Chapter 2
Physical and Chemical Nature of Nanoparticles

Sanmathi Chavalmane Subbenaik

Abstract Nanoparticles have some specific features, including physical properties, chemical properties, merits, and demerits, which have drawn much attention for their application in nanobiotechnology. This chapter explains the state of the art of different properties of nanoparticles and their potential beneficial roles. In addition, this chapter discusses on the research on nanoparticles essentiality for plants and describes the current knowledge concerning the key nanoparticles with important studies for their future applications.

Keywords Nanoparticles · Physiochemical nature · Merits and demerits

2.1 Introduction

Nanoparticles in general refer to particles having internal structural measurement or external dimensions within the size range of a few nanometers, preferable up to 100 nm size. According to the European Committee for Standardization, nanomaterials are defined as the materials with any external dimension at the nanoscale, or that possess nanoscale internal or surface structures. Nanoscale describes the size range from approximately 1–100 nm (ISO/TS 27687: 2008) (Lövestam et al. 2010). It is most frequently used as a specific size description (usually <100 nm, though sometimes <50 nm), and this book chapter will use the term nanoparticle to refer to particles of <100 nm.

Nanoparticles have been developed for use in the area of agriculture (Nair et al. 2010; Campos et al. 2014), where they can increase the efficiency and productivity of crops. To properly assign the mechanisms for the application of nanoscale materials in plants, their synthesis and characterization must be well understood. Scientists have many methods to synthesize NPs of different size, shape, and

S.C. Subbenaik (✉)
Nano Research Facility (NNIN-NSF), School of Engineering and Applied Science,
Washington University in St. Louis, St. Louis, MO 63130, USA
e-mail: sanmathi.nrf.wustl@gmail.com

C. Kole et al. (eds.), *Plant Nanotechnology*,
DOI 10.1007/978-3-319-42154-4_2

surface properties. The major synthesis routes are liquid phase, gas-phase, and biological methods (Klaus et al. 1999; Konishi et al. 2007; Raliya and Tarafdar 2012; Mittal et al. 2013). The main liquid phase syntheses of inorganic NPs are coprecipitation, solgel processing, micro-emulsions, hydrothermal or solvothermal methods, template synthesis, and biometric synthesis (Cushing et al. 2004). The biological method can be approached for synthesis of NPs, which is rapid and cost-effective. (Gilaki 2010; Raliya and Tarafdar 2012). Besides these synthesis methods, the gas-phase synthesis methods are of interest because they allow elegant way to control process parameter in order to be able to produce size-, shape-, and chemical composition-controlled nanostructures, and also can be used to prepare the large quantity of NPs (Jiang et al. 2007; Thimsen et al. 2008).

Nanoparticles are of two types: non-engineered and engineered NPs. Non-engineered NPs present in the environment are derived from natural events such as terrestrial dust storms, erosion, volcanic eruption, and forest fires (Nowack and Bucheli 2007). Engineered NPs (ENPs) are intentionally produced by man using many different materials, such as metals (including Au, Ag, Zn, Ni, Fe, and Cu) (Fedlheim and Foss 2001), metal oxides (TiO_2, Fe_2O_4, SiO_2, CeO_2, and Al_2O_3) (Fernández-García and Rodriguez 2011), nonmetals (silica and quantum dots) (Ehrman et al. 1999), carbon (graphene and fullerene) (Endo et al. 2013), polymers (alginate, chitosan, hydroxyethylcellulose, polyhydroxyalkanoates and polyhydroxyalkanoates, and poly-E-caprolactone) (Paques et al. 2014) (Rao and Geckeler 2011), and lipids (soybean lecithin and stearic acid) (Ekambaram et al. 2012).

Engineered NPs are able to enter into plants cells and leaves and also can transport DNA and chemicals into plant cells (Galbraith 2007; Tripathi et al. 2011; Raliya et al. 2015). The unique physical and chemical properties of nanoparticles could boost plant metabolism (Nair et al. 2011; Brew and Strano 2014). Here, we describe the physical and chemical nature of the NPs and compare their merits and demerits during application. Figure 2.1 shows the different physical and chemical nature of NPs.

