Nanoparticles: Their Classification, Types and Properties

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Abstract: The rapidly expanding class of materials known as nanostructures has generated a great deal of attention for a variety of applications. Numerous methods have been employed to determine the size, crystal structure, elemental makeup, and several other physical characteristics of nanoparticles. Physical characteristics may frequently be assessed using a variety of methods. Infrared spectroscopy, X-ray diffraction analysis, energy-dispersive X-ray analysis, scanning electron microscopy, and ultraviolet-visible spectroscopy were used to characterise the produced nanoparticles (SEM). Due to their high excitation binding energy at ambient temperature, UV-Vis spectra displayed typical absorption peaks at about 350 nm.

Keywords: Nanoparticles, classification, properties, agglomeration of nanoparticles characterization of nanoparticles.

1. INTRODUCTION

Nanotechnology is enabling technology that deals with nanometer-sized objects. It is expected that nanotechnology will be developed at several levels: materials, devices and systems. Nanotechnology is known as the field of research. So, nanotechnology was presented by Nobel laureate Richard P. Feynman during his 1959 lecture "*There's Plenty of Room at the Bottom*" (Khan, I. et al., 2017). International Organization for Standardization (ISO) defined a nanoparticle as a discrete nano-object where all three cartesian dimensions are less than 100nm in the year 2008. But in 2011 the commission of the European Union endorsed a more technical but wider-ranging definition: *a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1nm- 100nm* (King, S., et al., 2019). There has been a rapid increase in interest in nanotechnology and the use of nanoparticles in commercial applications. However, there is little known about the fate and behaviour of engineered nanoparticles in the environment

(Christian, P., et al. 2008). Due to their adjustable physicochemical properties, such as melting point, wettability, electrical and thermal conductivity, catalytic activity, light absorption, and scattering, NPs and NSMs have become more prominent in technological developments. These properties result in improved performance over their bulk counterparts. The International System of Units (Système international d'unités, SI) unit of a nanometer (nm) measures length terms of 10^{-9} metres. Although NMs are technically defined as having a diameter between 1 and 100 nm and a length of 1 to 1000 nm in at least one dimension, that is not how they are often characterised.

The Environmental Protection Agency (EPA) asserts that NMs *"may display distinct features differing from the identical chemical molecule in a greater dimension*." The US Food and Drug Administration (USFDA) defines NMs as *"materials that have at least one dimension in the range of about 1 to 100 nm and show dimension-dependent behaviours*." The International Organization for Standardization (ISO), in a similar vein, has referred to NMs as *"materials with any outward nanoscale dimension or possessing internal nanoscale surface structure*." The definitions of nanofibers, nanoplates, nanowires, quantum dots, and other related words are based on this ISO standard. Similar to how the word "nanomaterial" is defined as *"a manmade or natural material that comprises unbound, aggregated, or agglomerated particles with exterior diameters in the range of 1-100 nm",* according to the EU Commission.

The British Standards Institution recently offered the following definitions for the terminology used in science:

• Nanoscale: a size range of around 1 to 1000 nm.

• Nanoscience: The study of matter at the nanoscale that focuses on comprehending its size- and structure-dependent features and examines the emergence of individual atoms or molecules or changes in bulk materials.

• Nanotechnology: Using scientific knowledge for a variety of industrial and healthcare purposes, it is the manipulation and control of matter on the nanoscale dimension.

Materials with any internal or exterior structures on the nanoscale dimension are considered nanomaterials.

A material with one or more peripheral nanoscale dimensions is referred to as a nano-object.

Three exterior nanoscale dimensions are present in a nanoparticle, a nano-object. When nano-longest objects and shortest axes are different lengths, the words "nanorod" or "nanoplate" are used in place of "nanoparticle" (NP).

• Nanofiber: A nanomaterial is referred to as nanofiber if it has three dimensions total - two outside nanoscale dimensions that are comparable and one larger dimension.

• A multiphase structure containing at least one nanoscale phase is referred to as a nanocomposite.

• Nanostructure: a structure made up of interconnecting nanoscale building blocks.

•Nanostructured materials: Substances with either internal or external nanostructure (Jeevanandam J. et al. 2018).

