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Science and Technology of Nanomaterials: Introduction

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1.1 Introduction

The term nanotechnology refers to the organized study of materials having at least one dimension in the nanometer range (1–100 nm). Nanomaterials are characterized by their specific optical properties, magnetic properties, electrical properties, etc. These materials are widely used in biomedical, environmental, and electrical applications because of their unique properties. The properties of nanomaterials are, however, dependent on the length scales on the order of nanometers.

Opening up a new vista of study of nanoscience in the field of physics in the year 1959, Richard Feynman, a German scientist pointed out, “There is plenty of room at the bottom” [1]. Nanoscience discusses the management of nanomaterials, systems, and devices at atomic, molecular, and macromolecular levels, whereas, nanotechnology is the bunch of techniques involved in design, synthesis, characterization, and application of structures, materials, devices, and systems by manipulating shape and size at nanometer scale. Nanotechnology is the manufacturing of tools and nanodevices by controlling the matter at the atomic level.

Nanotechnology has a wide variety of applications in various fields, such as medicine, environmental remediation, and food science. Figure 1.1 depicts different applications of nanotechnology.

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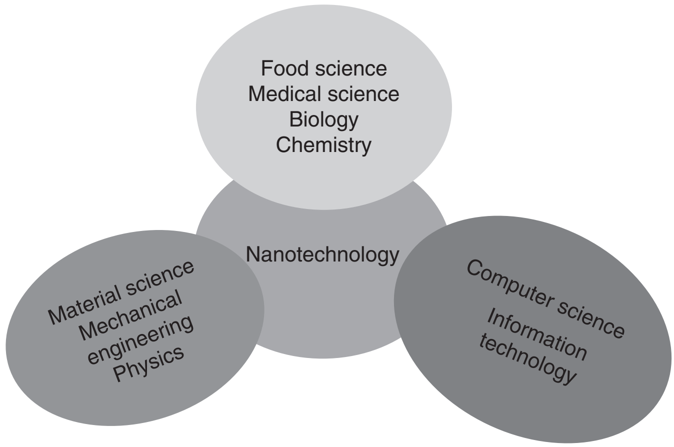

Figure 1.1 Applications of nanotechnology.

1.2 Classification of Nanomaterials

Nanomaterials are classified, based on their geometry, into zero-dimensional, one-dimensional, two-dimensional, and three-dimensional nanomaterials. Figure 1.2 represents the schematic sketch for each category.

1.3 Classes of Nanomaterials

Based on their origin, nanomaterials are mainly classified into organic nanoparticles (NPs), inorganic nanoparticles, and carbon-based nanoparticles.

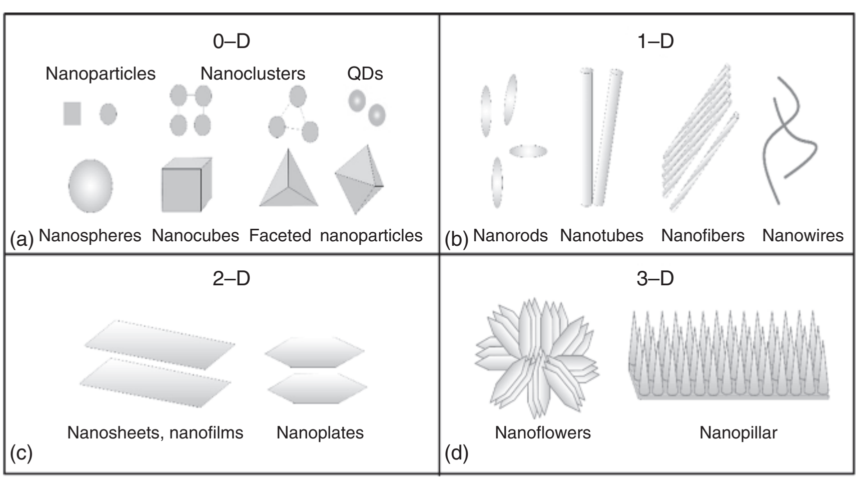

Figure 1.2 Scheme of (a) zero-, (b) one-, (c) two-, and (d) three-dimensional nanostructured materials with different morphologies. Source: Nikolova and Chavali [2]/MDPI/Licensed under CC 4.0.

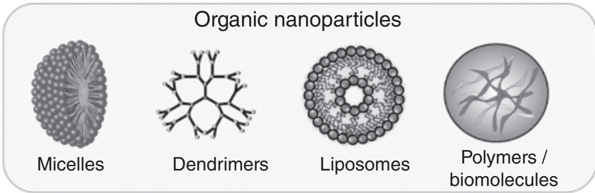

Figure 1.3 Different types of organic nanoparticles. Source: Gessner and Neundorf [3]/MDPI/Licensed under CC 4.0.

