, producing, and characterization of analyzing particles at the nanoscale [1]. Despite their tiny size, nano-sized particles gathering as whole units with definite physical and chemical behaviors. The size of fine particles lies between 100- 2500 nanometer, whereas ultrafine particles fall within 1-100 nanometer. Such designs can produce the drug more efficient and increase its medical benefits [2]. Due to their large surface area, some chemicals groups can be added, improving them connect with tumor cells. Their ability to converge in tumor areas, assuring option over conventional therapies. Nanoparticles made from metals, semiconductors, and polymers are widely used for imaging at the molecular level and targeted drug delivery [3]. The use of micelles, chitosan, silica nanoparticles and polyethyleneimine liposomes is significant in drug delivery [4]. They have also found use in cancer treatment. Essentially, nanotechnology is mainly concerned with developing artificial biological components and helping in protein formation [5]. The review summaries the classification, methods of synthesis, uses, benefits, and challenges of nanoparticles.

Nanoparticles provide more benefits compared to other delivery systems. Their small size helps nanoparticles can escape from circulation and lodge in small blood vessels, improving their targeted delivery [6]. Furthermore, a large amount of drug can usually be loaded into nanoparticles, or by trapping, mixing, or dissolving it, and this depends on how nanoparticles are produced, which affects how drug is discharged. Liposome purpose effective carriers as they help avoid drug degradation, targeted action, and reducing harmful side effects. However, despite their versatility, technical issues like inconsistent results and limited stability have been analysts [7]. One major disadvantage of liposomes in drug delivery is the tendency of the encapsulated drug to leak, which delays controlled discharged. Meanwhile, polymeric nanoparticles are known for stabilizing therapeutic agents and permitting sustained release [8]. They are also categorized by simple formulation processes, low excipient content, strong physical stability, and suitability for sustained release in managing chronic illnesses. By modifying both the polymer composition and particle morphology, it’s possible to achieve sustained and duration of drug release. According to Liversidge and Cundy, nanoparticles improved drug availability by 77% over similar microsphere-based systems [9]. The nanoparticle platform has also been utilized between various administration methods such as oral, nasal, injectable, and eye-based applications [10]. Some small molecule drugs like, anticancer compounds, can be delivered orally through nanoparticle systems, which might not be feasible via injections [11]. Nanoparticles are suitable as vaccine adjuvants and compromise benefits like improved interactions with epithelial cells, promoting higher drug curiosity [12].

Classification of nanoparticles

Nanoparticles Classification based on structural composition

Organic nanoparticles: Organic nanoparticles and non-toxic, organic nanostructures including liposomes and micelles are used in drug delivery because of their core-shell structure and sensitivity to environmental and stimuli such as temperature or light.

- **Dendrimers:** Dendrimers are synthetic nano polymers named Greek words for "*tree*" and "*part*". They have a controlled structure, uniform size, and a branched, globular shape [13].
- **Micelles:** Micelles formation occurs when amphiphilic molecules like soap organize with their hydrophobic tails inner and hydrophilic heads outward, helps in cleansing [14].
- **Liposomes:** Liposomes are spherical nanoparticles made of phospholipid bilayers, used to carry active compounds. They are commonly applied in pharmaceuticals, cosmetics, food, and agriculture for delivering unstable substances [15].

Inorganic nanoparticles

Inorganic nanoparticles usually refer to those made from metals and metal oxides, without carbon-based systems.

- **Metal based nanoparticles:** Common metals such as gold, silver, and copper form nanoparticles with distinct traits based on their shape, size, and surface features [16].
- **Metal-oxide based nanoparticles:** Metal oxide nanoparticles are produced by transforming metals into oxides such as TiO_2, ZnO and Fe_3O_4, proposing better effective than their metal forms [17].

Carbon-based nanoparticles

Nanoparticles made decently from carbon are mentioned as carbon-based nanomaterials.