Biomaterials-based NPs have drawn a lot of interest because they have the potential to transform medical therapy with more effective, safer, and intelligent therapies. For the aim of medicine administration, NPs can covalently conjugate or encapsulate hydrophobic pharmaceuticals to significantly increase their water solubility. Additionally, they can encapsulate hydrophilic pharmaceuticals or biomacromolecules (such proteins, peptides, or nucleic acids) to improve their stability in vivo, lengthen the period that blood circulates, and enable transmembrane administration. Because of the increased permeability and retention (EPR) effect, the nanoscale diameter of NPs enables the targeting of tumours and significantly lowers the nonspecific toxicity of chemo-drugs. Additionally, NPs with a wide surface area increased circulation duration, and high stability provides a platform for extremely accurate and sensitive molecular imaging by delivering the imaging probe or contrast agent to the target tissues or cells. (Yin et. al. 2020).

Nanoparticles are formed of a variety of substances, each of which comprises tens to thousands of atoms, and they reside in a space that straddles the quantum and Newtonian worlds. Every particle has new characteristics at those sizes that vary based on its size.

When the matter is reduced to the nanoscale, electrical and other characteristics drastically alter. Since nanoparticles may contain uncommon types of structural disorder that can dramatically change a material's characteristics, they cannot only be thought of as tiny fragments of bulk material (Jain K.K., 2011). According to Wang, Z. L. (2004) and Suchea, M, et al. (2006), they are truly modified forms of basic elements that were obtained by changing the atomic and molecular characteristics of the elements. The use of nanotechnology in medical applications, often known as "nanomedicine," aims to provide a new set of instruments, gadgets, and treatments for the management of a human disease. Numerous uses are being investigated, including biologically inspired nanomaterials, "nanomachines," biomaterials for tissue engineering, shape-memory polymers as molecular switches, biosensors, laboratory diagnostics, and nanoscale drug release devices [Wagner V, et al., 2006; Ferrari M. 2005 and Panchal RG 1998]. (Bedi et. al. 2015).

2. CLASSIFICATION OF NANOPARTICLES

Classification of nanoparticles is divided into the following types-

2.1. Classification of nanomaterials based on their dimensions:

The advancement of many nations' economies is currently being aided by the nanoscale manufacture of traditional goods, and this trend will continue. NPs and NSMs come in a wide variety of forms, and more are expected to develop in the future. As a result, the time is now for their classification. Gleiter et al. proposed the initial concept for NM classification. Here, NMs were categorised depending on their crystalline morphologies and chemical makeup. However, because the dimensionality of the NPs and NSMs was not taken into account, the Gleiter scheme was not entirely comprehensive. Pokropivny and Skorokhod created a new classification system for NMs in 2007 that incorporated recently produced composites like 0D, 1D, 2D, and 3D Nms.

The electron flow along the dimensions in the NMs has a significant impact on this categorization. For instance, in 0D NMs, electrons are confined to an incompressible area, whereas in 1D NMs, electrons are free to flow along the x-axis, which is less than 100

nm. Similar to this, in 2D and 3D NMs, electrons move along the x-y and x, y, and z axes, respectively.

The usefulness of the NMs' categorization depends on our capacity to forecast their characteristics. As stated in the "grain boundary engineering" notion in Gleiter's categorization, the characteristics of NMs are highly dependent on grain boundaries. Therefore, grain boundary engineering will increase the traditional inner size effects, such as melting point decreasing and diffusion augmentation. According to the "surface engineering" approach and the categorization of Pokropivny and Skorokhod, the features of NMs are related to the particle shape and dimensions. These justifications, to broaden the use of NSMs, emphasise the engineering of particle form and dimensions as well as a grain boundary.

2.2. Classification of nanomaterials based on their origin:

NPs and NSMs can be divided into natural and synthetic categories in addition to classifications based on dimension and substance.

(i) In nature, either life forms or human activity can yield natural nanomaterials. The creation of artificial surfaces with unique micro- and nanoscale templates and features for technological purposes is easily accomplished from natural sources. Regardless of human behaviour, found naturally NMs reside in all of the Universe's spheres (such as the hydrosphere, atmosphere, lithosphere, as well as biosphere). Several NMs that comprise Earth's spheres include the oceans, that is made up of seas, lakes, rivers, groundwater, and hydrothermal vents, the lithosphere, which is made up of rocks, soils, magma, or lava during specific phases of evolution, and the biosphere, which comprises lower and higher species including people and microorganisms.

(ii) Synthetic (designed) nanomaterials can be created by physical, chemical, biological, or hybrid means as well as through mechanical grinding, engine exhaust, and smoke. The use of engineered NMs in consumer and industrial industries, coupled with the growing development and subsequent release, has raised the topic of harm assessment methodologies recently. The behaviour and outcome of manufactured NMs across diverse environmental media may be predicted with great accuracy using these risk assessment methodologies. The main issue with designed NMs is determining when current information is sufficient to predict their behaviour or if they behave differently from wild NMs about their surroundings. Engineered NMs are now produced using a variety of sources that are relevant to possible uses [21].