1.3.1 Organic Nanoparticles

Organic nanoparticles are solid particles derived from organic compounds. Dendrimers, ferritin, liposomes, and micelles come under this category (Figure 1.3). The biodegradability and nontoxicity of these materials are remarkable. Organic nanoparticles are mainly used in the biomedical field for drug delivery applications.

1.3.2 Inorganic Nanoparticles

Inorganic nanoparticles are mainly of two types – metal nanoparticles and metal oxide nanoparticles. Metal nanoparticles are synthesized from metals. They can be synthesized from almost all metals, such as aluminum (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag), and zinc (Zn). These are characterized by their specific properties, such as high surface area-to-volume ratio, pore size, surface charge, and surface charge density.

The applicability of metal nanoparticles can be improved by the use of metal oxide nanoparticles. Table 1.1 gives a brief idea about applications of some metallic and metal oxide nanoparticles.

1.3.3 Carbon-Based Nanoparticles

If the complete skeleton of a nanoparticle is carbon, this class can be categorized into carbon-based nanoparticles. Fullerenes, graphene, carbon nanotubes (CNTs), carbon nanofibers, carbon black, etc., come under this category. Figure 1.4 represents the schematic diagram of different carbon-based nanoparticles, and Table 1.2 gives the applications of carbon-based nanoparticles.

1.4 Properties of Nanomaterials

1.4.1 Size and Surface Area

The interaction of nanomaterials mainly depends on their size and surface area. With decrease in size of nanomaterials, the surface area-to-volume ratio of nanomaterials increases and the reactivity of the surface becomes enhanced [60]. Each and every property of nanostructures depends on their size, shape, and surface area.

Table 1.1 Applications of some metallic and metal oxide nanoparticles.

Metals	Application of metallic and metal oxide nanoparticles
Titanium dioxide (Ti)	Solar cells, food wraps, medicines, pharmaceuticals, lacquers, construction, medical devices, gas sensing, photocatalyst, agriculture, paint, food, cosmetic, sterilization, antibacterial coatings [4]
Zinc and zinc oxide (Zn)	Medical and healthcare goods, sunscreens, packaging, ultraviolet (UV)-protective materials, such as textiles [5, 6]
Aluminum (Al)	Automobile industry, aircraft, heat shielding coatings, military application, corrosion, fuel additive/propellant [7, 8]
Gold (Au)	Sensory probes, cellular imaging, electronic conductors, drug delivery, therapeutic agents, organic photovoltaics, catalysis, nanofibers, textiles [9]
Iron (Fe)	Magnetic imaging, environmental remediation, glass and ceramic industry, memory tape, resonance imaging, plastics, nanowires, coatings, textiles, alloy, and catalyst applications [10]
Silica (Si)	Drug and gene delivery, adsorbents, electronic, sensor, catalysis, remediation of the environmental pollutants, additive in rubber and plastic industry, filler, electric and thermal insulators [11, 12]
Silver (Ag)	Antimicrobial coatings, textiles, batteries, surgery, wound dressings, biomedical devices, photography, electrical devices, dental work, burns treatment [13]
Copper (Cu)	Biosensors and electrochemical sensors, plastic additives, such as antibiotic, antimicrobial, and antifungal agents, coatings, textiles, nanocomposite coating, catalyst, lubricants, inks, filler [14, 15]
Cerium (Ce)	Chemical mechanical polishing/planarization, computer chip, corrosion, solar cells, fuel oxidation catalysis, automotive exhaust treatment [16]
Manganese and its oxides (Mn)	Molecular meshing, solar cells, batteries, catalysts, optoelectronics, drug delivery ion-sieves, imaging agents, magnetic storage devices, water treatment and purification [17]
Nickel (Ni)	Fuel cells, membrane fuel cells, automotive catalytic converters, plastics, nanowires, nanofibers, textiles, coatings, conduction, magnetic properties, catalyst, batteries, printing inks [18]

Source: Attarilar et al. [19]/Frontiers Media/Licensed Under CC 4.0.

