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A Review on Nanoparticles: Structure, Classification, Synthesis & Applications

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Abstract: **Nanoparticles (NPs) are the unique tiny materials which exist on a nanometer scale ranging from 1 to 100 nm. These NPs exist in variety of forms. They can be categorized into different groups such as Organic, Inorganic and Carbon-based NPs on the basis of their origin, properties, shape and size. The NPs exhibit enhanced physical and chemical properties such as high surface area, reactivity, stability, sensitivity etc. due to their small size. These NPs can be synthesized by various methods. In recent years, there has been an extensive employment of NPs in a number of industrial & environmental areas of application which is considered to be of prime importance. This critical review article highlights the classification, method of preparation and applications of NPs.**

Index Terms: **Carbon based NPs, Inorganic NPs, Nanoparticle, Organic NPs.**

I. Introduction

Nanotechnology is the fascinating branch of Science which encompasses study of systems having nano scale size. The prefix 'nano' comes from Latin word 'nanus' meaning dwarf or tiny. With the convention of International System of Units (SI) it is used to indicate a reduction factor of 109 times (1nm corresponding to 10^{-9} m). Nobel Laureate Richard P. Feynman first presented 'Nanotechnology' during his well famous 1959 lecture, 'There's Plenty of Room at the Bottom'. Since then, there have been various innovative and revolutionary developments in this field.

Nanoparticles (NPs) are the fundamental component of nanotechnology. Nanoparticles are the particulate matters with at least one dimension less than 100 nm. They can be made up of carbon, metal, metal oxides or organic matter.

On the basis of dimensions NPs can be classified into (Khan I., Khalid S., & Khan I., 2019; Kim K. S., Tiwari J. N. & Tiwari R. N, 2012):

1. Zero dimensional (0D) with length, breadth & height fixed at a single point. Eg. Nano dots
2. One dimensional (1D) which possess only one parameter. Eg. Graphene
3. Two dimensional (2D) which possess only two parameters i.e., length & breadth. Eg. Carbon nanotubes
4. Three dimensional (3D) possessing all three parameters viz. length, breadth & height. Eg. Gold nanoparticles.

The nanoparticles (NPs) can exist in different shape, size and structure such as spherical, cylindrical, tubular, conical, hollow core, spiral, flat, wire etc. It can be also be irregular in shape. The surface of NPs can either be uniform or irregular. They can also exist in crystalline and amorphous forms which can be either single crystal solid or multi- crystal solid. Multi- crystal solid can either be loose or agglomerated. The physio- chemical properties of these NPs are mostly influenced by their variation in size & shapes. Owing to unique physical and chemical properties, NPs has achieved great success in wide variety of applications in different fields such as medicinal, environmental, energy-based research, imaging, chemical & biological sensing, gas sensing etc. Researchers are more inclined towards nanotechnology as it is considered as one of the important factors for a clean and sustainable future.

II. Structure of Nanoparticles

Nanoparticles (NPs) have complex structure. They are comprised of two or three layers: (i) a surface layer: functionalized by a variety of small molecules, metal ions, surfactants or polymers (ii) The shell layer: can be purposely added and is chemically different from the core, and (iii) The core material: the central portion of NPs (Shin W. K., Cho J., Kanna A. G., Lee Y. S. & Kim D. W., 2016; Ealia S. A. M. & Saravanakumar M. P, 2019). The characteristic properties of NPs are generally due to the core material. Hence, NPs are often referred to by their core material only.

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III. CLASSIFICATION OF NANOPARTICLES

Nanoparticles (NPs) are mainly classified into various classes based on their morphology, size, physical & chemical properties. They are mainly classified into organic, inorganic and carbon-based NPs.