- **Fullerene:** The structure of fullerenes looks like a hollow ball, made from sp^2 hybridization, forming a stable, conductive cage-like framework with wide purposes [18].
- **Graphene:** Graphene forms the base for fullerenes, graphite, and nanotubes, with sp^2 bonds providing it high strength and conductivity [19].
- **Carbon Nano Tubes (CNT):** Carbon nanotubes are rolled graphene sheets, with monolayers being less than. 0.7 nm wide and multilayers varying in length [20].
- **Black carbon:** Black nanocarbon ranges 20 to 70 nm and lacks crystallinity. As the agglomerate near 500nm, particles strongly interact and cluster [21].

Classification based on the size of nanoparticles

- **Zero dimensional nanoparticles (0D):** 0D nanomaterials are those with nanoscale size in all directions.
- **One dimensional nanoparticle (1D):** Nanorods, nanotubes, and nanowires descent under 1-D nanomaterials with just one dimension below a nanometer.
- **Two dimensional nanoparticles (2D):** Two-dimensional nanomaterials such as nano coating and films are wide, with one dimension extending outside nanoscale.
- **Three dimensional nanoparticles (3D):** With size control in every direction, 3D nanomaterials maintenance applications like drug delivery, chemical reactions, and detection systems.

Methods of nanoparticles

Bottom-Up approach

Bottom-up synthesis uses atomic or molecular units to make nanostructures. It includes methods like sol-gel, chemical vapor deposition, spinning, co-precipitation, and pyrolysis. This approach authorizes better precision in morphology and composition than top-down techniques [22].

- **Chemical vapor deposition:** CVD produces nanomaterials by reacting vaporizes chemicals on a surface. It confirms pure and similar films, with types like PECVD and atomic layer epitaxy. While effective 2D nanoparticles synthesis, it poses risks due to toxic and flammable precursors and high processing costs [23].
- **Sol-gel method:** The sol-gel process generated nanoparticles by changing liquid precursors into solid gels through hydrolysis and condensation. This method provisions low-temperature synthesis, suggesting control over particle morphology, porosity, and purity ideal for ceramics, glass, and coating applications [24].

- **Pyrolysis:** Pyrolysis is used for industrial-scale nanoparticle synthesis. It involves burning precursors at high temperatures to form nanoparticles, it can also be done with flames or laser-based systems [25].
- **Co-precipitation:** The solvent displacement method is wet chemical method where a polymer dissolved in solvents like ethanol or acetone spreads into a non-solvent, producing nanoparticle formation through interfacial pressure [26].

Top-Down approach

Top-down method reduce large materials into nanosized particles. They are suitable for tough materials but cannot precisely control particle shape or size. Common techniques include milling, laser ablation, sputtering process, thermal decomposition, and nanolithography.

- **Laser ablation:** Laser ablation forms nanoparticles by vaporizing solids with lasers in an inert gas. As the vapor cools, clusters form, subsequent in nanomaterials such as core-shell particles and nanotubes [27].
- **Nanolithography:** Nanolithography tolerates precise nanopatterning (1 to 100 nm) through techniques like electron-beam and imprint lithography. It's accurate and efficient but costly [28].
- **Sputtering Process:** Sputtering forms nanoparticle layers by knocking atoms off a solid using ions. These atoms coat other surfaces and influenced by other type and processing conditions [29].
- **Thermal decomposition:** Heat-induced thermal decomposition forms stable, uniform nanoparticles. It is decent for scaling up but limited in versatility through different metal systems [30].

Green synthesis of nanoparticles

Green technology uses organisms to biosynthesize nanoparticles, recommending a non-toxic, eco-safe alternate to conservative methods.

