

Nanomaterials and their classification

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1 Introduction

A “nanomaterial (NM)” can be defined as a material with a nanoscale internal structure or with nanoscale external dimensions or surface structure. Most of the materials in the world qualify as NMs according to this definition because the structure of NMs is arranged at the nanoscale [1].

In general, materials can be divided into two classes as NMs and bulk materials. Nanomaterials are produced at nanometer scale between 1 and 100 nm. Bulk materials with a size greater than 100 nm are known as “particles.” Physical properties in bulk materials are independent of size, while their size and shape can depend on various physical properties [2].

There are different definitions of NMs internationally, which are accepted by different organizations [3]. According to the British Standards Institution, the specific terms have been used in scientific applications as shown in Table 1 [3].

NMs are produced using a broad range of chemical components, including carbon, semiconductors, polymers, metals, and metal oxides. They are intended for unique features and can be coated or treated on the surface. They come in a wide range of shapes, including balls, sticks, cables, tubes, fibers, coatings, rings, needles, shells, and plates [4].

Table 1 Terminology for NMs, British Standards Institution. PAS 136 2007.

Term	Definition
Nanoscale	Size ranges from approximately 1 to 100 nm
NMs	Materials with one or more external dimensions in the nanoscale or nanostructure
Nanostructure	A structure consisting of contiguous elements with one or more nanoscale dimensions, but excluding any primary atomic or molecular structure
Nanoparticle	A nanoobject with all three external dimensions in the nanoscale
Nanoobject	A discrete piece of material with one or more external dimensions in the nanoscale
Nanotechnology	A technology that pervades virtually every aspect of life and will enable dramatic advances to be realized in most areas of communication, manufacturing, health, materials, and knowledge-based technologies
Nanofiber	A flexible nanorod
Nanorod	A nanoobject with two similar external dimensions in the nanoscale and the third dimension being significantly larger than the other two external dimensions

2 Classification of nanomaterials

The interest in NMs is growing because of their unique physicochemical properties. However, the classification of the NMs started to be ambiguous in research studies. Therefore, the classification of NMs is important for the various utilization areas [5]. NMs can be divided into groups based on their morphology, size, shape, chemical composition, state, and dimensionality, as shown in Fig. 1 [6]. In this chapter, the classification of the NMs is discussed according to the features of the materials.

2.1 Dimensionality

According to their shape and dimension, NMs can be classified into four types according to dimensionality: zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D), as shown in Fig. 2. NMs can be produced from elementary blocks in 0D, 1D, and 2D, while 3D NMs are formed in a more complex way [8]. It must be noted that NMs can be harmful to human health because of the substrates that they are fixed on or because of nanopores. Likewise, free nanoparticles can cause respiratory problems when they become airborne [1].