A. Organic Nanoparticles

Organic nanoparticles are the solid particles composed of organic compounds such as lipids or polymers with a diameter in the range of 10 nm to 1 μm (Ealia S. A. M. & Saravanakumar M. P, 2019; Khalisanni K. et al., 2020; Khan I., Khalid S., & Khan I., 2019). Some commonly known organic NPs are dendrimers, liposomes, micelles, ferritin etc. These organic NPs are environment friendly, biodegradable, non- toxic, economical and more suitable in biomedical field. Both micelles and liposomes have a hollow core also known as nanocapsules and are sensitive to thermal and electromagnetic radiations. These unique properties make organic NPs an ideal choice for drug delivery. They are highly efficient in target drug delivery.

B. Inorganic Nanoparticles

Inorganic nanoparticles are the particles that are not made of carbon. It includes metal and metal oxides (Ealia S. A. M. & Saravanakumar M. P, 2019; Khalisanni K. et al., 2020; Khan I., Khalid S., & Khan I., 2019). As compared with organic NPs in inorganic NPs enormous research and commercial investments has been made.

1) Metal Based Nanoparticles

Metal based nanoparticles can be obtained from metals such as aluminium (Al), gold (Au), silver (Ag), cadmium (Cd), cobalt (Co), copper (Cu), iron (Fe), lead (Pb) and zinc (Zn). The most widely used metals in are Ag, Au, Cu, Fe and Zn. Transition metals are found to be the best candidates for the synthesis of metal-based NPs due to the presence of partially filled d- orbitals which make them more redox active (Elena S. L., et al., 2020). This in turn facilitates nanoparticle aggregation. Metal based NPs have size in the range of 10 to 100 nm. They exist in different shapes such as spherical and cylindrical. They show unusual properties such as high surface area to volume ratio, pore size, surface charge and surface charge density, crystalline and amorphous structures, high reactivity and sensitivity to environmental factors such as air, moisture, heat, sunlight etc. Due to these unusual properties, they find promising applications in numerous research areas.

2) Metal Oxides Based Nanoparticles

Metal based NPs can be converted into their corresponding oxides known as metal oxides-based NPs. Metal oxides-based NPs have exceptional properties as compared with their metal counterparts. Some examples of metal oxides-based NPs are Iron oxide (Fe_2O_3), Magnetite (Fe_3O_4), Aluminum oxide (Al_2O_3), Cerium oxide (CeO_2), Silicon dioxide (SiO_2), Titanium oxide (TiO_2), Zinc oxide (ZnO) (Sathyanarayanan, M. B., Balachandranath, R., Genji Srinivasulu, Y., Kannaiyan, S. K., & Subbiahdoss, G., 2013). These metal oxides based NPs found to be more reactive and efficient.

C. Carbon Based Nanoparticles

The nanoparticles composed of carbon are known as carbon based NPs. Carbon based NPs can exist in different shapes such as tube- shaped, horn- shaped, spherical or ellipsoidal. Two major classes of carbon based NPs are fullerene and carbon nanotubes (CNTs). Other classes of carbon- based NPs are graphene, nano fibers, carbon black (Bhaviripudi S., Mile E., Iii S. A. S., Zare A. T., Dresselhaus M. S., Belcher A. M. & Kong J., 2007; Patel K. P., Singh R. K., Kim, H. W., 2019).

1) Fullerene

Nobel laureates H. W. Kroto, R. F. Curl and R. E. Smalley discovered fullerenes in the year 1985. The fullerene family includes a number of atomic clusters (Cn) where n > 20. Fullerene C_{60} is the most common fullerene having 60 carbon atoms. It is also known as bucky ball. It is spherical in shape. Each carbon atom is sp^2 hybridized and are linked together by covalent bonds. All the carbon atoms located at the vertices of 20 hexagons and 12 pentagons. About 28 to 1500 carbon atoms form the spherical structure with diameters up to 8.2 nm for a single layer and 4 to 36 nm for multi-layered fullerenes.

