Paradigm Academic Press
Innovation in Science and Technology
ISSN 2788-7030
JAN. 2023 VOL.2, NO.1

A Review on Nanomaterials: Types, Synthesis, Characterization Techniques, Properties and Applications

Iqra Shaheen[1], Adnan Khalil[1], Rahila Shaheen[1] & M. Bilal Tahir[1]

[1] Department of Physics, Khwaja Fareed University of Engineering and Information Technology, 64200, Rahim Yar Khan

Correspondence: Rahila Shaheen, Department of Physics, Khwaja Fareed University of Engineering and Information Technology, 64200, Rahim Yar Khan.

doi:10.56397/IST.2023.01.04

Abstract

Nanotechnology is science, technology, and engineering that is directed at the nano scale (1-100 nm). This is a diverse and attractive field, owing to its unique properties and applications. The surface- to- volume ratio is the most important property of a material, which makes a clear difference between bulk materials and materials at nano scale. Nano can be referring to materials, particles, thin films, wires, fibers, etc. Nanotechnology is a revolutionary method for developing of new systems and technologies. In this study, the types of nano materials on their structures are discussed. The remarkable properties of the nanomaterials have also been explained. Common characterization techniques are explained and highlight the applications of nano materials. The conclusions of all the sections are presented at the end of the paper.

Keywords: nanotechnology, nanomaterials, applications, nanoparticles, thin films, nano fibers, properties, characterization

1. Introduction

Nano scale science is known as nanotechnology. Nano scale is defined as the scale of 1-100nm, diameter of human hair is about 80,000-100,000nm wide and the thickness of sheet of paper is about 100,000nm. Nanotechnology can be Top-down and Bottom-up. In Top-down, a block of material is etching to the required shape. Microprocessors and chips are the examples of Top-down approach. In Bottom-up, material is built atom by atom such as Lego. Quantum dots and nanotubes such as carbon nanotubes are the examples of Bottom-up approach. Nano can be referred to the particles, nanomaterials, thin films, quantum dots, tubes, flowers, wires etc. But the main focus is for nano materials due to its wide use in workplaces. Nanomaterials can be occurring in three ways 1) Naturally 2) Engineered and 3) Formed by human activity. In naturally occurring nanomaterials, there are viruses, mineral composites, forest fires, sea spray and volcanic ash etc. In engineered nanomaterials, there are metals, nanocapsules, buckyballs, nanotubes, quantum dots and sunscreen pigment etc. These materials are produced by humans by using different methodologies and techniques. In the third one, these nanomaterials are incidental materials occur due to human activity as a product of other activity performed such as smoke, welding fumes, industrial waste and diesel exhaust etc. Surface size can differentiate nanomaterials from bulk materials as at the nano scale surface size is large as compared to bulk materials. When surface size (surface to volume ratio) varies then the properties of material at nano scale become changes i.e., conductivity, shape, melting point, reactivity and fluorescence. The paper explains the types of nanomaterials on the basis of dimensions and structures. The most common methodologies for the synthesis of nanomaterials and characterization techniques are discussed. After that the properties with applications of nanomaterials are being discussed briefly. At the end, the conclusion of whole paper is explained.

2. Classification of Nanomaterials

On the base of dimensionality, nanomaterials are classified into four classes (F. Trotta & A. Mele, 2019):

(1) 0-D nanomaterials- nanoclusters, nanoparticles, quantum dots, fullerenes, nanospheres.

(2) 1-D nanomaterials- nanorods, nanowires, nanotubes and nanofibers.

(3) 2-D nanomaterials- thin films, coatings and nano-layered sheets.

(4) 3-D nanomaterials- polycrystalline, liposomes and bulk nanomaterials.

3. Synthesis of Nanomaterials Using Top-Down and Bottom-Up Approach

There are some most common techniques that are used to synthesize nanomaterials by using top-down and bottom-up approaches. In top-down approach, sputtering process, grinding and polishing, ball milling, lithography vapor deposition (LVD), electric arc deposition method, laser ablation, thermal evaporation techniques can use. In bottom-up approach, wet chemical method, chemical vapor deposition (CVD), condensation, soft lithography, hydrothermal, sol-gel and co-precipitation methods can be used (N. Abid, A. M. Khan, S. Shujait, K. Chaudhary, M. Ikram, M. Imran & M. Maqbool, 2021; I. Khan & K. Saeed I. Khan, 2019).