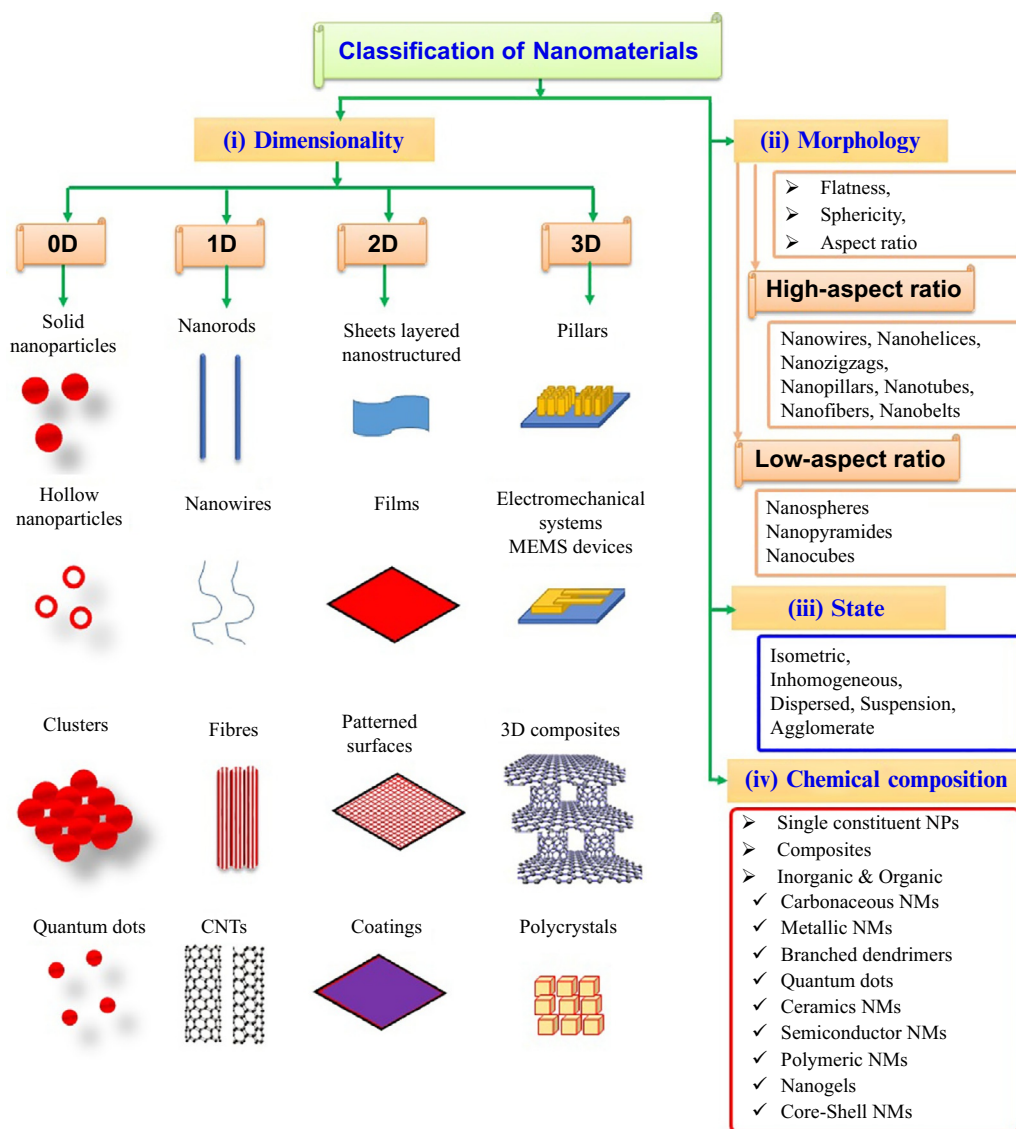


Fig. 1 The classification of NMs based on different criteria [2].

2.1.1 0D nanomaterials

The 0D NMs contain several types of nanoparticles, including dendrimers, branched macromolecules, palladium, anatase titanium dioxide, carbon (fullerenes), gold or tungsten, zinc oxide, vanadium oxide, magnesium oxide, molybdenum disulfide, and silicon carbide nanoparticles. All these substances have their