2) Carbon Nanotubes (CNTs)

Carbon nanotubes are allotropes of carbon and were discovered by the Japanese scientist S. Iijima in the year 1991. CNTs are having exceptional properties such as rigidity, strength and elasticity which have created noteworthy commercial interests. They also show high thermal and electrical conductivity. CNTs are cylindrical structures with a diameter of several nanometers, consisting of rolled graphene sheets. They may vary in length, diameter, symmetry and number of layers. The ends of CNTs can either be hollow or closed by a half fullerene molecule. Depending on their structure they can be broadly classified into two main groups: (a) single- walled carbon nanotubes (SWCNTs) having a diameter of 1-3 nm and few micrometers in length and (b) multi-walled carbon nanotubes (MWCNTs) with a diameter of 5-40 nm and a length of around 10 μm. However, CNTs with a length of 550 nm have also been reported.

3) Graphene

Graphene is another allotropic form of carbon. It has a two-dimensional honeycomb like lattice. Graphene sheet is generally 1 nm in thickness.

4) Carbon Nanofibers

Carbon nanofibers (CNFs) are also made up of graphene sheets. In this graphene layers are arranged as stacked cones, cups or plates. CNFs have excellent mechanical properties, high thermal and electrical conductivity. Their diameter varies form 10 nm to 500 nm. Hence, these CNFs find application in many fields such as drug delivery, energy devices, sensors, nanocomposites, photocatalysis etc.

5) Carbon Black

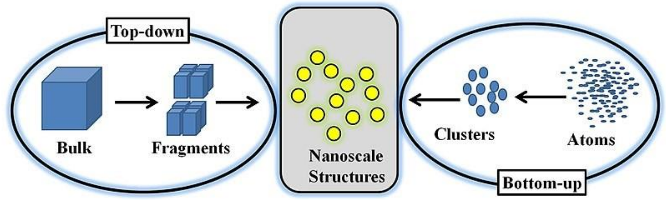
Carbon black nanoparticles (CBNP) or nano powders are amorphous materials mainly composed of elemental carbon. It is also known as 'soot' or 'shouen'. These are spherical in shape with diameter in the range of 20 to 70 nm. CBNP form agglomerate of 500 nm size due to high interaction between the particles. These generally find application in laser printing, copy machine inks. They are also used as rubber reinforcement preservatives as well as pigments in plastic industries.

IV. Synthesis Of Nanoparticles

Various methods have been employed to synthesize nanoparticles (NPs) with controlled shape, size, dimensions and structure. There are two main approaches for the synthesis of NPs viz., Top- down and Bottom- up approach (Arole, V. M., & Munde, S. V., 2014; Hasan, S., 2015; Khan, F. A., 2020; Khan I., Khalid S., & Khan I., 2019; Rane, A. V., Kanny, K., Abitha, V. K., & Thomas, S., 2018;).These methods are further divided into different categories based on the operations and reaction conditions (Scheme 1 & 2).