1.4.2 Mechanical Properties

Mechanical properties of different nanomaterials vary with respect to the nature of materials. Nanomaterials possess excellent mechanical properties due to the unique features of nanoparticles, such as volume, surface, and quantum effects. The addition of nanoparticles to other systems will improve the grain boundary and promote the mechanical properties of materials [61, 62]. Al Ghabban et al. [63] found that addition of 3 wt% nano-SiO_2 to concrete can enhance its compressive strength, bending strength, and splitting tensile strength. Addition of up to 0.1 wt% of nanochitosan to electrospun poly lactic acid (PLA) fibers led to an increase in tensile strength of the PLA/chitosan nanoparticles (nCHS) nanocomposite membranes. Lower concentration of nCHS in the nanocomposite gave superior tensile strength compared to the

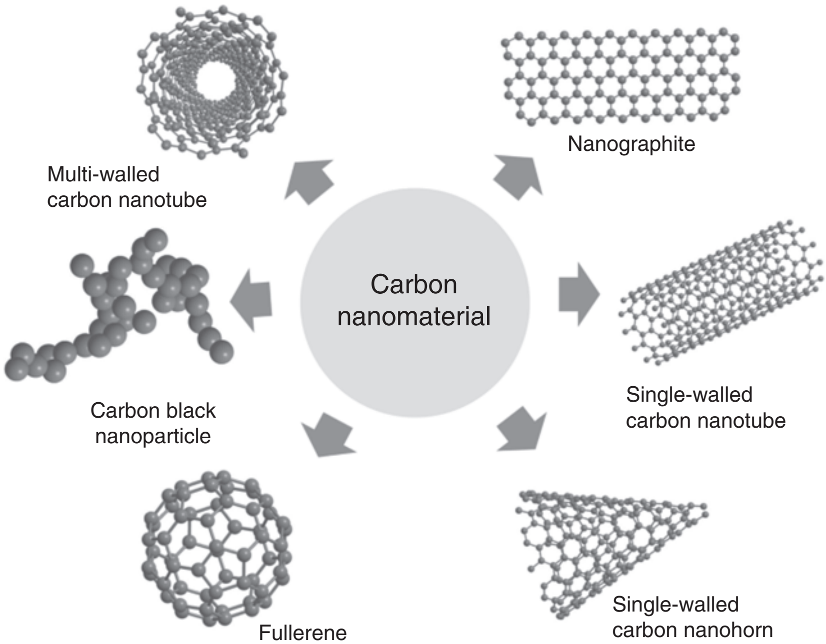

Figure 1.4 Schematic diagram of different carbon-based nanoparticles. Source: Yuan et al. [20]/Springer Nature/Licensed under CC 4.0.

Table 1.2 Applications of carbon-based nanoparticles.

Carbon-based nanoparticles	Applications
Fullerenes	Photovoltaics [21, 22], catalysis [23, 24], biomedicine [25], rechargeable batteries [26]
Graphene	Light emitting diode [27], superconductor [28], drug carrier [29, 30], hydrogen storage materials [31], battery [32, 33]
Carbon nanotubes	Electrical emitters [34], *air and water filtration* [35, 36], *biomedical* [37–39], solar collection [40]; catalyst supports [41, 42]; and coatings [43]
Carbon nanofibers	Electrocatalytic applications [44], CO_2 adsorption [45], batteries [46, 47], supercapacitors [48, 49], *biomedical* [50, 51], biosensors [52, 53]
Carbon black nanoparticles	Elastomer-reinforcing agent in rubber [54], inks, coatings, dyes [55], electrical conductivity agent in batteries [56, 57], UV stabilizer [58], heavy metal removals [59]

neat PLA membrane [64]. The key factors that improved the mechanical properties of the composites with such a low concentration of the filler are uniform stress distribution, minimized formation of stress-concentration centers, increased interfacial area for stress transfer from the polymer matrix to the fillers, and the decreased fiber diameter [65]. However, at higher loading, above 0.1 wt% the tensile strength seemed to be lowered. This is because of the aggregation of nCHS particles having large surface area and surface energy, which leads to the poor dispersion of nCHS in PLA matrix [66].

1.4.3 Optical and Electrical Properties

The optical properties of NPs can be utilized for the construction of optoelectronic devices. Semiconductor nanomaterials are widely used in photovoltaics and photocatalysis. The size and shape of the nanoparticles are the key factors determining the optical properties. The surface modifications also affect the optical properties of nanoparticles [67]. Size and shape of modifiers also influence the optical properties of nanoparticles. The optical properties mainly depend on the internal electronic structure and are responsible for the color of the nanoparticles. The color of nanomaterial varies with its size and is characteristic of surface plasmon resonance (SPR) that occurs by the interaction of outer electron band of nanomaterial with light wavelengths [68]. Usually, metallic nanoparticles show very high optical properties [68]. Noble metal nanoparticles show outstanding plasmonic properties. Sakhno et al. [69]reported that nanocomposites of transparent polymer matrices containing nanoparticles of noble metals are specially designed for photonics, linear and nonlinear optics, laser physics, and sensing applications. They found that presence of Au and Ag NPs improved the photosensitivity of nanocomposite.