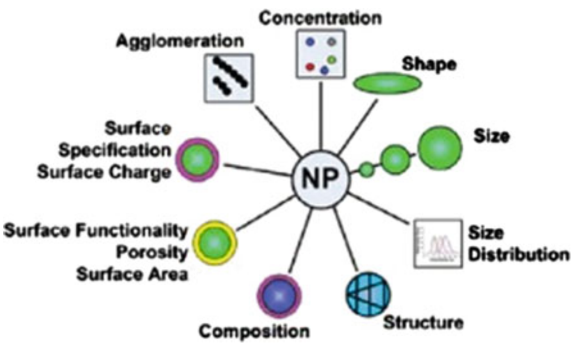

Fig. 2.1 Physical and chemical nature of nanoparticles

2.2 Physical Properties of Nanoparticles

Physical properties of NPs include shape, size, specific surface area, agglomeration/ aggregation, state of size distribution, surface morphology/topography, and structure including crystallinity, defect structure, and solubility (Cadden 1987; Rao and Biswas 2009). The size, shape, surface area, and size distribution of NPs are important deciding factors controlling their uptake by plants as it is highly dependent on cell wall pores and size of stomata (Eichert et al. 2008; Schreck et al. 2012; Wang et al. 2013). The following section will describe the basics of each physical property of NPs.

2.2.1 Size and Shape

The size and shape can be identified as the most important parameter to define the nanomaterial in general. Jolivet et al. (2004) and Jolivet et al. (2004) postulated that NPs below 20–30 nm in size are characterized by an excess of energy at the surface and are thermodynamically unstable because of the interfacial tension, acting as a driving force, which leads to a spontaneous reduction of the surface area. However, most types of particles have a critical size of about 30 nm below which NPs exhibit their typical "nano" properties from their bulk material. When the size of a nanoparticle decreases, the amount of molecules present at the particle's surface increases in an exponential trend. Slomberg and Schoenfisch (2012) studied the size-dependent effects of silica particles on Arabidopsis (*Arabidopsis thaliana*) plants. The studies showed reduced development of plants for treatment with 50 and 200 nm silica NPs. Figure 2.2 shows the effect of different size of silica NPs on growth of Arabidopsis plant.

The design of NPs has gained a lot of attention, resulting in particles with various shapes such as spheres, rods, tubed, fibers, and disks, and more extraordinary geometries such as worms, squares, urchins, and ellipsoids. The optical properties of NPs also depend on its size and shape. Figure 2.3 exemplifies the difference in the optical properties of gold NPs for different shapes (synthesis and characterization done in Nano Research Facility, Washington University, in Saint Louis using the article (Wu et al. 2010).

2.2.2 Surface and Size Distribution of Nanoparticles

The surface morphology and surface area of NPs can be analyzed using scanning electron microscope (SEM) and Brunauer–Emmett–Teller (BET), respectively (Hayat 1974). To get a higher resolution of approximately 0.2 nm, atomic force microscopy (AFM) can be used. It provides real topographical images of sample

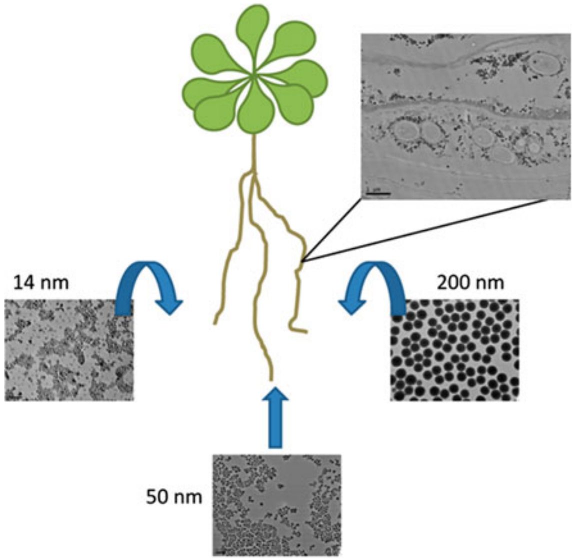

Fig. 2.2 Effect of different sized (14, 50, and 200 nm) silica nanoparticles on growth of *Arabidopsis thaliana* plant (reprinted with permission from Slomberg and Schoenfisch 2012 copyright of American Chemical Society)