A. Top-Down Approach

Top- down approach involves the breaking down of the bulk

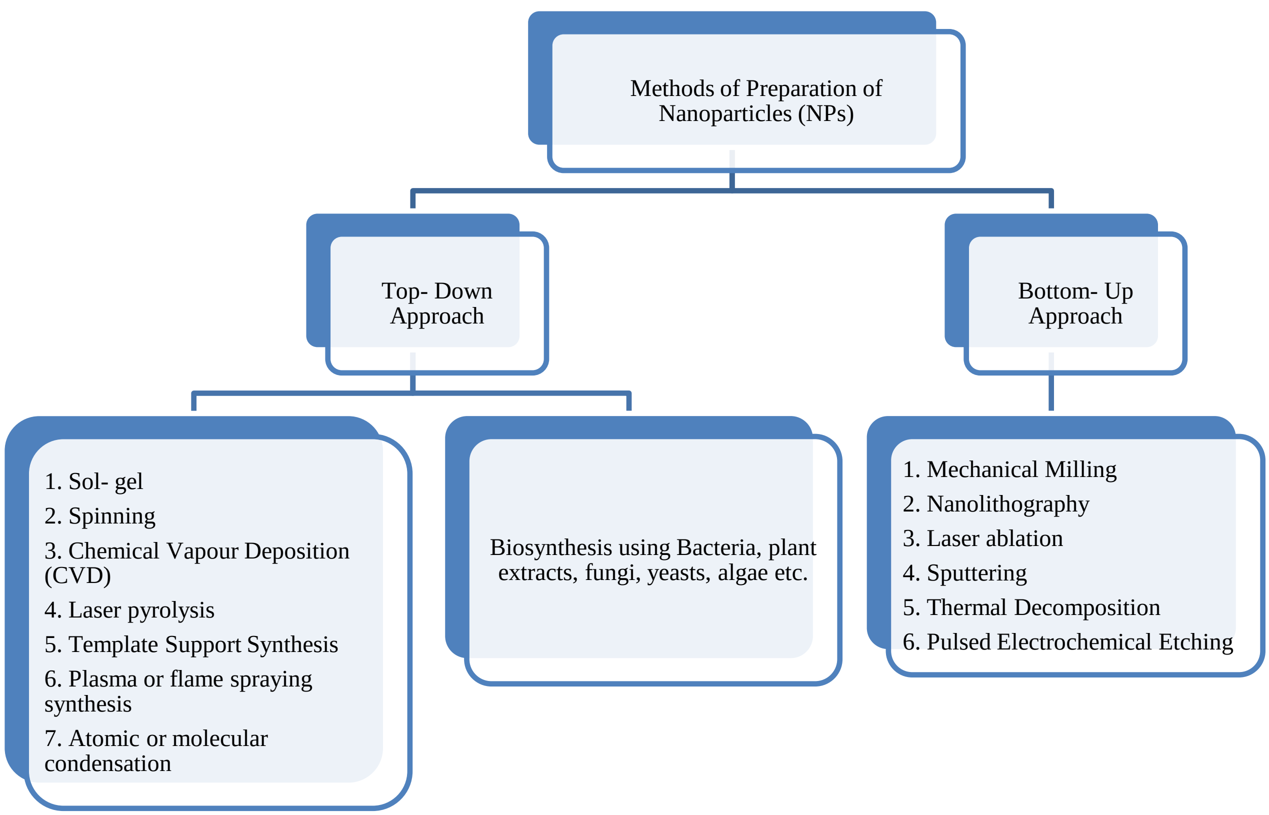


Scheme 1. Schematic representation of Top- down approach & Bottom- up approach (Source: nanoscience.com)

material into nanosized particles. It is a destructive method. Top- down approaches is simpler and depend either on removal or division of bulk material or miniaturization of bulk fabrication processes to produce desired structure with appropriate properties. Mechanical milling, nanolithography, laser ablation, sputtering and thermal decomposition are some of the most widely used nanoparticle synthesis methods.

B. Bottom- Up Approach

Bottom- up or constructive method is an alternative approach which employs build- up approach where nanoparticles are build- up from clusters which in turn are obtained from atoms.



Scheme 2. Methods of Preparation of NPs: Top- down approach & Bottom- up approach (Source: Khan I., Khalid S., & Khan I., 2019)

This approach generally involves sedimentation and reduction technique. This approach is considered to be more economical as it has the potential of creating less waste. Most commonly used examples of this method are Sol-gel, spinning, green synthesis, chemical vapour deposition (CVD), pyrolysis and biosynthesis.