- **Synthesis using plant extract**: Nanoparticles can be made using plant extracts, which react with metal salts rapidly. This process is affected by extract type, concentration pH, temperature, and duration [31].
- **Bacterial synthesis of nanoparticles:** Bacteria synthesize silver and gold nanoparticles also inside or outside their cells by reducing metal ions, frequently consuming enzymes, constructing them natural nano-factories for green nanoparticle production [32].
- **Synthesis by Fungi:** Fungi are widely used in the synthesis of metallic nanoparticles because of their remarkable metal-accumulating capacity, strong metal ion binding ability, and cellular behavior similar to bacteria. These characters make them ideal for bioreduction processes [33].
- **Synthesis by Yeast:** Nanoparticles produced using yeast are non-toxic and present strong biological properties, such as antibacterial, antiviral, and anticancer effects. Their mode of action commonly involves oxidative pressure induction, metabolic disruption, and interaction with cellular membranes [34].
- **Synthesis by Algae:** Functional biomolecules including peptides, pigments, and polysaccharides certainly present in algae act as reducing and stabilizing agents to originate nanoparticle formation [35].

Characterization of nanoparticles

Nanoparticles are commonly studied using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), UV-visible spectroscopy, Fourier Transform Infrared (FTIR), Atomic Force Microscopy (AFM), Dynamic Light Scattering (DLS) and X-ray diffraction to control their size, shape, and surface structure at the nanoscale level [36].

Nanoparticle size: Nanoparticle size and structure, generally measured through electron microscopy, play a crucial role in drug delivery. Tiny particles release drugs earlier due to larger surface area; however larger ones enable deeper drug loading but slower release. Particle size also contributes to the rate of polymer analysis [37].

Surface Charge: Nanoparticle surface area, calculated by BET or NMR, which impacts their properties. Surface charge, fundamental for stability and interaction, is measured using zeta potential in liquid DMA in gases [38].

UV-visible: UV-visible spectroscopy is widely used to differentiate nanoparticles via their surface plasmon resonance (SPR), which occurs from collective electron oscillation in metal nanoparticles. This technique helps monitor synthesis, optical behavior, and stability. Each nanoparticle type shows exclusive peaks, such as silver (417-448 nm) and CuO (236-670 nm) [39].

Fourier Transform Infrared (FTIR): FTIR spectroscopy is used to identify functional groups and compounds concerned with nanoparticle stabilization. Variations in spectra signify compositional changes. Its set up involves an IR source, interferometer, and detector linked to a processing system [40].

Scanning Electron Microscopy (SEM): SEM is commonly used to characterize the surface structure and morphology of nanoparticles. The process includes drying the sample, coating it with a conductive layer (commonly gold), and scanning it with a focused electron beam. The resultant images, produced from secondary electron emission, enable specified observation of shape and surface characteristics. Despite its resolution advantages, SEM cannot precisely reflect the average size or distribution within large populations, and the vacuum environment may damage sensitive polymer-based nanoparticles. Hence, SEM is often accompanied by other size-determining techniques like DLS [41].

Transmission Electron Microscopy (TEM): TEM provides high resolution internal imaging by transmitting electrons through thin samples and discloses internal structure. Samples are stained or frozen to confirm stability under the electron beam [42].

Atomic Force Microscopy (AFM): Atomic Force Microscopy (AFM) is a precise imaging technique that scans surface at the nanoscale using analysis that cooperates with the sample through physical or non-contact modes. It can seize topographical data with atomic precision, making it highly effective for analyzing nanoparticle size and structure. AFM is mainly suitable for soft, non-conductive materials like biological tissues and polymers, involving no conductive coating. It provides accurate particle size and distribution data that reflect the true morphology of the sample [43].

X-ray diffraction (XRD): XRD is used to determine crystallinity and estimate nanoparticles size. Peaks at specific angles reflect atomic arrangements. The Debye-Scherrer equation was used to calculate crystallite size of 47 nm for Ag nanoparticles derived from *A. haussknechtii.*
[44]

Dynamic Light Scattering (DLS): DLS processes nanoparticle size in solution by analyzing fluctuations in scattered light caused by particle motion. It deals with rapid consequences, while sizes are generally bigger than those seen in TEM, reflecting the dynamic nature of particles in fluid [45].

Properties of nanoparticles
Surface Properties: When bulk materials are decreased to the nanoscale, their total volume remains constant, but surface area increases significantly. This raises the surface-to-volume ratio, producing much atoms available at the surface. As a result, nanoparticles exhibit high surface energy, increased reactivity, and reduced melting points [46].