2.3 Nanoparticle morphology

The morphological properties of flatness, sphericity, and aspect ratio must be considered. High- and low-aspect-ratio particles can be broadly categorised. Nanotubes and nanowires with different geometries, such as helices, zigzags, belts, or maybe nanowires with diameter that changes with length, are examples of high-aspect-ratio nanoparticles. Spherical, oval, cubic, prismatic, helical, or pillar morphologies are examples of low-aspect-ratio shapes. Colloids, suspensions, and powders are all different types of particle collections.

2.4 Nanoparticle composition:

Nanoparticles can be made of a single basic material or a composite of several materials. While it is currently possible to readily create significant elements with a single composition, nanoparticles in nature are routinely accumulations of substances with various compositions.

2.5 Nanoparticle uniformity and agglomeration:

Nanoparticles can exist as suspended/colloids, agglomerates, or dispersed aerosols depending on their chemistry and electromagnetic characteristics. For instance, unless their surfaces are covered with a nonmagnetic substance, magnetic nanoparticles tend to aggregate and create an agglomeration state. Depending on the size of the agglomeration, nanoparticles may act like bigger particles while they are in an agglomerate form. Therefore, it is clear that when evaluating health and environmental standards for novel materials, nanoparticle aggregation, size, and surface reactivity, along with shape and size, must be taken into account (Buzea et. al 2007).

3. TYPES OF NANOPARTICLES

The majority of the present NPs and NSMs may be categorised into four material-based groups. Recent reviews of these several kinds of NMs are cited in the sources.

3.1 Carbon-based nanomaterials:

Typically made of carbon, these NMs can take the form of spheres, ellipses, or hollow tubes. The group of carbon-based NMs comprises fullerenes (C60), carbon nanotubes (CNTs), carbon nanofibers, carbon black, graphene (Gr), and carbon onions. The key manufacturing processes for the fabrication of this carbon-based material include laser ablation, arc discharge, and chemical vapour deposition (CVD) (except carbon black).

3.2 Inorganic-based nanomaterials:

These NMs include metal and metal oxide NPs and NSMs. Metals like Au or Ag NPs, metal oxides like TiO2 and ZnO NPs, semiconductors like silicon, and ceramics may all be made from these NMs using synthetic methods.

3.3 Organic-based nanomaterials:

Nanomaterials with a mostly organic composition are referred to as organic-based nanomaterials (NMs), as opposed to those with a carbon or inorganic composition. The self-assembly and design of molecules with the aid of noncovalent (weak) interactions enables the transformation of organic NMs into desirable structures including dendrimers, micelles, liposomes, and polymer NPs.

3.4 Composite-based nanomaterials:

Composite NMs are multiphase NPs and NSMs having one phase on the nanoscale dimension. They can either combine NPs with other NPs or NPs with bigger or bulkier materials (for example, hybrid nanofibers) or more complex structures, such as metal-organic frameworks. The composites may combine metal, ceramic, or organic bulk components with carbon, metal, or organic NMs in any way (Jeevanandam J. et al. 2018).

4. PROPERTIES OF NANOPARTICLES

Nanomaterials differ greatly from their bulk counterparts in terms of their chemical, physical, electrical, optical, thermal, mechanical, and biological characteristics. This is mostly because of their tiny sizes, varied forms, and large specific surface areas. For instance, copper nanoparticles (NPs) smaller than 50 nm display ultra-hard behaviour and lack the ductility and malleability of bulk copper (Suganeswari, M. 2011). These materials offer a wide range of potential uses now that they may be used at the nanoscale, including optoelectronics, catalysis, electronics, water treatment, and many other fields. Metal, semiconductor, or oxide-based NPs have been applied as quantum dots (Yi, D.K. et. al. 2005), chemical catalysts (Tsunoyama, H. et. al. 2004), adsorbents (Wang, W. et. al. 2012), drug delivery systems (Kumari, A. et. al. 2010), and biosensors (Luo, X. et. al. 2006), among other applications. NPs are of scientific interest because they successfully span the gap between the characteristics of bulk materials on the one hand and the atomic/molecular structure features on the other. In the case of gold and silver nanoparticles (AuNPs and AgNPs, respectively), they exhibit size-dependent properties like surface plasmon resonance (Jain, P.K. et. al. 2007) and superparamagnetic (Lu, A.-H. et. al. 2007), which allows them to confine their electrons and produce quantum effects (also known as quantum confinement) in semiconducting NPs (Yanhong, L. et. al. 2004).