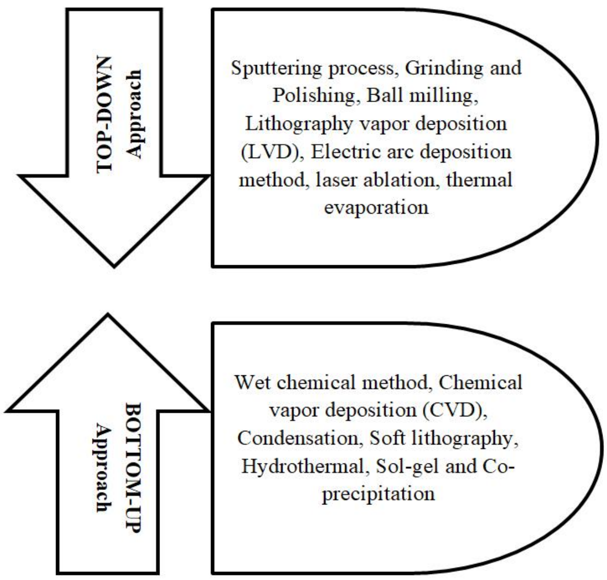

Figure 1. Synthesis of nanomaterials using approaches (1) Top-down and (2) Bottom-up

4. Types of Nanomaterials

Nanomaterials can be classified on the basis of structure. Most common are discuss here;

4.1 Nano Particles (NPs)

Nanoparticles (NPs) are zero dimensional particles which have size in the range of 1-100nm. It can’t be seen by naked eye. Most of the nanoparticles are formed by hundreds of atoms. The surface size of nanoparticles is very large, so more atoms of material interact with neighboring atoms. Hence, its chemical reactivity is more. There are several kinds of nanoparticles on the basis of chemical properties, size and morphology such as carbon nanoparticles, semi-conductor nanoparticles, polymeric nanoparticles, lipid nanoparticles, ceramics nanoparticles and metal nanoparticles (I. Khan & K. Saeed I. Khan, 2019). Carbon NPs are formed of carbon such as graphene, carbon nanotubes (CNTs) and fullerenes and they are need in the application of environment treatment (J.M. Ngoy, N. Wagner, L. Riboldi & O. Bolland, 2014) and as a medium for support (L.F. Mabena, S. Sinha Ray, S.D. Mhlanga & N.J. Coville, 2011). Semi- conductor NPs properties are in between conductors and insulators. There are several applications of semi-conductor NPs is given in literature (S. Ali, I. Khan, S.A. Khan, M. Sohail, R. Ahmed, A. Rehman, M.S. Ur Ansari & M.A. Morsy, 2017; I. Khan, A. Abdalla & A. Qurashi, 2017). The beauty of semi-conductor NPs is its wide energy band gap. Due to varying band gap, its properties are changes. Hence, this material is considered best for photocatalysis, electronic devices and photo-optics (S. Sun, 2000). This material is efficient for water splitting and it is used widely due to suitable energy gap (T. Hisatomi, J. Kubota & K. Domen, 2014). Polymeric NPs are usually organic nanoparticles. They are in the form of capsular or sphere (M. Mansha, I. Khan, N. Ullah & A. Qurashi, 2017) and have several applications in drug delivery (N.H. Abd

Ellah & S.A. Abouelmagd, 2016). Lipid based NPs are usually liposomes and have several applications in bio medical field such as drug design, drug delivery (A. Puri, K. Loomis, B. Smith, J.-H. Lee, A. Yavlovich, E. Heldman & R. Blumenthal, 2009) and cancer therapy (M. Gujrati, A. Malamas, T. Shin, E. Jin, Y. Sun & Z.-R. Lu, 2014). Ceramics NPs are synthesized by cooling or heating. These are usually non-metals inorganic particles. They are using in several applications such as photocatalysis, dye degradation, imaging and drug delivery (S. Thomas, B. S. P. Harshita, P. Mishra & S. Talegaonkar, 2015). Metal NPs are made up of metals such as gold, silver and copper nanoparticles. These NPs possess excellent optical properties and due to this they are widely used in many applications such as biomedicine, drug design, biosensors etc.