Electronic and optical properties: The optical behavior of nanoparticle changes from bulk materials because of quantum confinement and LSPR, as size decreases, energy levels become isolated, involving higher energy (shorter wavelength) for excitation. These consequences in size-dependent color changes. Noble metal nanoparticles displayed LSPR, where collective electron oscillations produce sharp absorption bands and improved light scattering, useful in sensing and imaging [47].

Magnetic Properties: Nanoparticles show different behavior related to bulk material, frequently due to transformed electron distribution and synthesis methods. Their magnetization curves shift with size, producing them suitable for targeted applications in medicine, catalysis, and environmental elimination. Magnetic nanoparticles are most applicable between 10 to 20 nm in size [48].
Superconductivity: Superconductivity involves zero resistance and perfect diamagnetism below a critical temperature. Since its innovation in 1911, it has permitted technologies like MRI and superconducting magnets. However, its function is limited by temperature and magnetic fields [49].

Mechanical Properties: Mechanical properties such as friction and elasticity in nanoparticles are size-dependent and improved by coatings or surface interactions. This behavior is crucial in surface engineering and advanced material design [50].

Thermal Properties: Thermal behavior of nanoparticles changes as their size decreases. The increased surface area helps transfer heat economically. In liquids, they increase thermal conductivity through micro-convention. These particles often have higher heat capacity and lower melting points than bulk materials due to phonon effects and surface energy changes [51].

Antimicrobial Properties: Green-synthesized nanoparticles using light, such as Ag or TiO_2, interact with bacteria across different pathways. Their small size enters cells and release ROS that terminate fundamental cell parts. These properties are examined using common lab assays and show potential in healthcare and antibacterial materials [52].

Antioxidant properties: The antioxidant properties of plant-based nanoparticles originate from natural compounds on their surface during light synthesis. These stabilize the particles and help them conflict free radicals. Their activity is measured by standard analyses such as DPPH and FRAP. They are widely used in medicine, food preservation, and cosmetics [53].

Catalytic Properties: Green-synthesized nanoparticle present strong catalytic activity in classification pollutants like rhodamine B and methylene blue. Their efficiency is increased by sunlight-induced electron movement and surface phytochemicals that increase stability [54].

Application of nanoparticles

Nanoparticles are used in different field like healthcare, cosmetic, food industry, medicine, drug delivery, textiles, electronics, etc due to their small size and large surface area, which develop their properties throughout bulk materials.

Medicine: Medicinal use of nanoparticles such as imaging and targeted therapies. Iron oxides specify magnetic benefits, silver compromises antimicrobial affects, and gold aids cancer treatment. Biodegradable nanoparticles enable controlled drug release, increasing treatment efficiency [55].

Drug delivery: Due to their optical traits and biocompatibility, gold nanoparticles are used in cancer treatment, imaging, and drug delivery. Coordinated drug discharge can be constant or produced by pH, enzymes, or light. ZnO targets cancer cells, Cu shows antimicrobial potential, and Ag is used in medical materials [56].

Healthcare: In healthcare, nanotechnology allow specific drug delivery, imaging, and diagnostics. Nanoparticles can release drugs when produced by chemical or physical signals, with gold, titanium, and magnetic types being common. Polymeric combinations improve affecting, particularly in cancer therapy using gold and silver nanocarriers [57].

Cancer therapy: Photodynamic therapy uses laser light to produce cytotoxic oxygen that targets cancer cells. These cells captivate more photosensitive dye than healthy ones, produce more susceptible. Moreover, the dye accumulates in sensitive tissues, affecting light sensitivity for weeks. To reduce light sensitivity, the dye is surrounded in porous Ormosil nanoparticles. This confines the dye while preserving oxygen production through 1 nm pores [58].

Textile industry: The textile industry has contained nanotechnology to increase textile quality and performance. By inserting materials and nanoscale fibers, textiles develop new properties like improved durability and reliability. Polymeric coatings promote resistance and functionality during processes like dyeing and finishing [59].