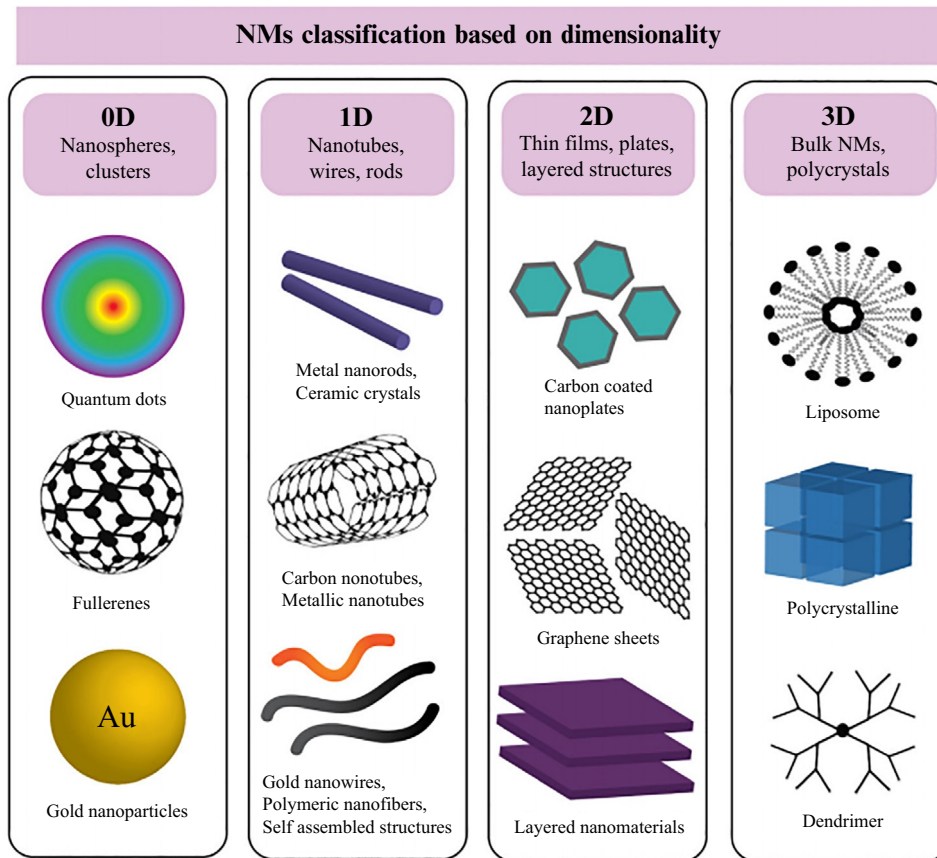


Fig. 2 The basic materials classified due to their dimensionality [7].

dimensions in nanoscales lower than 100 nm [9, 10]. These NMs can be produced for several purposes, such as cell markers [11], emulsifiers [12], or reinforcement fillers [13]. One of the best-known 0D materials is the quantum dot (QD), whose dimensions are below 10 nm. One of the most important properties of these materials is that they are semiconductors and therefore they have important roles in electronics to confine electrons and holes [14].

2.1.2 1D nanomaterials

1D NMs consist of metallic, nanotube, polymeric, nanowire, ceramic, nanorod filament, or fiber substances, and nanofibers with 2D are in nanoscale; however, one of the dimensions is not

in nanoscale. Such materials can be used as a thin film for surface coatings attached to a substrate [10].

Nanotubes have a peculiarly crystalline, cylindrical form, shaped like pentagons, hexagons, and heptagons [15]. The best-known nanotubes are made of carbon, but molybdenum, boron nitride, copper sulfides or tungsten, and various halides such as cadmium chloride, cadmium iodine and nickel chloride can also be manufactured with nanotubes [15].

Nanowires, classified as 1D NMs with length of 1–1000 nm in at least one dimension have multiple unique features for photoelectrochemical applications that exhibit better performance than their bulk counterparts [16]. They can be produced with semiconductor compounds, metals, and electrical insulators such as silicon, nickel, and titanium dioxide [15].

Nanorods are positioned with an aspect ratio of usually between 3:1 and 2:1 at the border between 0D and 1D NMs [17]. Some nanorods have the potential to alter their reflectivity when an electric field modifies their orientation. They can also emit heat when they adsorb infrared radiation [9].

Nanofibers are widely used NMs that can be developed using inorganic materials, such as carbon, nitride, platinum, and titanium; and from various polymers including nylon, polyurethane, and polyvinyl alcohol. The establishment of the nanofibers can be like a web that can be used in filtration applications or formed yarn [18].

2.1.3 2D nanomaterials

2D NMs have a structure with one dimension in nanoscale while the others are not. These 2D materials comprise amorphous or crystalline nanocoating, thin films, nanoplates, and single-layered and multilayered [10].

Ceramic and metal coatings consist of thin films [19]. In physics and electronics, they are often used to modify optical reflectivity of surfaces or to create electronic components with conductive or insulating surface properties. Several materials, including polymers and composites, can also be used to manufacture nanocoatings [20]. In that case, the aim would be to increase hardness, corrosion, or resistance to abrasion, or to have an insulating layer. Nanoplates can be produced as smectic clay or developed as nanoplates of graphene, gold, silver, bismuth telluride, or bismuth selenide. Nanoplates are usually a number of nanometers thick, and their length and width are up to 600 nm for nanoribbons of graphene [21, 22], and 70–150 nm for nanoclay [21]. Nanoplates can be used to improve the properties of their mechanical,

thermal, and diffusion barriers as modules in electronics and as composites, they respond favorably [9].

2.1.4 3D nanomaterials

3D NMs exhibit internal nanoscale characteristics, but at the nanoscale, there is no external dimension [23]. Therefore, it can be noted that 3D materials have dimensions over 100 nm size [8, 24]. Nanotubes, carbon nanobuds, foams, fibers, polycrystals, pillars, fullerenes, layer skeletons, and honeycombs are the types of 3D NMs that can be combined in different directions [24, 25]. Also, nanocomposites and nanostructured materials are the best-known 3D NMs.