4.2 Thin Film

Thin film enhanced the surface of the material such as absorption, reflection, hardness, corrosion and resistance etc. These are created by the deposited of atoms on a substrate and form layer. The process through which thin films are created called deposition. There are few deposition techniques that are using for the production of thin films such as physical vapor deposition (PVD), Chemical vapor deposition (CVP), sputtering, laser ablation, vacuum evaporation. These are many applications including sensors, electro-catalysis, drug delivery, optoelectronics, solar cells and photovoltaic cells etc. (A. Edwin, 2015).

4.3 Quantum Dots

Quantum dots are artificially (man-made) made semiconductor particles at nano scale. The purpose of these quantum dots is to transport the electrons. When ultra violet (UV) light is fall on these semiconductor particles, they start emitting different colors of light. These are used in several applications due to its extra unique properties such as in solar cells, composites, drug design, biological labeling and imaging.

4.4 Nano Wires

Nano wires are in the form of wires at nano-scale having diameter of the order of 10^{-9} or nm. The morphology of these wires is straight or curved. On the basis of shape and length these nanowires are classify into three types 1) Belt shape 2) Zigzag shape 3) Helix. Nanowires are usually formed of metals and semiconductors such as copper, silver, cobalt, gold and silicon. CVD is used for the synthesis of nanowires. Nano wires can also prepare of insulators and superconductors (S. Jung & K. Yong, 2011). These can be preparing by different techniques such as solution phase synthesis, non-catalytic growth, vapor liquid solid method and DNA template metallic nano wires. In solution phase synthesis, number of nanowires are produced more as compared to the other types of techniques. This is more convenient techniques used for preparing lead, platinum, gold and silver nanowires. In non-catalytic growth (J. B. Rivest & P. K. Jain, 2013), the simplest method to prepare nano wires is of heating metals with joule heating in air. These nanowires are also prepared with the help of catalyst, but numbers of steps are minimized. In vapor liquid solid method; it is most common technique use introduced in 1964 by Ellis and Wagner. By using this method, nanowires of diameter produced are about hundreds of µm to hundreds of nm. In DNA template metallic nano wires, production of nanowires is so easy and metallic nano wires are prepared and used for the applications of the biosensors.

4.5 Nano Fibers

Nano fibers are 1-D material in the shape of fiber and have size of 50-1000nm. These have high surface to volume ratio, controlled morphology, high porosity, high thermal stability, high chemical stability and high mass transport. Highly pure nano fibers are synthesized from a technique named electrospinning. Electrospinning is most convenient and excellent to produce large amount of pure nano fibers due to high surface area. Electrospinning is work on the principle of electrohydrodynamics in which high electric voltage is applied across collector surface and a liquid solution, then solution is ejected from nozzle and formed a jet and then this jet start producing fibers on the surface of collector (J. Xue, T. Wu, Y. Dai & Y. Xia, 2019).

5. Characterization Techniques Used for Nanomaterials

There are several techniques which are used for characterization of chemical and physical properties of materials. These chemical and physical properties are including size, structure, morphology, composition, stability, texture and surface area. Moreover, there are also other properties present in a material such as electrical, optical, biological and photochemical properties. Most common characterization techniques along with properties of nanomaterials are listed in Table 1.

Table 1. Listed Properties of nanomaterials using characterization techniques

Properties	**Techniques Used**
Chemical Properties	EDX Spectroscopy, FTIR Spectroscopy and Ultra-violet visible Spectroscopy