5. CHARACTERIZATION OF NANOPARTICLES

Size and form are two of the primary factors investigated during NP characterisation. Credible and reliable measuring techniques for NPs will have a significant impact on the use of these materials in commercial applications and enable industry (Mourdikoudis, S., et al. 2018). Sophisticated microscopic methods like scanning electron microscopy are used to characterise nanoparticles in broad terms based on their size, shape, and surface charge. The average particle diameter, size distribution, and charge all have an impact on the nanoparticles' physical stability and in vivo dispersion. To assess the general form of polymeric nanoparticles—which may impact their toxicity—electron microscopy methods are highly helpful (Konwar et. al 2016). The characterisation of nanoparticles (NPs) and their wide range of preparation methods are the main topics of this article. Unsolved issues with NP characterisation include measuring their concentration *in situ* and online (Mourdikoudis, S., et al. 2018).

Size

Using microscopy methods like scanning electron microscopy or atomic force microscopy, NP size may be directly seen and measured. By combining

statistics, it is possible to determine the particle thickness and examine the size distribution. With AFM, it is possible to create a high-resolution picture of the three-dimensional shape of NPs using the probe's response to the material. The most used approach for characterising NP size is dynamic light scattering. DLS can correctly determine NP size below 5 m, although the findings are vulnerable to interference. Sample preparation is essential and should be transparent, homogenous, and free of haze. When there are more nanoparticles present, multi-scattering occurs, where the light from many particles is dispersed. (Yin 2020).

Surface Charge

There hasn't been a method that works well enough to date to directly determine the surface charge of NPs in liquid. The potential being measured is known as the zeta potential (-potential), which is connected to the movement of tiny particles in a liquid. Zeta potential can be influenced by concentration, electrolyte type, and pH. In the solution state, the absolute magnitude of this potential is greater, and the repulsive force between particles is greater, making the system more stable. There are three ways for measuring zeta potential: electrophoretic light scattering, acoustic, and electroacoustic. The most used method is ELS because it possesses the requisite sensitivity, precision, and adaptability. Recently, commercial equipment has been frequently utilised to measure zeta potential. Analysis of samples in nonaqueous dispersions is successfully prevented by the Zetasizer Nano series (Malvern, UK) (Yin 2020).

Morphology

Microscopy techniques such as SEM, TEM, and AFM are capable of observing the NPs' morphology. The morphology may be described by several characteristics, such as circularity, aspect ratio, elongation, convexity, and fractal dimension. The use of diffraction techniques including powder XRD,

small angle X-ray scattering (SAXS), neutron scattering (SANS), and electron diffraction (ED) is also an option. SAXS can characterize the structure of a crystal at lower resolutions and does not require a crystalline sample (Yin 2020).

5.1 Particle size:

The most crucial factors in the characterisation of nanomaterials are their shape and particle size distribution. Nanoparticles are primarily used for medicine delivery and targeting. By using electron microscopy, one can determine morphology and size. It has been discovered that particle size has an impact on medication release. It was discovered that as the size of the particles increased, the average of poly (lactic-co-glycolic acid) degradation also increased (Konwar et. al 2016).

5.2 Dynamic light scattering (DLS):

Photon-correlation spectroscopy (PCS) or dynamic light scattering is the quickest and most widely used method for assessing particle size (DLS). The size of Brownian nanoparticles in colloidal solutions in the nano- and submicron ranges is frequently assessed using DLS. As monochromatic light is shone upon a solution of spherical particles in Brownian motion, its lighting creates a Doppler shift when it hits the moving particle. (Konwar et. al 2016).

5.3 XRD:

One of the most widely used methods for characterising NPs is X-ray diffraction (XRD). The crystalline structure, phase, lattice parameters, and crystalline grain size are all revealed by XRD. It is unsuitable for amorphous materials, and the peaks are too wide for particles smaller than 3 nm. Using X-ray line broadening (XRD), the average crystallite size of magnetite NPs was discovered to be between 9 and 53 nm. This is more than the value estimated using XRD for samples containing very big particles. There are several crystal barriers on the surface of larger-than-50-nm particles (Mourdikoudis, S., et al. 2018).

Table 1: Determining the necessary parameters and using the appropriate characterisation methods (Mourdikoudis, S., et al. 2018).