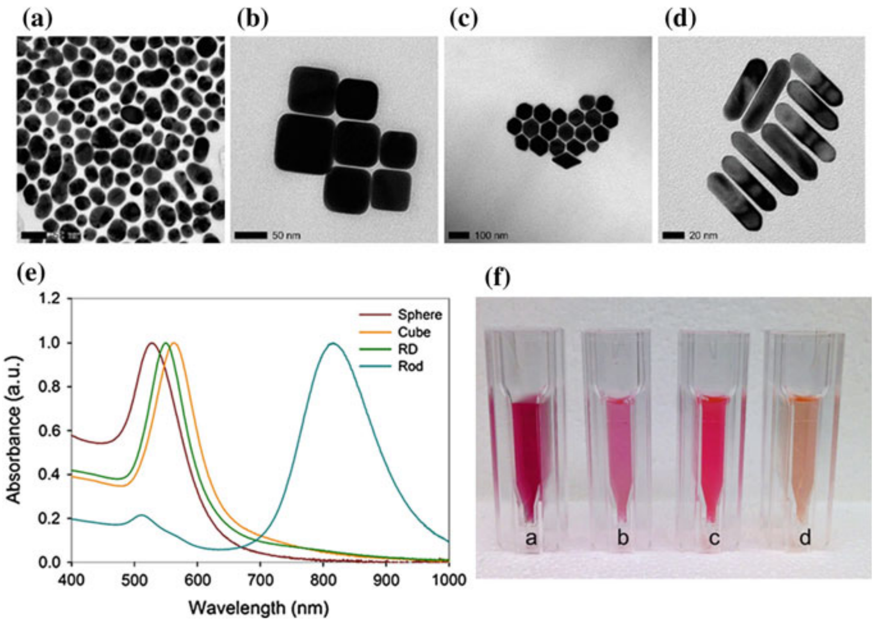

Fig. 2.3 Characterization of gold NPs. TEM images of gold nanostructure **a** spheres, **b** truncated cubes, **c** rhombic dodecahedra, and **d** rods **e** UV–visible absorption spectra showing characteristic absorption peak(s) for each nanostructre **f** Pictured from *left* **a** to *right* **d**: nanospheres, truncated cubes, rhombic dodecahedra, and rods as synthesized in aqueous suspension

surfaces. Dynamic light scattering (DLS) enables evaluation of the size distribution of NPs, and zetasizer can be used to determine the surface charge of NPs. The attachment of NPs to cell membrane seems to be most affected by the surface charge of the NPs (Honary and Zahir 2013). The plant cellular uptake is usually a prerequisite and is also governed by surface hydrophobicity and charge in addition to size. Compared to NPs having a neutral or negative charge, positively charged NPs are taken up at faster rate. The dispersion status of NPs in aqueous media principally depends on the surface charge of the given NPs. A number of in vitro studies with different NPs have been published in which the effect of the different parameters such as dispersion, surface properties, and agglomeration and de-agglomeration can be controlled using ultrasonication, ionic strength and pH of aqueous solutions, physiological buffers, and cell culture media (Orts-Gil et al. 2011; Barreto et al. 2015).

2.2.3 Structural and Species Specifics of Nanoparticles

Determinations of purity of NPs are important in biological application. X-ray diffraction (XRD) is the most essential tool used to characterize crystal structures (Warren 1969). The most commonly used database for the identification of crystal structures is the Joint Committee on Powder Diffraction Standards—International Center for Diffraction Data (JCPDS-ICDD) system. Detailed profile analysis of experimental XRD patterns provides information about a given material's space group and structural parameters. (Jain et al. 2009; Kumar and Yadav 2009). Syu et al. (2014) studied the effects of size and shape of silver NPs on growth and gene expression in Arabidopsis plants and found that the application could result in a complex physiological response in the treated tissues. The literature reported the species specificity of NPs in which their effects vary with the type of NPs and type and nature of biological systems that got treated with NPs (Zhang et al. 2013; Song et al. 2014).

2.3 Chemical Properties of Nanoparticles

Chemical properties include the elemental composition of nanomaterials and its surface chemistry such as zeta potential and photocatalytic properties (Cadden 1987; Rao and Biswas 2009). The chemical properties of a material are determined by the type of motion of its electrons. There is a wide range of NPs contributing to many different chemical properties (Schmid 2011). Here, we describe the chemical characteristics separately with different kinds of NPs.

2.3.1 Metallic Nanoparticles

Compared with other nanostructures, metallic NPs have been proven to be the most flexible nanostructures owing to the synthetic control of their size, shape, composition, structure, assembly, and encapsulation, as well as the resulting tunability of their optical properties. Compared with other metallic nanostructures, colloidal gold and silver NPs are especially promising in nanobiotechnology because of their simple and fast preparation and bioconjugation. The attraction of surface plasmon excitations for the applications typically arises from the large electromagnetic field enhancement near the metal surface and the dependence of the resonance wavelength on the size, shape, and local dielectric properties of NPs. Such nanoparticles work as platform materials for biomolecular ultrasensitive detection, hyperthermal treatment for cancer, cell and protein labeling, and targeted delivery of therapeutic agents within the cells. Whereas silver NPs have a comparatively high cytotoxicity (Greulich et al. 2009), gold NPs are biologically almost inert (Mahl et al. 2011) and have a remarkable role on seed germination and antioxidant systems in Arabidopsis and altered levels of micro-RNAs expression that regulates various morphological, physiological, and metabolic processes in plants (Kumar et al. 2013).