Purity, composition and conformational changes	Nuclear Magnetic Resonance (NMR)
Functional group analysis and Bioconjugate conformational analysis	Surface enhance Raman Spectroscopy, Raman Spectroscopy and Infrared Spectroscopy (IR)
Elemental composition and chemical composition	X-rays photoelectron Spectroscopy (XPS)
Size and shape	Transmission electron microscope (TEM), Scanning electron microscope (SEM), Scanning tunneling electron microscope (STEM), Field emission scanning electron microscope (FESEM), Near field scanning optical microscope(NSOM), Atomic force microscope AFM and Dynamic light scattering (DLS)
Size distribution	Scanning electron microscope (SEM), Scanning tunneling electron microscope (STEM), Field emission scanning electron microscope (FESEM) and Transmission electron microscope (TEM).
Structure	Raman Spectroscopy and IR Spectroscopy, NMR, Atomic force microscope (AFM) and Dynamic light scattering (DLS), Mass Spectrometry (MS)
Aggregation analysis	Scanning electron microscope (SEM), Scanning tunneling electron microscope (STEM), Field emission scanning electron microscope (FESEM) and Transmission electron microscope (TEM) Dynamic light scattering (DLS) and Atomic force microscope (AFM).
Surface Properties	XRD, BET, Dynamic light scattering (DLS), Atomic force microscope (AFM), TEM and SEM, MS
Optical Properties	Microscopy, Double photon correlation Spectroscopy
Size distribution (Hydrodynamic)	Dynamic light scattering (DLS)
Electrical Properties	Electro-kinetics
Surface charge stability	Zeta Potential
Molecular weight	Mass spectrometry (MS)
Contents	High performance liquid chromatography (HPLC)
Biological Properties	In vivo, In vitro cell and microbial colony viability
Interaction between polymer and drug, physiochemical state	Differential scanning calorimeter (DSC)

6. Properties and Applications of Nanomaterials

Properties of nanomaterials decided its application. So, once the properties get knows then the material can be used in required application. Here all the properties of nanomaterials and its application are discussed below.

6.1 Magnetic Properties

Magnetic properties are affected by the size of particle. If the size of particle is less than 35nm, these particles will show excellent performance (R. Lamouri, O. Mounkachi, E. Salmani, M. Hamedoun, A. Benyoussef & H. Ez-Zahraouy, 2019; V.G. Shrimali, K. Gadani, B. Rajyaguru, H. Gohil, D.K. Chudasama, D. Dhruv, A.D. Joshi, D.D. Pandya, P.S. Solanki & N.A. Shah, 2019). The number of magnetic atoms shows the value of magnetic moment of molecule in single type compound nanoparticles but according to VESPR theory, the number of lone pairs of electrons shows the value of magnetic moment of molecule in multi type compound nanoparticles. When the size of particle changes, lattice parameter is changes and hence magnetization values will change. For metals, lattice parameter does not change because the change in the size of particles is so small in metals. Meanwhile, in case of metals which consist of metal oxides on its surface will influence by the change in size of particle which changes the lattice parameter of metal oxides and metal. Therefore, magnetization value of metal and metal oxides changes. Magnetic properties are also influenced by the synthesis methods and by changes composition of material (H.R. Lakshmiprasanna, V. Jagadeesha Angadi, B. Rajesh Babu, M. Pasha, K. Manjunatha & S. Matteppanavar, 2019; F.J. Owens, 2015). Magnetic nanomaterials are used in medical and environmental applications.

6.2 Electronic Properties

Electronic properties are influenced by the size of particle, chemical composition, alteration and area of surface (S.W. Shin, I.H. Song & S.H. Um, 2015). Surface characterization of nanomaterials can be improved by the organic compound for example ligands. Structural characterization affected by the use of ligands monomers of different types. In aggregation process, the material size is control by the modification of aluminum oxide (Al_2O_3) along with organic ligands (C. Henkel, J.E. Wittmann, J. Träg, J. Will, L.M.S. Stiegler, P. Strohriegl, A. Hirsch, T. Unruh, D. Zahn, M. Halik & D.M. Guldi, 2019). Different electrical properties are getting by this kind of modification. Polymers system with the addition of inorganic compounds enhanced the electric properties of nanocomposites polymers (M.L. Hassan, A.F. Ali, A.H. Salama & A.M. Abdel-Karim, 2019). With the addition of perovskite structure and piezoelectric properties material such as Barium titanate, electrical properties are improved such as dielectric constant and conductivity.