Catalysis: Platinum, palladium, nickel, and iron nanoparticles play vital roles as catalysts, enabling efficient chemical transformation like hydrogenation and oxidation. Their ability to purpose at lower temperatures makes them valuable in industrial applications [60].

Biosensing: Nanoparticles are fundamental in electrochemical sensing, with gold and platinum improving biosensor accuracy. They are used in diagnostics through modified electrodes and nanostructures such as gold-liposomes and gallic acid-based nanoflowers, accompanying methods like SERS and SPR [61].

Fertilizers: Nano fertilizers deal improved nutrient efficiency and plant growth potential, helps by elements like silver and aluminium. Although, their performance is not always superior to regular fertilizers, and constant assessment is necessary to address safety and environmental concerns [62].

Electronics: The use of nanoparticle-based managing in printed electronics allows the conception of flexible, low-cost devices. Semiconducting and metallic nanostructures propose ideal properties for modern electronics, authorized by bottom-up and self-assembly methods [63].

Conclusion

This review emphasizes photosynthetic nanoparticle synthesis as a green, sustainable alternate to conventional chemical methods. Emphasis is placed on characterization, low toxicity, and general applications through fields such as medicine, drug delivery, healthcare, and electronics. Potential work should focus on scalability, reproducibility, and specific mechanisms to help practical use. The role of plant-derived compounds in defining and stabilizing nanoparticles needs more detailed analysis. The final properties of nanoparticle can vary a lot with small changes in effects such as pH, heat, or salt can harm major change in the nanoparticle produced. To achieve consistent and efficient outcomes, these factors must have study completely. Future studies should focus on their behavior in real conditions, including human biology, and consider how well they store and remain stable overtime.

Reference:

1. Majuru, S., & Oyewumi, M. O. (2009). Nanotechnology in drug development and life cycle management. *Nanotechnology in drug delivery*, 597-619.
2. Smola, M., Vandamme, T., & Sokolowski, A. (2008). Nanocarriers as pulmonary drug delivery systems to treat and to diagnose respiratory and non-respiratory diseases. *International journal of nanomedicine*, *3*(1), 1-19.
3. Riehemann, K., Schneider, S. W., Luger, T. A., Godin, B., Ferrari, M., & Fuchs, H. (2009). Nanomedicine—challenge and perspectives. *Angewandte Chemie International Edition*, *48*(5), 872-897.
4. Sinha, R., Kim, G. J., Nie, S., & Shin, D. M. (2006). Nanotechnology in cancer therapeutics: bioconjugated nanoparticles for drug delivery. *Molecular cancer therapeutics*, *5*(8), 1909-1917.
5. Sandhiya, S., Dkhar, S. A., & Surendiran, A. (2009). Emerging trends of nanomedicine–an overview. *Fundamental & clinical pharmacology*, *23*(3), 263-269.
6. Mosqueira, V. C. F., Legrand, P., Morgat, J. L., Vert, M., Mysiakine, E., Gref, R., ... & Barratt, G. (2001). Biodistribution of long-circulating PEG-grafted nanocapsules in mice: effects of PEG chain length and density. *Pharmaceutical research*, *18*, 1411-1419.
7. Allen, T. M., & Cullis, P. R. (2004). Drug delivery systems: entering the mainstream. *Science*, *303*(5665), 1818-1822.
8. Calvo, P., Remunan-Lopez, C., Vila-Jato, J. L., & Alonso, M. J. (1997). Novel hydrophilic chitosan-polyethylene oxide nanoparticles as protein carriers. *Journal of applied polymer science*, *63*(1), 125-132.
9. Alex, R., & Bodmeier, R. (1990). Encapsulation of water-soluble drugs by a modified solvent evaporation method. I. Effect of process and formulation variables on drug entrapment. *Journal of microencapsulation*, *7*(3), 347-355.
10. Pignatello, R., Bucolo, C., Ferrara, P., Maltese, A., Puleo, A., & Puglisi, G. (2002). Eudragit RS100® nanosuspensions for the ophthalmic controlled delivery of ibuprofen. *European journal of pharmaceutical sciences*, *16*(1-2), 53-61.
11. Mu, L., & Feng, S. S. (2001). Fabrication, characterization and in vitro release of paclitaxel (Taxol®) loaded poly (lactic-co-glycolic acid) microspheres prepared by spray drying technique with lipid/cholesterol emulsifiers. *Journal of Controlled Release*, *76*(3), 239-254.