2.3.2 Metal Oxide Nanoparticles

Metal oxide NPs can exhibit unique chemical properties due to their limited size and a high density of corner or edge surface sites. Particle size is expected to influence important groups of basic properties in any material. The properties such as structural characteristics, namely the lattice symmetry, cell parameters, and effect of size, are related to the electronic properties of the oxide, and structural and electronic properties obviously drive the chemical properties of the solid and also by size in a simple classification (Ayyub et al. 1995). Metal oxide particles serve many functions in the various field of plant technology (Picó and Blasco 2012; Raliya and Tarafdar 2013; Tarafdar et al. 2013). For example, nanosized silicon dioxide (SiO_2) treatments in proper concentration increased the percentage germination (Siddiqui and Al-Whaibi 2014). It was also reported that alumina NPs increased the root growth of plants (Lin and Xing 2007). Magnetic NPs exhibit a wide variety of attributions, which make them highly promising connection with biological system and bioapplications usually exists or can be prepared in the form of either single domain or superparamagnetic magnetite (Fe_2O_3) or greigite (Fe_3S_4). Due to their favorable beneficial effects, magnetic NPs approved for clinical use by Food and Drug Administration.

2.3.3 Quantum Dots

The size effects in metal oxide chemistry have frequently two interrelated faces, structural/electronic quantum-size and size-defect or non-stoichiometry effects. Structurally quantum dots (QDs) consist of a variety of metal complexes such as semiconductors, metals, and magnetic transition metals. The bioactivity of QDs can be improved by suitable surface coating with biocompatible material and/or modification with desired functional groups.

Depending on their size, it fluoresces with different colors and QD's composed of cadmium selenide core wrapped in zinc sulfide shell is such of a kind (Chan and Nie 1998; Kloepfer et al. 2003). To make them biologically compatible/active, newly synthesized QDs are functionalized or given secondary coatings, which improves water solubility. Studies also reported the effects of QDs on plant system showing both positive and negative effects (Nair et al. 2011).

2.3.4 Carbon Nanoparticles

The fullerene provided an exciting insight into carbon nanostructure and how architectures built from sp^2 carbon units based on simple geometrical principles can change the physical and chemical properties. Carbon nanotubes (CNTs) represent the more evident example. About decade after discovery, the knowledge available increased the interest in biological and biomedical applications of carbon nanotubes (Liu et al. 2007; Prato et al. 2007). There is a certain duality in the nanotubes. On the one hand, single-walled nanotubes consist of a single graphite sheet seamlessly wrapped into a cylindrical tube. Multiwalled nanotubes comprise an array of such nanotubes that are concentrically nested like rings of a tree trunk. Several of the enabling technology required for nanotube application are under development, for example, the ability to disperse individual multiwalled nanotubes uniformly into a polymer matrix and controlling its alignment within a composite material (Qian et al. 2000; Andrews et al. 2002). Recently, several works have been reported with the use of CNTs as smart delivery system for the delivery of desired molecules/chemicals to animal and plant cells. Another carbon modification from the NPs group are graphene oxide (GO) and their best known representative precursor for chemical preparation of graphene (Zhang et al. 2011). Recently, graphene/GOs have been extensively explored as imaging agents, drugs carries, and tissue engineering materials. The main advantage of these material is biodistribution and pharmacokinetics properties that can be turned by controlling the size, the surface chemistry, and the targeting ligand and highest Young's modulus among any known materials and the ability to increase the tensile strength of other materials. The combination of these advantages makes graphene an ideal platform for multimodal application in the biotechnological fields. Apart from these advantages, the important challenge and current limitations in this area are still the potential long-term toxicity. It was reported that fullerene and carbon nanotubes increased the water-retaining capacity, biomass, and fruit yield in plants up to 118 % which is highly remarkable (Husen and Siddiqi 2014).

2.3.5 Polymeric Nanoparticles

Polymer NPs have attracted the interest of many plant research groups. The term polymer nanoparticle is given for any type of polymer NPs but specifically for nanospheres and nanocapsules. These are obtained from synthetic such as from synthetic polymers, such as polycaprolactone (Bilensoy et al. 2009), polyacrylamide (Bilensoy et al. 2009), and polyacrylate (Turos et al. 2007), or natural polymers, albumin, DNA and chitosan (Martínez et al. 2011), gelatin, and poly (L-lactide) (PLA) (Mainardes et al. 2010; Saraogi et al. 2010). The various polymer NPs had been used to improve the pharmacokinetics and pharmacodynamics properties of various drugs, for example, chitosan polymer used as a carrier of plant extract (Bhatia et al. 2011).