6.3 Optical Properties

Optical properties are influenced by the varying size, shape, distribution size and the modification type. These factors increased the wavelength of absorption in semiconductor materials. UV visible spectroscopy has been used to study the optical properties of NiO-doped Nd (M.A. Rahman, R. Radhakrishnan & R. Gopalakrishnan, 2018). Due to Nd^{+3} localized electrons and the electrons exchange in energy band, energy value is shifted to lower value of NiO-doped Nd as compared to pure NiO (N. Pauly, F. Yubero, F.J. García-García & S. Tougaard, 2016). Optical properties can find out by using basic principles of light such as reflection, refraction, diffraction, scattering etc. and beer-lambert law. Composition of nanomaterials such as modification of surface and doping of metal ion also influenced the optical properties of nanomaterials. By the change of particle size of nanomaterials, optical properties changes such as scattering and reflectance process (N. Piri, A. Shams-Nateri & J. Mokhtari, 2016). The reflectance is directly proportional to particle size but inversely proportional to the refractive index. Scattering pattern of particle is also changes with the change of particle size (M.M. Mikhailov, S.A. Yuryev & A.A. Lovitskiy, 2018). Due to optical properties, nanomaterials usually semiconductors are used in many applications such as photovoltaic cells and photocatalysis.

6.4 Mechanical Properties

Mechanical properties such as stress, hardness, strain, modulus and the adhesion are influenced by the surface area of nanomaterials. As nanomaterials have large surface area and also can easily modify, so the above mechanical properties increased. Nanomaterials of inorganic compounds provide mechanical properties although organic compounds nanoparticles show low mechanical properties. So, the inorganic compounds are added in organic compounds to enhance the mechanical properties. SnO_2 metal oxide adds in acrylic polyurethane and studied mechanical properties (T.M.A. Bui, T.V. Nguyen, T.M. Nguyen, T.H. Hoang, T.T.H. Nguyen, T.H. Lai, T.N. Tran, V.H. Nguyen, V.H. Hoang, T.L. Le, D.L. Tran, T.C. Dang, Q.T. Vu & P. Nguyen-Tri, 2020). If more metal oxides add in polymer matrix, it may influence the reduction of mechanical properties due to the more metal oxide presence, which can reduce the interaction of polymer-polymer, metal oxide and polymer interaction and possible process of agglomeration. Mechanical properties are also depending on the size of particle, as the size is greater, surface area will be greater and therefore there is more possibility of interaction of atom with neighbor atoms reported by other studies (L. An, D. Zhang, L. Zhang & G. Feng, 2019).

6.5 Thermal Properties

Nanoparticles have higher surface area therefore their thermal properties are much better as compared to their liquid form. Heat is transfer directly on the material surface. When addition of polycarbonate with metal oxide SiO_2 is increases then thermal properties increased gradually (J. Nomai & A.K. Schlarb, 2019). When nanofiller of high thermal conductivity are added to nanoparticles, they affect the thermal properties of nanomaterials (H. Jeon & K. Lee, 2019). There are following factors on which thermal properties are dependent on i.e., surface area, volume dispersion of nanoparticles in fraction, concentration of mass and nanoparticle's energy ratio of atoms.

7. Conclusion

Nanotechnology is advance interdisciplinary field. Surface size is most important property involve in changing the nature of material from bulk to nano scale. Surface size influenced all properties of nanomaterials such as mechanical, electronic, optical, magnetic and thermal properties. When surface size (surface to volume ratio) varies then conductivity, shape, melting point, reactivity and fluorescence also change accordingly. On the base of dimensionality, nanomaterials are classified into four classes O-D, 1-D, 2-D and 3-D. There are two techniques that are used to synthesize nanomaterials 1) Top-down and 2) Bottom-up approaches. The process through which thin films are created called deposition. The purpose of quantum dots is to transport the electrons. Highly pure nano fibers are synthesized from a technique named electrospinning. Electrospinning is most convenient and excellent method to produce large amount of pure nano fibers due to high surface area. Moreover, for the synthesis of nanomaterials, the most common and widely used methods are co precipitation, sol-gel and hydrothermal. But these methods may create toxicity, cause environmental effects and expensive. Therefore, green synthesis method becomes so popular due to its extra ordinary significance and environmental friendly. In green synthesis, nanoparticles are synthesized by using plant extract (N. Jayarambabu, A. Akshaykranth, T. Venkatappa Rao, K. Venkateswara Rao & R. Rakesh Kumar, 2020). Characterization techniques have been summarized in this paper. In future, environment friendly and cost-effective methods are needed to introduce for the fabrication of nanomaterials.