Entity characterized	Characterization techniques suitable
Size (structural properties)	TEM, XRD, DLS, NTA, SAXS, HRTEM, SEM, AFM, EXAFS, FMR, DCS, ICP-MS, UV-Vis, MALDI, NMR, TRPS, EPLS, magnetic susceptibility
Shape	TEM, HRTEM, AFM, EPLS, FMR, 3D-tomography
Elemental-chemical composition	XRD, XPS, ICP-MS, ICP-OES, SEM-EDX, NMR, MFM, LEIS

Crystal structure	XRD, EXAFS, HRTEM, electron diffraction, STEM
Size distribution	DCS, DLS, SAXS, NTA, ICP-MS, FMR, superparamagnetic relaxometry, DTA, TRPS, SEM
Chemical state-oxidation state	XAS, EELS, XPS, Mossbauer
Growth kinetics	SAXS, NMR, TEM, Cryo-TEM, Liquid-TEM
Ligands binding/ composition/ density/arrangement/mass, Surface composition	XPS, FTIR, NMR, SIMS, FMR, TGA, SANS
Surface area, specific surface area	BET, liquid NMR
Surface charge	Z-potential, EPM
Concentration	ICP-MS, UV-Vis, RMM-MEMS, PTA, DCS, TRPS
Agglomeration state	Z-potential, DLS, DCS, UV-Vis, SEM, Cryo-TEM, TEM
Density	DCS, RMM-MEMS
Single particle properties	Sp-ICP-MS, MFM, HRTEM, liquid TEM
3D visualization	3D-tomography, AFM, SEM
Dispersion of NP in matrices/supports	SEM, AFM, TEM
Structural defects	HRTEM, EBSD
Detection of NPs	TEM, SEM, STEM, EBSD, magnetic susceptibility
Optical properties	UV-Vis-NIR, PL, EELS-STEM
Magnetic properties	SQUID, VSM, Mossbauer, MFM, FMR, XMCD, magnetic susceptibility

*XRD - X Ray Diffraction; UV-Vis - UV-Visible spectroscopy; SEM - Scanning Electron Microscopy; TEM - Transmission Electron Microscopy; HR TEM – High Resolution Transmission Electron Microscopy; DCS- ; DLS- Dynamic Light Scattering; NTA – Nanoparticle Tracking Analysis; SAXS – Small Angle X Ray Scattering; AFM – Atomic Force Microscopy; EXAFS-Extended X-ray Absorption Fine Structure; ICP-MS- Inductively Coupled Plasma Mass Spectrometry; SQUID – Superconducting Quantum Interference Device; VSM- Value Stream Mapping; STEM - Scanning Transmission Electron Microscope; EBSD – Electron Backscatter Diffraction; PL – Photoluminescence Spectroscopy; Sp-ICP-MS – Single Particle Inductively Coupled Mass Spectrometry, MFM – Magnetic Force Microscopy; RMM-MEMS - ; PTA – Percutaneous Transluminal Angioplasty; EPM - ; NMR - Nuclear Magnetic Resonance; BET – Brunauer Emmett Teller; XPS – X Ray Photoelectron Spectroscopy; FTIR – Fourior Transform Infrared Spectroscopy; SIMS – Secondary Ion Mass Spectrometry; FMR – Functional Magnetic Resonance; TGA – Thermogravimetric Analysis; SANS – Small Angle Neutron Scattering; XAS – X Ray Absorption Spectroscopy; EELS – Electron Energy Loss Spectroscopy; DTA – Differential Thermal Analysis; TRPS – Tunable Resistive Pulse Sensing; XMCD – X Ray Magnetic Circular Dichrosim;

5.4 FTIR:
The measurement of electromagnetic radiation absorption at wavelengths between 4000 and 400 cm1 is the foundation of the Fourier transform infrared spectroscopy (FTIR) method. When a particle absorbs IR light, its dipole moment changes, and it becomes IR active. A recorded spectrum reveals the positions of bands associated with the strength and kind of bonds, as well as specific functional groups, offering details on molecular interactions and structure (Mourdikoudis, S., et al. 2018).

5.5 NTA:
Nanoparticle tracking analysis (NTA) is a relatively new but rapidly gaining popularity technology for measuring NP size and has a lower concentration detection limit than DLS. It makes use of both light scattering and Brownian movement features to get an NP size distribution of samples in the liquid dispersion. One significant benefit of NTA over other size assessment approaches is it's not biased toward bigger NPs or aggregates (Mourdikoudis, S., et al. 2018).

6.CONCLUSION

This tendency will continue, and traditional items will continue to be manufactured on a nanoscale. There are several varieties of NPs and NSMs, and new ones are anticipated to emerge. Therefore, it is now necessary to classify nanomaterials. Nanomaterials span the gap between the characteristics of bulk materials and atomic/molecular structure features. They may be used in optoelectronics, catalysis, electronics, water treatment, and many other fields. Metal, semiconductor, or oxide-based NPs have been applied as quantum dots.

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