Figure 2.4 shows the selective uptake, translocation, and biotransformation pathway of different NPs in plant organs. According to the scientist, data about NPs uptake by plants are still not conclusive (Rico et al. 2011).

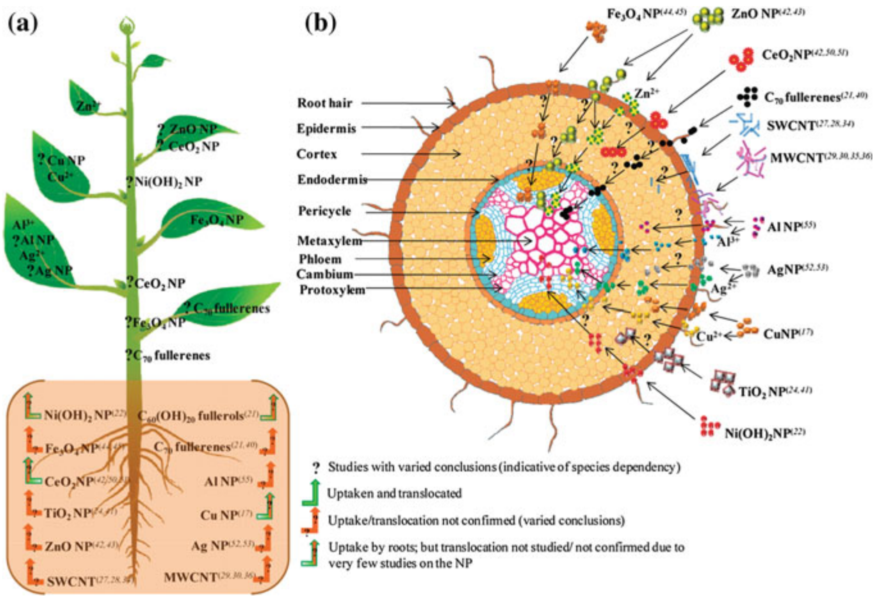

Fig. 2.4 Selective uptake, translocation, and biotransformation pathway of different NPs in plant organs (reprinted with permission from Cyrén and Hermansson 2012, copyright of American Chemical Society)

2.4 Merits and Demerits of Nanoparticles

Due to instability of the NPs, retaining the size and shape of NPs is highly challenging. As the kinetics associated with NPs is rapid and is highly reactive, they inherently interact with impurities. In addition, encapsulation of NPs becomes necessary when they are synthesized in a solution. Synthesis of pure NPs becomes highly difficult. Hence, retaining high purity in NPs can become a challenge hard to overcome. It is noticeable that most experimental studies with NPs have been carried out with aggregates/agglomerates of NPs. This has significantly repercussions on the biokinetics of the material. Several questions can be raised: What is the size distribution of the aggregates/agglomerates and what is the portion of the particles present as a monodispersed material?

Current research work revealed that the uptake, translocation, and accumulation of NPs depend on the species of plant and the size, chemical composition, functionalization, and stability of the NPs (Kole et al. 2013; Raliya et al. 2015). Among the carbon-based NPs, only the fullerene C_{70} and fullerols were shown to get readily accumulated in plants (Rico et al. 2011; Nair et al. 2012). Most of the data corresponding to the germination stage and cell culture, because the protocols for quantification of NPs within tissues, are not well defined yet.

The discussion of the current research is more oriented to the effect of the NPs on plants. A very few of the NPs to the next generation of plants exposed to NPs is unknown.

2.5 Conclusion

The major physical and chemical properties and comparative merits and demerits of NPs are discussed. NPs are capable of penetrating living plant tissues and migrating to different organs of the plant, although detailed study of their nature is very important. These studies allow us to constitute an important step forward in elucidating the mechanisms of interaction between plant cells and NPs and thus in designing strategies for using NPs for targeted delivery of substances. Although there are many exciting potential applications of NPs, considerable challenges and issues remain to be resolved. For example, nanomaterial remains a major problem, and it is hard to precisely control the number of functional molecules on the surface of NPs. Researchers need to develop better strategies for producing NPs that have precise composition, uniform surface modification, and reproducible functionalization. For applications, the purity, dispersity, and stability of the NPs in a physiological environment are highly important. Therefore, it is necessary to further study and explore physical and chemical properties for creating successful nanobiotechnology. Also, more studies are needed to explore the mode of action of NPs and their interaction and status in plant biomass.