To define nanofillers distributed in a bulk matrix, the term “nanocomposite” is commonly used. Matrices can be polymers, ceramics, or metals, while nanofillers may consist of 0D, 1D, or 2D NMs. The final material can be a film, fiber, or volume. Bones are one of the best-known natural nanocomposites, and it consists of a collagen matrix and calcium hydroxyapatite nanocrystals distributed within it.

Owing to the high surface-to-volume ratio of nanofilling, there is a difference between nanocomposite and composite materials. Due to their strength and rigidity, polymer matrix nanocomposites have been identified for various applications [26], superhydrophobic coatings with nanoprotrusions [27], block copolymers [28], and nanostructured alloys and metals.

2.2 Classification of nanomaterials by morphology and state

NPs can be classified as inhomogeneous and isometric or agglomerate and dispersed, based on uniformity. Sphericity and flatness, as well as aspect ratio, comprise the morphological nature of NPs. On the other hand, nanoparticles with a decreased aspect ratio display various shapes such as cubes, helical, spherical, pillarlike, and pyramidal. The electromagnetic properties of NPs such as magnetism and surface charge rely on this stack. In addition, the agglomeration of NPs in a fluid depends on functionalization and morphology, leading to hydrophilicity or hydrophobicity. NPs are nanotubes, nanostars, nanohooks, nanorods, nanocubes, nanohelices, nanozigzags, nanobelts, nanopillars, and nanoplates with various morphologies [2, 10].

The properties of NPs, such as durability, are provided by nanocomposites that integrate NPs into a standard material matrix. Metals such as zinc, iron, alumina, silver, titanium, silica,

and copper are made from these metallic NMs. Another type of NMs is the linked dendrimer, which has a branchlike nanoscale structure [2].

NPs can be categorized according to their chemical composition, such as monocomposite or nanocomposites. Carbonaceous NMs are mainly derived from carbon, such as carbon nanotubes (CNTs), graphenes and fullerenes. NMs may occur in scattered shapes, colloids, and suspensions or in an agglomerated state according to their chemical and electromagnetic properties. For example, magnetic NPs appear to be clustered into an agglomerate if their surface is not functionalized [2].

2.3 Classification of NMs by chemical composition

NMs can be divided into two groups as organic and inorganic materials [29]. Moreover, NMs can be produced using two or more materials. For example, they can be encapsulated or coated [10].

2.3.1 *Inorganic-based NMs*

These NMs can be developed by using metals, metal oxides, and semiconductors such as Au, TiO₂, and silicon, respectively. On the other hand, Ag, ZnO, and ceramics can be used to synthesize inorganic-based NMs [3].

2.3.1.1 Carbon-based NMs

As the name implies, carbon is the main component of carbon-based NMs, and they can be developed in different morphologies, such as hollow tubes, ellipsoids, and spheres. These NMs can be used in different fields according to their structure and properties that depend on the unique structure of carbon. Carbon can be found in various forms, such as diamond and graphite [30]. Carbon-based NMs include such materials as carbon nanofibers, CNTs, carbon onions, carbon black, fullerenes (C₆₀), and graphene. Production methods for carbon-based NMs include arc discharge, laser ablation, and chemical vapor deposition (CVD) [31]. These NMs contain hybridized sp² carbon atoms, which can be produced in several dimensions (Fig. 3) [30, 32, 33].

Carbon-based NMs can be used in many applications. Therefore, these materials become attractive to many scientists and producers according to their chemical and physical properties that include conductivity, thermal properties, and other characteristics. Carbon-based NMs and carbon can be divided into four groups: fullerene, CNTs, graphene sheets, and graphite and nanodiamonds.