12. Boudad, H., Legrand, P., Lebas, G., Cheron, M., Duchene, D., & Ponchel, G. (2001). Combined hydroxypropyl-β-cyclodextrin and poly (alkylcyanoacrylate) nanoparticles intended for oral administration of saquinavir. *International journal of pharmaceutics*, *218*(1-2), 113-124.
13. Lee, C. C., MacKay, J. A., Fréchet, J. M., & Szoka, F. C. (2005). Designing dendrimers for biological applications. *Nature biotechnology*, *23*(12), 1517-1526.
14. Moroi, Y. (2013). *Micelles: theoretical and applied aspects*. Springer Science & Business Media.
15. Jesorka, A., & Orwar, O. (2008). Liposomes: technologies and analytical applications. *Annu. Rev. Anal. Chem.*, *1*(1), 801-832.
16. Ijaz, I., Gilani, E., Nazir, A., & Bukhari, A. (2020). Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles. *Green chemistry letters and reviews*, *13*(3), 223-245.
17. Ealia, S. A. M., & Saravanakumar, M. P. (2017, November). A review on the classification, characterisation, synthesis of nanoparticles and their application. In *IOP conference series: materials science and engineering* (Vol. 263, No. 3, p. 032019). IOP Publishing.
18. Astefanei, A., Núñez, O., & Galceran, M. T. (2015). Characterisation and determination of fullerenes: a critical review. *Analytica chimica acta*, *882*, 1-21.
19. Mondal, A., & Jana, N. R. (2014). Graphene-nanoparticle composites and their applications in energy, environmental and biomedical science. *Reviews in Nanoscience and Nanotechnology*, *3*(3), 177-192.
20. Popov, V. N. (2004). Carbon nanotubes: properties and application. *Materials Science and Engineering: R: Reports*, *43*(3), 61-102.
21. Koike, E., & Kobayashi, T. (2006). Chemical and biological oxidative effects of carbon black nanoparticles. *Chemosphere*, *65*(6), 946-951.
22. Abid, N., Khan, A. M., Shujait, S., Chaudhary, K., Ikram, M., Imran, M., ... & Maqbool, M. (2022). Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review. *Advances in Colloid and Interface Science*, *300*, 102597.
23. Choy, K. L. (Ed.). (2019). *Chemical vapour deposition (CVD): advances, technology and applications*. CRC Press.
24. Cauqui, M. A., & Rodriguez-Izquierdo, J. M. (1992). Application of the sol-gel methods to catalyst preparation. *Journal of Non-Crystalline Solids*, *147*, 724-738.
25. Bridgwater, A. V., & Bridge, S. A. (1991). A review of biomass pyrolysis and pyrolysis technologies. *Biomass pyrolysis liquids upgrading and utilization*, 11-92.
26. Petcharoen, K., & Sirivat, A. J. M. S. (2012). Synthesis and characterization of magnetite nanoparticles via the chemical co-precipitation method. *Materials Science and Engineering: B*, *177*(5), 421-427.
27. Kim, M., Osone, S., Kim, T., Higashi, H., & Seto, T. (2017). Synthesis of nanoparticles by laser ablation: A review. *KONA Powder and Particle Journal*, *34*, 80-90.
28. Pimpin, A., & Srituravanich, W. (2012). Review on micro-and nanolithography techniques and their applications. *Engineering journal*, *16*(1), 37-56.
29. Shah, P., & Gavrin, A. (2006). Synthesis of nanoparticles using high-pressure sputtering for magnetic domain imaging. *Journal of magnetism and magnetic materials*, *301*(1), 118-123.
30. Król-Morkisz, K., & Pielichowska, K. (2019). Thermal decomposition of polymer nanocomposites with functionalized nanoparticles. In *Polymer composites with functionalized nanoparticles* (pp. 405-435). Elsevier.
31. Mittal, A. K., Chisti, Y., & Banerjee, U. C. (2013). Synthesis of metallic nanoparticles using plant extracts. *Biotechnology advances*, *31*(2), 346-356.
32. Kumar, U., Shete, A., Harle, A. S., Kasyutich, O., Schwarzacher, W., Pundle, A., & Poddar, P. (2008). Extracellular bacterial synthesis of protein-functionalized ferromagnetic Co3O4 nanocrystals and imaging of self-organization of bacterial cells under stress after exposure to metal ions. *Chemistry of Materials*, *20*(4), 1484-1491.
33. Mukherjee, P., Ahmad, A., Mandal, D., Senapati, S., Sainkar, S. R., Khan, M. I., ... & Sastry, M. (2001). Fungus-mediated synthesis of silver nanoparticles and their immobilization in the mycelial matrix: a novel biological approach to nanoparticle synthesis. *Nano letters*, *1*(10), 515-519.