Modern electronics are based on the electrical properties of nanoparticles, such as conductivity, semiconductivity, and resistivity, and these properties are always interconnected with optical properties.

1.4.4 Magnetic Properties

Magnetic properties of nanomaterials depend on the particle size, composition of the nanostructure, and synthesis methods [70]. It is a surface-dependent property and influenced by surface roughness and surface impurity [71]. Nanoparticles of less than 35 nm show the best magnetic properties. They also have peculiar magnetic properties, such as low Curie temperature, high magnetic susceptibility, and superparamagnetism [72, 73]. Metal nanoparticles, alloys, oxides, and ferrites are some examples of nanomaterials with magnetic properties.

1.5 Characterization of Nanomaterials

The different physicochemical properties of nanostructures can be studied by various characterization techniques. Some of the instrumental tools and techniques are discussed here.

1.5.1 Surface Morphology, Surface Area, Size, and Shape of Nanoparticles

Microscopic techniques are mainly used to study the morphology of nanostructures. Transmission electron microscopy (TEM), atomic force microscopy (AFM), scanning probe microscopy, and scanning tunneling microscopy (STM) are various microscopic techniques used.

The TEM is used as a strong analytical tool for structural and chemical characterization at the nanoscale. The detailed structural analysis of nanomaterials can be obtained from TEM imaging, diffraction, and microanalytical techniques [74]. A field emission source armed with a high-intensity probe beam is a characteristic of TEMs that permit elemental analysis in samples with spatial resolution 1 nm [74]. The crystal structure imaging and structure analysis of nanomaterials with a spatial resolution of 0.045 nm can be done with the help of high-resolution transmission electron microscopy (HRTEM). The interatomic distances and crystalline defects can also be studied by HRTEM imaging.

AFM is a type of scanning probe microscope, which is used to measure morphology and mechanical properties of materials at nanoscale level. The three-dimensional analysis and visualization of nanomaterials can be achieved by AFM analysis. The applicability of AFM analysis can be extended to image biological entities, analyze material interactions, study molecular force interaction, manipulate molecules on surface, investigate material nanomechanics, and mechanically fabricate 3D nanostructures.

Dynamic light scattering (DLS) is also called photon correlation spectroscopy or quasielastic light scattering. DLS technique provides information regarding hydrodynamic size, shape, structure, aggregation state, biomolecular confirmation, size distribution, and polydispersity of molecules. The basic principle of DLS is the measurement of scattered intensity at a fixed scattering angle with time. DLS is commonly used for the characterization of colloidal suspensions or dispersions, polymer solutions, and gels.

Brunauer–Emmett–Teller (BET) analysis, as well as differential mobility analyzer, can be used for surface area measurements of nanoparticles. BET analysis gives idea about the surface area, pore volume, and pore diameter of the nanomaterials.

1.5.2 Elemental and Mineral Composition

X-ray photoelectron spectroscopy (XPS), otherwise known as electron spectroscopy for chemical analysis (ESCA), is a necessary analytical weapon for the characterization of chemical composition of variety of materials.

The crystallographic studies of nanomaterials can be done by using XRD analysis and it is a nondestructive technique. XRD is used to determine interlayer spacings, elucidate structural strains, and detect impurities. The elemental analysis can be done by using inductively coupled plasma mass spectroscopy (ICP-MS) and atomic absorption spectroscopy (AAS).

1.5.3 Structures and Bonds in Nanoparticles

The chemical bonding in nanostructures like metal–oxygen bond can be studied by using Fourier transform infrared spectroscopy (FT-IR) and XPS. Surface configuration of nanoparticles is also provided by XPS, which is used for the characterization of doped graphitic carbon nanomaterials [75]. X-ray absorption spectroscopy (XAS) can also be used to get specific qualitative information about metal/metalloid species, as well as about their quantitative distribution [76]. Raman spectroscopy can also give specific information regarding the molecular interaction among nanoparticles. But low sensitivity is a problem of this technique and this can be overcome by the use of surface-enhanced Raman spectroscopy (SERS) [77]. SERS can be used at super-low concentration, even down to single-molecule level.