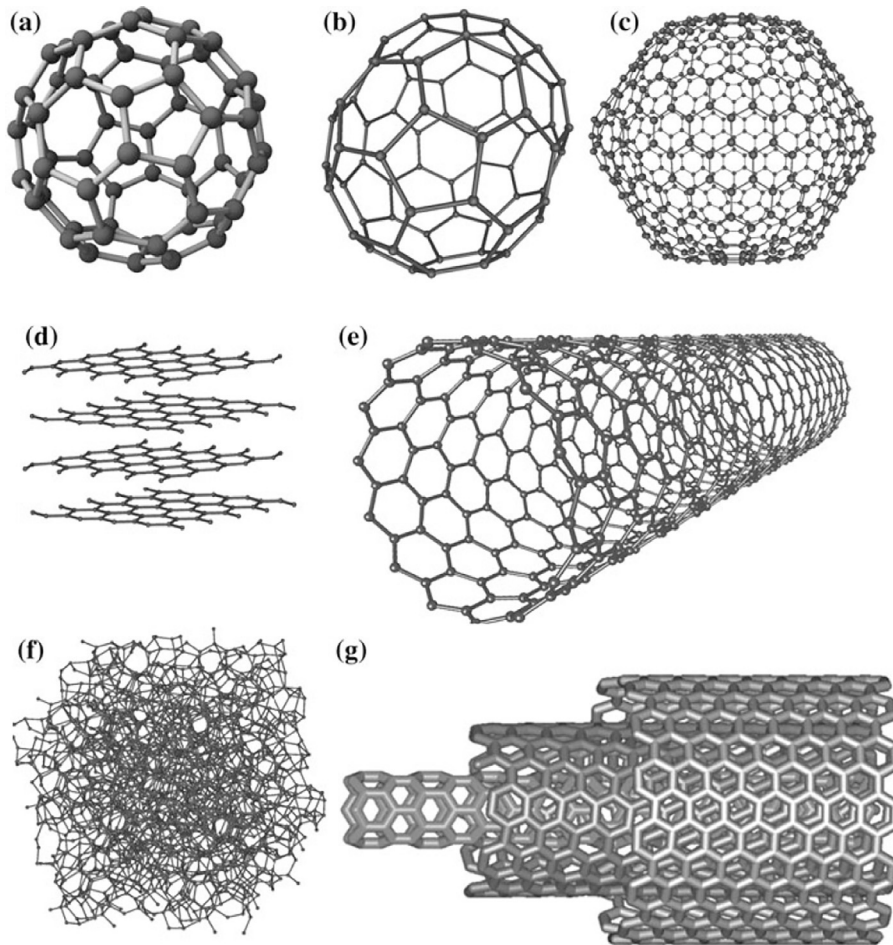


Fig. 3 Carbon allotrope structures in nanoform: (A) fullerene C60; (B) C70; (C) C540; (D) graphite; (E) single-walled carbon nanotube (SWCNT); (F) amorphous carbon; (G) multiwalled carbon nanotube (MWCNT) [10].

- (1) *Fullerene (0D)*: Derivatives are an allotrope of carbon consisting of 60 °C atoms that can neutralize oxygen and nitrogen [34].
- (2) *CNTs (1D)*: Hexagonal structures consisting of carbon atoms that linked to form a hexagonal structure. Chemical and physical modifications of CNTs have varying characteristics based on the materials used. It can be synthesized directly using the CVD process [35].
- (3) *Graphene sheets (2D)*: Performed by graphene and carbon atoms that bond covalently to each other to form a honeycomb or hexagonal lattice. Graphene sheets have several

structural properties, including good stability, chemical reactivity, high electrical conductivity, and large surface area. Graphite is the source of graphene in which mechanical and chemical methods can be used for the extraction of graphene [36].

- (4) *Graphite and nanodiamonds (3D)*: Basically used for semiconductors, coating, and abrasives. Graphite is formed by sp^2 carbon atoms that are arranged in a hexagonal shape. On the other hand, nanodiamonds have a layered, spherelike shape, and their optical and magnetic features distinguish them from the other materials [37, 38].

2.3.1.2 Metallic nanomaterials

Gold, silver, and iron are metal NMs that have unique chemical, electrical, and optical properties [24]. Metallic NMs can be produced by ultrasonic vibration and sonoelectrochemical [25]. Designation processes can affect the size of metallic nanoparticles. For example, if you reduce the size of a metal particle in a nanometer range, with a significant number of atoms appearing on the top by different electronic quantities, the electronic build band gap can vary. These surface atoms can become more effective by reducing the size of nanometers due to the growing distance between unsaturated sites and atomic coordinates. Au NPs, for example, can be prepared and synthesized by mixing ultrasonic vibration and sonoelectrochemical [25]. Metal NPs can typically absorb light through in-band (such as Cu, Au, Al, and Ag) and interband (such as Ni, Pt, Ru, and Pd) transitions. Earlier studies have found that light irradiation can increase the catalytic activity of metal NPs [39].

2.3.1.2.1 Metal oxide nanomaterials Metal oxides form another chemical group of NMs. Applications have been reported for titanium dioxide as an ultraviolet (UV) filter, a catalyst in chemical reactions, and an antibacterial agent that can be used in cosmetics, cleaning products and wall paint, and filtration systems, respectively. Moreover, titanium dioxide is also important in the production of solar cells [40].