34. Voiniciuc, C., Dama, M., Gawenda, N., Stritt, F., & Pauly, M. (2019). Mechanistic insights from plant heteromannan synthesis in yeast. *Proceedings of the National Academy of Sciences*, *116*(2), 522-527.

35. Khan, F., Shahid, A., Zhu, H., Wang, N., Javed, M. R., Ahmad, N., ... & Mehmood, M. A. (2022). Prospects of algae-based green synthesis of nanoparticles for environmental applications. *Chemosphere*, *293*, 133571.

36. Chu, B., & Liu, T. (2000). Characterization of nanoparticles by scattering techniques. *Journal of Nanoparticle Research*, *2*, 29-41.

37. Sozer, N., & Kokini, J. L. (2009). Nanotechnology and its applications in the food sector. *Trends in biotechnology*, *27*(2), 82-89.

38. Subhapriya, S., & Gomathipriya, P. J. M. P. (2018). Green synthesis of titanium dioxide (TiO2) nanoparticles by Trigonella foenum-graecum extract and its antimicrobial properties. *Microbial pathogenesis*, *116*, 215-220.

39. Begum, R., Farooqi, Z. H., Naseem, K., Ali, F., Batool, M., Xiao, J., & Irfan, A. (2018). Applications of UV/Vis spectroscopy in characterization and catalytic activity of noble metal nanoparticles fabricated in responsive polymer microgels: A review. *Critical reviews in analytical chemistry*, *48*(6), 503-516.

40. Amir, R. M., Anjum, F. M., Khan, M. I., Khan, M. R., Pasha, I., & Nadeem, M. (2013). Application of Fourier transform infrared (FTIR) spectroscopy for the identification of wheat varieties. *Journal of food science and technology*, *50*, 1018-1023.

41. Inkson, B. J. (2016). Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for materials characterization. In *Materials characterization using nondestructive evaluation (NDE) methods* (pp. 17-43). Woodhead publishing.

42. Jin, H. H., Cho, H. D., Kwon, S. C., Shin, C., & Kwon, J. (2012). Modified preparation technique of TEM sample for various TEM analyses of structural materials. *Materials Letters*, *89*, 133-136.

43. Fotiadis, D., Scheuring, S., Müller, S. A., Engel, A., & Müller, D. J. (2002). Imaging and manipulation of biological structures with the AFM. *Micron*, *33*(4), 385-397.

44. Seeck, O. H., & Murphy, B. (Eds.). (2015). *X-ray diffraction: modern experimental techniques*. CRC Press.

45. Stetefeld, J., McKenna, S. A., & Patel, T. R. (2016). Dynamic light scattering: a practical guide and applications in biomedical sciences. *Biophysical reviews*, *8*, 409-427.