References

F. Trotta and A. Mele, (2019). Nanomaterials: classification and properties. *Nanosponges: Synthesis and Applications: First Edition,* Wiley, London.

N. Abid, A. M. Khan, S. Shujait, K. Chaudhary, M. Ikram, M. Imran and M. Maqbool, (2021). 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*(15), 102597.

I. Khan, K. Saeed I. Khan, (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*, *12*(7), 908-931.

J.M. Ngoy, N. Wagner, L. Riboldi, O. Bolland, (2014). A CO2 capture technology using multi-walled carbon nanotubes with polyaspartamide surfactant, *Energy Procedia, 63*, pp. 2230-2248.

L.F. Mabena, S. Sinha Ray, S.D. Mhlanga, N.J. Coville, (2011). Nitrogen-doped carbon nanotubes as a metal catalyst support, *Appl. Nanosci., 1*, pp. 67-77.

S. Ali, I. Khan, S.A. Khan, M. Sohail, R. Ahmed, A. Rehman, M.S. Ur Ansari, M.A. Morsy, (2017). Electrocatalytic performance of Ni@Pt core–shell nanoparticles supported on carbon nanotubes for methanol oxidation reaction, *J. Electroanal. Chem., 795*, pp. 17-25.

I. Khan, A. Abdalla, A. Qurashi, (2017). Synthesis of hierarchical WO3 and Bi2O3/WO3 nanocomposite for solar-driven water splitting applications, *Int. J. Hydrogen Energy, 42*, pp. 3431-3439.

S. Sun, (2000). Monodisperse FePt nanoparticles and ferromagnetic FePt nanocrystal superlattices, *Science, 287*(5460), pp. 1989-1992.

T. Hisatomi, J. Kubota, K. Domen, (2014). Recent advances in semiconductors for photocatalytic and photoelectrochemical water splitting, *Chem. Soc. Rev., 43*, pp. 7520-7535.

M. Mansha, I. Khan, N. Ullah, A. Qurashi, (2017). Synthesis, characterization and visible-light-driven photoelectrochemical hydrogen evolution reaction of carbazole-containing conjugated polymers, *Int. J. Hydrogen Energy*.

N.H. Abd Ellah, S.A. Abouelmagd, (2016). Surface functionalization of polymeric nanoparticles for tumor drug delivery: approaches and challenges, *Expert Opin. Drug Deliv.*, 1-14.

A. Puri, K. Loomis, B. Smith, J.-H. Lee, A. Yavlovich, E. Heldman, R. Blumenthal, (2009). Lipid-based nanoparticles as pharmaceutical drug carriers: from concepts to clinic, *Crit. Rev. Ther. Drug Carrier Syst., 26*, pp. 523-580.

M. Gujrati, A. Malamas, T. Shin, E. Jin, Y. Sun, Z.-R. Lu, (2014). Multifunctional cationic lipid-based nanoparticles facilitate endosomal escape and reduction-triggered cytosolic siRNA release, *Mol. Pharm., 11*, pp. 2734-2744.

S. Thomas, B. S. P. Harshita, P. Mishra, S. Talegaonkar, (2015). Ceramic nanoparticles: fabrication methods and applications in drug delivery, *Curr. Pharm. Des., 21*, pp. 6165-6188.

A. Edwin, (2015). Thin Films/Properties and Applications. In (Ed.), *Thin Films*. IntechOpen.

S. Jung and K. Yong, (2011). Fabrication of CuO–ZnO nanowires on a stainless steel mesh for highly efficient photocatalytic applications. *Chemical Communications, 47*(9), 2643-2645.

J. B. Rivest and P. K. Jain, (2013). Cation exchange on the nanoscale: an emerging technique for new material synthesis, device fabrication, and chemical sensing. *Chemical Society Reviews, 42*(1), 89-96.

J. Xue, T. Wu, Y. Dai and Y. Xia, (2019). Electrospinning and Electrospun Nanofibers: Methods, Materials, and Applications. *Chemical reviews, 119*(8), 5298–5415.

R. Lamouri, O. Mounkachi, E. Salmani, M. Hamedoun, A. Benyoussef, H. Ez-Zahraouy, (2019). Size effect on the magnetic properties of CoFe2O4 nanoparticles: A Monte Carlo study, *Ceramics International*.