1.6 Current State of Nanotechnology

Nowadays, nanoscience and nanotechnology have been found to achieve incredible interest in the academic and research field. Nanotechnology finds its application in various interdisciplinary areas of chemistry, physics, life sciences, medicine, and engineering. It was found that nanotechnology has an impact on the chemical, energy, electronics, and space industries. Nanotechnology has the potential to overcome several limitations associated with conventional technology. Nanomaterials are characterized by their surface and mechanical properties. These advantages are taken into consideration in material science.

The unique size of nanomaterials helps it to pierce into cells of animals, and thus, these materials are widely used in biology and medicine for targeted drug delivery and detection of diseases. Researchers found that the nanoparticles are capable of protecting drug from degradation because of their shield-like properties.

In industry, nanoscale materials are used in consumer products, such as cosmetics and sunscreens, fibers and textiles, dyes, and paints [78]. Electronic engineering field also finds emerging applications of nanoscale materials because of the utility of nanostructured materials as smaller, faster data storage devices [79]. Optical devices have also taken the advantage of data storage devices because that can produce images of atomic and molecular processes at surfaces [80].

1.7 Safety Issues of Nanotechnology

In spite of the wide applicability of nanomaterials, the safety of nanomaterials is still debated. The risks of nanomaterials and their products are uncertain. The alarms about the potential hazards of nanomaterials are based on their exceptional surface area, catalytic and magnetic properties, and the impact of these properties in biological systems and the environment. Due to these peculiar properties', nanomaterials are highly reactive and transformed into other forms. The transformations may occur through agglomeration, redox reactions, dissolution, exchange of surface moieties, and reactions with biomacromolecules. For example, the use of nanoparticles

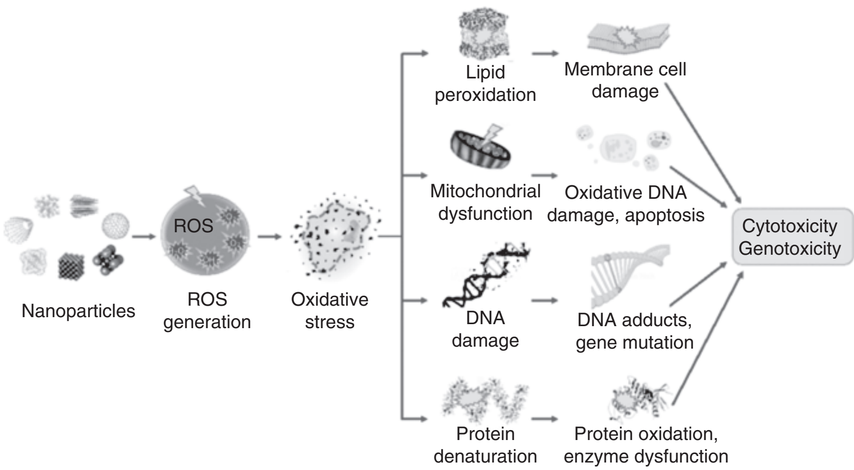

Figure 1.5 Toxicity mechanism of nanoparticles mediated by reactive oxygen species (ROS) generation. Source: Sengul and Asmatulu [81]/with permission of Springer Nature.

may lead to the release of respirable particles with unusual nanostructures; the degradation of nanoproducts at the end of their life may lead to previously encapsulated nanostructured materials being released into the environment.

Researchers found that exposure to nanoparticles leads to the production of reactive oxygen species (ROS), resulting in toxicity [81]. Accumulation of iron oxide, ZnO, TiO_2 nanoparticles in lung, liver, spleen, etc., leads to oxidative stress resulting in inflammation, low cell viability, cell lysis, and disturbance of the blood coagulation system.

Figure 1.5 is the model that describes extracellular sources of ROS as exposure routes for the engineered nanoparticles. Intracellular ROS can be generated from the mitochondria, which later causes lipid peroxidation, DNA damage, and protein denaturation [81].

In food sector, nanopackaging may lead to some hazardous effects due to poor packaging. These hazardous effects depend on toxicity of the nanomaterial used, nature of packaging matrix, degree of migration, and ingestion rate of the particular food [82, 83]. Presence of some inorganic nanoparticles, such as silver nanoparticles, may also get agglomerated in various internal organs of animals [84].

1.8 Conclusion

In this chapter, we have provided a short understanding of nanoscience and nanotechnology, properties of nanomaterials, and different characterization techniques. This chapter also covers the current state of nanomaterials and their risk assessment. Nanomaterials are smart materials with a wide range of applications in the field of biology, medicine, optoelectronics, food technology, etc. But there are some risk factors also associated with this field. The safe and sustainable use of nanomaterials is desirable.

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