References

Andrews R, Jacques D, Minot M, Rantell T (2002) Fabrication of carbon multiwall nanotube/polymer composites by shear mixing. Macromol Mater Eng 287:395–403

Ayyub P, Palkar V, Chattopadhyay S, Multani M (1995) Effect of crystal size reduction on lattice symmetry and cooperative properties. Phys Rev B 51:6135

Barreto Â, Luis LG, Girão AV, Trindade T, Soares AM, Oliveira M (2015) Behavior of colloidal gold nanoparticles in different ionic strength media. J Nanopart Res 17:1–13

Bhatia A, Shard P, Chopra D, Mishra T (2011) Chitosan nanoparticles as carrier of immunorestoratory plant extract: synthesis, characterization and immunorestoratory efficacy. Int J Drug Deliv 3:381–385

Bilensoy E, Sarisozen C, Esendağlı G, Doğan AL, Aktaş Y et al (2009) Intravesical cationic nanoparticles of chitosan and polycaprolactone for the delivery of Mitomycin C to bladder tumors. Int J Pharmaceut 371:170–176

Brew JA, Strano MS (2014) Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nat Mater 13:400–408

Cadden A (1987) Comparative effects of particle size reduction on physical structure and water binding properties of several plant fibers. J Food Sci 52:1595–1599

Campos EVR, de Oliveira JL, Fraceto LF (2014) Applications of controlled release systems for fungicides, herbicides, acaricides, nutrients, and plant growth hormones: a review. Adv Sci Eng Med 6:373–387

Chan WC, Nie S (1998) Quantum dot bioconjugates for ultrasensitive nonisotopic detection. Science 281:2016–2018

Cushing BL, Kolesnichenko VL, O'Connor CJ (2004) Recent advances in the liquid-phase syntheses of inorganic nanoparticles. Chem Rev 104:3893–3946

Cyrén B, Hermansson B (2012) Linear actuator assembly. U.S. Patent Application No. 14/359,669.

Ehrman SH, Friedlander SK, Zachariah MR (1999) Phase segregation in binary SiO2/TiO2 and SiO2/Fe2O3 nanoparticle aerosols formed in a premixed flame. J Mater Res 14:4551–4561

Eichert T, Kurtz A, Steiner U, Goldbach HE (2008) Size exclusion limits and lateral heterogeneity of the stomatal foliar uptake pathway for aqueous solutes and water-suspended nanoparticles. Physiol Planta 134:151–160

Ekambaram P, Sathali AAH, Priyanka K (2012) Solid lipid nanoparticles: a review. Sci Rev Chem Commun 2:80–102

Endo M, Iijima S, Dresselhaus MS (eds) (2013) Carbon Nanotubes. Elsevier, Shinshu University, Japan

Fedlheim DL, Foss CA (2001) Metal Nanoparticles: Synthesis, Characterization, and Applications. CRC Press, Boca Raton, FL, USA

Fernández-García M, Rodriguez JA (2011) Metal oxide nanoparticles. Encycl Inorg Bioinorg Chem. Instituto de Catálisis y Petroleoquímica, CSIC, Madrid, Spain and Brookhaven National Laboratory, Upton, NY, USA

Galbraith DW (2007) Nanobiotechnology: silica breaks through in plants. Nat Nanotechnol 2:272–273

Gilaki M (2010) Biosynthesis of silver nanoparticles using plant extracts. J Biol Sci 10:465–467

Greulich C, Kittler S, Epple M, Muhr G, Köller M (2009) Studies on the biocompatibility and the interaction of silver nanoparticles with human mesenchymal stem cells (hMSCs). Langenbeck's Arch Surg 394:495–502

Hayat MA (1974) Principles and Techniques of Scanning Electron Microscopy. Biological Applications,vol 1. Van Nostrand Reinhold Company, New Jersey, USA

Honary S, Zahir F (2013) Effect of zeta potential on the properties of nano-drug delivery systems-a review (Part 1). Trop J Pharmaceut Res 12:255–264

Husen A, Siddiqi KS (2014) Carbon and fullerene nanomaterials in plant system. J Nanobiotechnol 12:16

Jain D, Daima HK, Kachhwaha S, Kothari S (2009) Synthesis of plant-mediated silver nanoparticles using papaya fruit extract and evaluation of their anti microbial activities. Digest J Nanomater Biostruct 4:557–563