V. Applications Of Nanoparticles

Nanoparticles exhibit unique physical and chemical properties such as: electronic & optical properties, mechanical properties, magnetic properties & thermal properties. This uniqueness has led to its application in different areas. Some of the significant applications of NPs are discussed below:

A. Medicine

Nanoparticles have made major contributions to clinical medicine in the areas of medical imaging and drug/gene delivery. Iron oxide particles such as magnetite (Fe_3O_4) or its oxidized form hametite (Fe_2O_3) are most commonly employed for biomedical applications. Ag NPs are being used increasingly in wound dressings, catheters and various households' products due to their antimicrobial activity. Gold nanoparticles are emerging as promising agents for cancer therapy, as drug carriers, photothermal agents, contrast agents and radiosensitisers (Cai, W., Gao, T., Hong, H., & Sun, J., 2008; Jain, S., Hirst, D. G., & O'Sullivan, J., 2012; Sztandera, K., Gorzkiewicz, M., & Klajnert-Maculewicz, B., 2018). Over past few decades there has been considerable interest in developing biodegradable NPs as effective drug delivery devices. Various polymers have been used in drug delivery research as they can effectively deliver the drugs to the target site thus increases the therapeutic benefit, while minimizing side effects.

B. Environmental Remediation

Nanoparticles are commonly used for environmental remediation, since they are highly flexible towards both in situ and ex situ applications in aqueous systems. Silver nanoparticles (AgNPs) due to their antibacterial, antifungal, and antiviral activity has been extensively used as water disinfectants (Zhang, C., Hu, Z., Li, P., & Gajaraj, S., 2016). TiO_2 NPs have been increasingly studied for waste treatment, air purification (Haider, A., Al-Anbari, R., Kadhim, G., & Jameel, Z., 2018), self-cleaning of surfaces (Veziroglu, S., Hwang, J., Drewes, J., Barg, I., Shondo, J., Strunskus, T., & Aktas, O. C., 2020), and as a photocatalyst in water treatment (Peng, Y., Yu, Z., Pan, Y., & Zeng, G., 2018) application due to their characterized low-cost, non-toxicity, semiconducting, photocatalytic, electronic, gas sensing, and energy converting properties.

C. Mechanical Industries

Owing to excellent young modulus, stress and strain properties, NPs finds applications in mechanical industries especially in coating, lubricants (Ghaednia, H., Hossain, M. S., & Jackson, R. L., 2016), adhesives (Cao, Z., & Dobrynin, A. V., 2016) and manufacturing of mechanically stronger nanodevices. Pal et al. (2021) reported two-step dip-coating method using silver nanoparticles (AgNPs) and fluorine-free silane monomer, 3-(Trimethoxysilyl) propyl methacrylate (TMSPM) for the fabrication of hydrophobic coating on cotton fabric.

D. Food

Nanoparticles have been increasingly incorporated into food packaging to control the ambient atmosphere around food, keeping it fresh and safe from microbial contamination (Bhardwaj M. & Saxena D.C., 2017). Now-a-days, inorganic & metal NPs are extensively used as alternatives to petroleum plastics in the food packaging industry as they can directly introduce the anti-microbial substances on the coated film surface (Hoseinnejad, M., Jafari, S. M., & Katouzian, I., 2018).

E. Electronics

Unique structural, optical and electrical properties of one-dimensional semiconductor and metals make them the key structural block for a new generation of electronic, sensors and photonic materials.

F. Energy Harvesting

Due to scarcity of fossil fuels scientist have been shifting their research interests in the development of different strategies which can help in generating renewable energies from easily available resources at cheap cost. NPs are the suitable candidate for this purpose due to their large surface area, optical behavior and catalytic nature. NPs are widely used to generate energy from photoelectrochemical (PEC) and electrochemical water splitting (Avasare et al., 2015). Other advanced options such as electrochemical CO_2 reduction to fuels precursors, solar cells and piezoelectric generators also utilized to generate energy. Ibrahim et al. (2019) reported use of graphene as a source of energy as well as next generation smart energy storage devices.

Conclusion

In this review article we have given a brief overview of nanoparticles, their structure, classification, method of synthesis, and applications in various fields. Owing to tunable physicochemical as well as biological properties, nanoparticles have gained prominence in medicine, environmental remediation, energy harvesting and many other areas.

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