V.G. Shrimali, K. Gadani, B. Rajyaguru, H. Gohil, D.K. Chudasama, D. Dhruv, A.D. Joshi, D.D. Pandya, P.S. Solanki, N.A. Shah, (2019). Size dependent dielectric, magnetic, transport and magnetodielectric properties of BiFe0.98Co0.02O3 nanoparticles, *Journal of Alloys and Compounds*, 152685.

H.R. Lakshmiprasanna, V. Jagadeesha Angadi, B. Rajesh Babu, M. Pasha, K. Manjunatha and S. Matteppanavar, (2019). Effect of Pr3+-doping on the structural, elastic and magnetic properties of Mn–Zn ferrite nanoparticles prepared by solution combustion synthesis method, *Chemical Data Collections, 24*, 100273.

F.J. Owens, (2015). Properties of Magnetic Nanoparticles, in: *Physics of Magnetic Nanostructures*, pp. 35-53.

S.W. Shin, I.H. Song and S.H. Um, (2015). Role of Physicochemical Properties in Nanoparticle Toxicity, *Nanomaterials, 5*, 1351-1365.

C. Henkel, J.E. Wittmann, J. Träg, J. Will, L.M.S. Stiegler, P. Strohriegl, A. Hirsch, T. Unruh, D. Zahn, M. Halik and D.M. Guldi, (2019). Mixed Organic Ligand Shells: Controlling the Nanoparticle Surface Morphology toward Tuning the Optoelectronic Properties, *Small, 16*(2), 1903729.

M.L. Hassan, A.F. Ali, A.H. Salama and A.M. Abdel-Karim, (2019). Novel cellulose nanofibers/barium titanate nanoparticles nanocomposites and their electrical properties, *Journal of Physical Organic Chemistry, 32*, e3897.

M.A. Rahman, R. Radhakrishnan and R. Gopalakrishnan, (2018). Structural, optical, magnetic and antibacterial properties of Nd doped NiO nanoparticles prepared by co-precipitation method, *Journal of Alloys and Compounds, 742*, 421-429.

N. Pauly, F. Yubero, F.J. García-García and S. Tougaard, (2016). Quantitative analysis of Ni 2p photoemission in NiO and Ni diluted in a SiO2 matrix, *Surface Science, 644*, 46-52.

N. Piri, A. Shams-Nateri and J. Mokhtari, (2016). The relationship between refractive index and optical properties of absorbing nanoparticle, *Color Research & Application, 41*, 477-483.

M.M. Mikhailov, S.A. Yuryev and A.A. Lovitskiy, (2018). On the correlation between diffuse reflectance spectra and particle size of BaSO4 powder under heating and modifying with SiO2 nanoparticles, *Optical Materials, 85*, 226-229.

T.M.A. Bui, T.V. Nguyen, T.M. Nguyen, T.H. Hoang, T.T.H. Nguyen, T.H. Lai, T.N. Tran, V.H. Nguyen, V.H. Hoang, T.L. Le, D.L. Tran, T.C. Dang, Q.T. Vu and P. Nguyen-Tri, (2020). Investigation of crosslinking, mechanical properties and weathering stability of acrylic polyurethane coating reinforced by SiO2 nanoparticles issued from rice husk ash, *Materials Chemistry and Physics, 241*, 122445.

L. An, D. Zhang, L. Zhang and G. Feng, (2019). Effect of nanoparticle size on the mechanical properties of nanoparticle assemblies, *Nanoscale, 11*, 9563-9573.

J. Nomai and A.K. Schlarb, (2019). Effects of nanoparticle size and concentration on optical, toughness, and thermal properties of polycarbonate, *Journal of Applied Polymer Science, 136*, 47634.

H. Jeon and K. Lee, (2019). Effect of gold nanoparticle morphology on thermal properties of polyimide nanocomposite films, *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 579*, 123651.

N. Jayarambabu, A. Akshaykranth, T. Venkatappa Rao, K. Venkateswara Rao, R. Rakesh Kumar, (2020). Green synthesis of Cu nanoparticles using Curcuma longa extract and their application in antimicrobial activity, *Materials Letters, 259*, 126813.