Jiang J, Chen D-R, Biswas P (2007) Synthesis of nanoparticles in a flame aerosol reactor with independent and strict control of their size, crystal phase and morphology. Nanotechnology 18:285603

Jolivet J-P, Froidefond C, Pottier A, Chanéac C, Cassaignon S et al (2004) Size tailoring of oxide nanoparticles by precipitation in aqueous medium. A Semi-Quant Model J Mater Chem 14:3281–3288

Klaus T, Joerger R, Olsson E, Granqvist C-G (1999) Silver-based crystalline nanoparticles, microbially fabricated. Proc Natl Acad Sci USA 96:13611–13614

Kloepfer J, Mielke R, Wong M, Nealson K, Stucky G, Nadeau J (2003) Quantum dots as strain-and metabolism-specific microbiological labels. Appl Environ Microb 69:4205–4213

Kole C, Kole P, Randunu KM, Choudhary P, Podila R et al (2013) Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (*Momordica charantia*). BMC Biotechnol 13:37

Konishi Y, Ohno K, Saitoh N, Nomura T, Nagamine S et al (2007) Bioreductive deposition of platinum nanoparticles on the bacterium (*Shewanella algae*). J Biotechnol 128:648–653

Kumar V, Guleria P, Kumar V, Yadav SK (2013) Gold nanoparticle exposure induces growth and yield enhancement in *Arabidopsis thaliana*. Sci Total Environ 461:462–468

Kumar V, Yadav SK (2009) Plant-mediated synthesis of silver and gold nanoparticles and their applications. J Chem Technol Biotechnol 84:151–157

Lin D, Xing B (2007) Phytotoxicity of nanoparticles: inhibition of seed germination and root growth. Environ Pollut 150:243–250

Liu Z, Sun X, Nakayama-Ratchford N, Dai H (2007) Supramolecular chemistry on water-soluble carbon nanotubes for drug loading and delivery. ACS Nano 1:50–56

Lövestam G, Rauscher H, Roebben G, Klüttgen BS, Gibson N et al (2010) Considerations on a definition of Nanomaterial for regulatory purposes. Publications Office of the European Union

Mahl D, Diendorf J, Meyer-Zaika W, Epple M (2011) Possibilities and limitations of different analytical methods for the size determination of a bimodal dispersion of metallic nanoparticles. Colloids Surf A Physicochem Eng Asp 377:386–392

Mainardes RM, Khalil NM, Gremião MPD (2010) Intranasal delivery of zidovudine by PLA and PLA–PEG blend nanoparticles. Int J Pharmaceut 395:266–271

Martínez A, Iglesias I, Lozano R, Teijón J, Blanco M (2011) Synthesis and characterization of thiolated alginate-albumin nanoparticles stabilized by disulfide bonds. Evaluation as drug delivery systems. Carbohyd Polym 83:1311–1321

Mittal AK, Chisti Y, Banerjee UC (2013) Synthesis of metallic nanoparticles using plant extracts. Biotechnol Adv 31:346–356

Nair R, Mohamed MS, Gao W, Maekawa T, Yoshida Y et al (2012) Effect of carbon nanomaterials on the germination and growth of rice plants. J Nanosci Nanotechnol 12:2212–2220

Nair R, Poulose AC, Nagaoka Y, Yoshida Y, Maekawa T, Kumar DS (2011) Uptake of FITC labeled silica nanoparticles and quantum dots by rice seedlings: effects on seed germination and their potential as biolabels for plants. J Fluores 21:2057–2068

Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS (2010) Nanoparticulate material delivery to plants. Plant Sci 179:154–163

Nowack B, Bucheli TD (2007) Occurrence, behavior and effects of nanoparticles in the environment. Environ Pollut 150:5–22

Orts-Gil G, Natte K, Drescher D, Bresch H, Mantion A et al (2011) Characterisation of silica nanoparticles prior to in vitro studies: from primary particles to agglomerates. J Nanopart Res 13:1593–1604