46. Abdelmouleh, M., Boufi, S., Belgacem, M. N., Duarte, A. P., Salah, A. B., & Gandini, A. (2004). Modification of cellulosic fibres with functionalised silanes: development of surface properties. *International Journal of Adhesion and Adhesives*, *24*(1), 43-54.

47. McConnell, W. P., Novak, J. P., Brousseau, L. C., Fuierer, R. R., Tenent, R. C., & Feldheim, D. L. (2000). Electronic and optical properties of chemically modified metal nanoparticles and molecularly bridged nanoparticle arrays. *The Journal of Physical Chemistry B*, *104*(38), 8925-8930.

48. Pauling, L., & Coryell, C. D. (1936). The magnetic properties and structure of hemoglobin, oxyhemoglobin and carbonmonoxyhemoglobin. *Proceedings of the National Academy of Sciences*, *22*(4), 210-216.

49. Schrieffer, J. R. (2018). *Theory of superconductivity*. CRC press.

50. Meyers, M. A., Mishra, A., & Benson, D. J. (2006). Mechanical properties of nanocrystalline materials. *Progress in materials science*, *51*(4), 427-556.

51. Kasap, S., Málek, J., & Svoboda, R. (2017). Thermal properties and thermal analysis: fundamentals, experimental techniques and applications. *Springer handbook of electronic and photonic materials*, 1-1.

52. Staroń, A., & Długosz, O. (2021). Antimicrobial properties of nanoparticles in the context of advantages and potential risks of their use. *Journal of Environmental Science and Health, Part A*, *56*(6), 680-693.

53. Bedlovičová, Z., Strapáč, I., Baláž, M., & Salayová, A. (2020). A brief overview on antioxidant activity determination of silver nanoparticles. *Molecules*, *25*(14), 3191.

54. Cuenya, B. R. (2010). Synthesis and catalytic properties of metal nanoparticles: Size, shape, support, composition, and oxidation state effects. *Thin Solid Films*, *518*(12), 3127-3150.

55. Zhang, L., Gu, F. X., Chan, J. M., Wang, A. Z., Langer, R. S., & Farokhzad, O. C. (2008). Nanoparticles in medicine: therapeutic applications and developments. *Clinical pharmacology & therapeutics*, *83*(5), 761-769.

56. Chattopadhyay, I. (2020). Application of nanoparticles in drug delivery. *Model organisms to study biological activities and toxicity of nanoparticles*, 35-57.
57. Ansari, M. T., Sami, F., Khairudiin, F. A., Atan, M. Z., bin Tengku Mohamad, T. A., Majeed, S., & Ali, S. (2018). Applications of zinc nanoparticles in medical and healthcare fields. *Current Nanomedicine (Formerly: Recent Patents on Nanomedicine)*, *8*(3), 225-233.
58. Aghebati-Maleki, A., Dolati, S., Ahmadi, M., Baghbanzhadeh, A., Asadi, M., Fotouhi, A., ... & Aghebati-Maleki, L. (2020). Nanoparticles and cancer therapy: Perspectives for application of nanoparticles in the treatment of cancers. *Journal of cellular physiology*, *235*(3), 1962-1972.
59. Patra, J. K., & Gouda, S. (2013). Application of nanotechnology in textile engineering: An overview. *J. Eng. Technol. Res*, *5*(5), 104-111.
60. Spivey, J. (2014). Metal nanoparticles for catalysis: advances and applications.
61. Luo, X., Morrin, A., Killard, A. J., & Smyth, M. R. (2006). Application of nanoparticles in electrochemical sensors and biosensors. *Electroanalysis: An International Journal Devoted to Fundamental and Practical Aspects of Electroanalysis*, *18*(4), 319-326.
62. Rehmanullah, Muhammad, Z., Inayat, N., & Majeed, A. (2020). Application of nanoparticles in agriculture as fertilizers and pesticides: challenges and opportunities. *New frontiers in stress management for durable agriculture*, 281-293.
63. He, Z., Zhang, Z., & Bi, S. (2020). Nanoparticles for organic electronics applications. *Materials Research Express*, *7*(1), 012004.