Paques JP, van der Linden E, van Rijn CJ, Sagis LM (2014) Preparation methods of alginate nanoparticles. Adv Colloid Interf Sci 209:163–171
Picó Y, Blasco C (2012) Nanomaterials in food, which way forward? Analys Risk Nanomater Environ Food Samp 59:305
Prato M, Kostarelos K, Bianco A (2007) Functionalized carbon nanotubes in drug design and discovery. Accounts Chem Res 41:60–68
Qian D, Dickey EC, Andrews R, Rantell T (2000) Load transfer and deformation mechanisms in carbon nanotube-polystyrene composites. Appl Phys Lett 76:2868–2870
Raliya R, Nair R, Chavalmane S, Wang W-N, Biswas P (2015) Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (*Solanum lycopersicum* L.) plant. Metallomics 7:1584–1594
Raliya R, Tarafdar J (2012) Novel approach for silver nanoparticle synthesis using *Aspergillus terreus* CZR-1: mechanism perspective. J Bionanosci 6:12–16
Raliya R, Tarafdar J (2013) ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in Clusterbean (*Cyamopsis tetragonoloba* L.). Agric Res 2:48–57
Rao C, Biswas K (2009) Characterization of nanomaterials by physical methods. Annu Rev Analyt Chem 2:435–462
Rao JP, Geckeler KE (2011) Polymer nanoparticles: preparation techniques and size-control parameters. Prog Polymer Sci 36:887–913
Rico CM et al (2011) Interaction of nanoparticles with edible plants and their possible implications in the food chain. J Agric Food Chem 59:3485–3498
Saraogi GK, Gupta P, Gupta U, Jain N, Agrawal G (2010) Gelatin nanocarriers as potential vectors for effective management of tuberculosis. Int J Pharmaceut 385:143–149
Schmid G (ed) (2011) Nanoparticles: From Theory to Application. Wiley-VCH, Weinheim, Germany
Schreck E, Foucault Y, Sarret G, Sobanska S, Cécillon L et al (2012) Metal and metalloid foliar uptake by various plant species exposed to atmospheric industrial fallout: Mechanisms involved for lead. Sci Total Environ 427:253–262
Siddiqui MH, Al-Whaibi MH (2014) Role of nano-SiO_2 in germination of tomato (*Lycopersicum esculentum* seeds Mill.). Saudi J Biol Sci 21:13–17
Song L, Connolly M, Fernández-Cruz ML, Vijver MG, Fernández M et al (2014) Species-specific toxicity of copper nanoparticles among mammalian and piscine cell lines. Nanotoxicology 8:383–393
Slomberg DL, Schoenfisch MH (2012) Silica nanoparticle phytotoxicity to Arabidopsis thaliana. Environ Sci Technol 46(18):10247–10254
Syu Y-y, Hung J-H, Chen J-C, Chuang H-W (2014) Impacts of size and shape of silver nanoparticles on Arabidopsis plant growth and gene expression. Plant Physiol Biochem 83:57–64
Tarafdar A, Raliya R, Wang W-N, Biswas P, Tarafdar J (2013) Green synthesis of TiO2 nanoparticle using Aspergillus tubingensis. Adv Sci Eng Med 5:943–949
Thimsen E, Rastgar N, Biswas P (2008) Nanostructured TiO_2 films with controlled morphology synthesized in a single step process: Performance of dye-sensitized solar cells and photo watersplitting. J Phys Chem C 112:4134–4140
Tripathi S, Sonkar SK, Sarkar S (2011) Growth stimulation of gram (*Cicer arietinum*) plant by water soluble carbon nanotubes. Nanoscale 3:1176–1181
Turos E, Shim J-Y, Wang Y, Greenhalgh K, Reddy GSK et al (2007) Antibiotic-conjugated polyacrylate nanoparticles: New opportunities for development of anti-MRSA agents. Bioorg Med Chem Lett 17:53–56

Wang W-N, Tarafdar JC, Biswas P (2013) Nanoparticle synthesis and delivery by an aerosol route for watermelon plant foliar uptake. J Nanopart Res 15:1–13

Warren BE (1969) X-ray Diffraction. Courier Dover Publications. Reprint of the Addison- Wesley Publishing Compnay, Inc,. Reading Massachusettes, USA, 1969 edn

Wu H-L, Kuo C-H, Huang MH (2010) Seed-mediated synthesis of gold nanocrystals with systematic shape evolution from cubic to trisoctahedral and rhombic dodecahedral structures. Langmuir 26:12307–12313

Zhang P, Ma Y, Zhang Z, He X, Li Y et al (2013) Species-specific toxicity of ceria nanoparticles to *Lactuca* plants. Nanotoxicology 9:1–8

Zhang Y, Ren L, Wang S, Marathe A, Chaudhuri J, Li G (2011) Functionalization of graphene sheets through fullerene attachment. J Mater Chem 21:5386–5391

Springer

http://www.springer.com/978-3-319-42152-0

Plant Nanotechnology
Principles and Practices
Kole, C.; Kumar, D.S.; Khodakovskaya, M.V. (Eds.)
2016, XV, 383 p. 73 illus., 54 illus. in color., Hardcover
ISBN: 978-3-319-42152-0