Zinc oxide is also used as an antistatic agent, with fascinating antibacterial and catalytic properties [9]. Nanosilica is used as a hollow carrier for drug delivery because of its chemical properties [41]. Nanoalumina is used as a chemical catalyst, a mechanical, optical reinforcement, and a thermally conductor for abrasion-resistant coatings [9]. Iron oxides can be used as ion exchangers and pigment flocculants in electrical, water purification, and

biomedical applications due to their excellent magnetic properties [42]. Cerium oxide is used as a vehicle exhaust catalyst, a chemical polishing agent for silicone wafers, a fuel cell, and a UV absorber used to coat wood [9].

Several kinds of metal oxides, such as Fe_2O_3 , TiO_2 , ZnO , SiO_2 , and Al_2O_3 , have been synthesized through hydrothermal or sol-gel reactions. A metal oxide has a considerable number of uses, such as catalysts, semiconductors, and chemical sensors, because of differentiation of its surface properties that affects the bandgap energy of the material [43]. The biocompatibility of these materials with a highly active surface area is the reason why these materials have a more important property. Several responses, such as adding a polymer chain, doping metal ions, or a binding agent, can easily change the surface of NPs [44, 45].

To modify the structure of NPs, many organic compounds are used, such as amines [46], epoxies [47], anionic compounds [48], and thiols [49]. Modification of the structure of NPs, especially surface modification, provides them with unique chemical and physical properties [2].

2.3.1.3 Quantum dots

QDs are ultrasmall semiconductor nanocrystals composed of 100–10,000 atoms in the 1.5–10-nm size range [50]. They are nanoparticles of semiconductors that exhibit optical and electronic (optoelectronic) properties depending on their size and composition. Recently, QD nanotechnology has been used in various electronic and biomedical sectors successfully [50].

Due to quantum mechanics, QDs are small semiconductor particles with optical and electronic properties that differ from those of larger particles. They exhibit distinctive electronic and optical properties by absorbing UV or white light and reemitting it at a different wavelength [2].

Initially used in determining surface kinetics, QDs are now successfully used as drug delivery agents and diagnostic markers. They are nanocrystals made up of a core semiconductor material further enclosed within another semiconductor material with a wider spectral band gap [51]. Besides their nano-size, QDs have an application potential in nanodiagnostics, imaging, targeted drug delivery, and photodynamic therapy due to their specific characteristics, such as wide-range excitation, high fluorescence, size-tunable narrow emission spectra, and high photostability [51].

2.3.1.4 Semiconductor nanomaterials

Semiconductor NMs were characterized with various morphologies and compositions that can be used easily in several applications [52]. They are controlled by quantum mechanics [53]. Nanosilicon is one of the most usable semiconductor NMs, which can play a role in solar cells, rechargeable batteries, electronics, and solid-state lighting. Gallium nitride is used to produce transistors for electric vehicles, light-emitting diodes (LEDs), and photonic and optoelectronic devices, which are versatile and water resistant. Indium gallium nitride can be developed as LED nano-rings, photovoltaic nanocolumns, and optoelectronic nanoflowers. Gallium arsenide, a semiconductor NM, can be used as a optomechanics and photodetector in solar cells [9].

2.3.1.5 Ceramics nanomaterials

Ceramic nanomaterial is defined as inorganic, heat-resistant metal compounds that are less than 100 nm size and nonmetallic solids [6, 8].

Several chemical and physical methods have been explored and reported for preparation of ceramic NMs. These materials have been found to show improved superconductive, electrooptical, structural, ferroelectric, and ferromagnetic properties [54]. Similarly, by changing the concentration of doping, the physical and structural properties of nanoceramics can be changed, which could reduce oxygen vacancy and induce structural material distortion [55].

Calcium hydroxyapatite (CaHAP) porous nanoceramics have been produced by high-purity methylcellulose and can be prepared by the precipitation of hydroxyapatite (HAP). The porosity of CaHAP and its exact surface area depend on the sintering process temperature. Their capacity to activate antimicrobials is impaired by interactions between bacteria and their surface charges. $\text{Al}_2\text{O}_3\text{-ZrO}_2$ nanoceramics are generated in low-temperature and pressureless conditions by synthesizing nanoceramics. The results of this analysis showed that the grain size of NPs and homogeneous mixture were successfully formed with amorphous materials at low temperatures [56].

2.3.1.6 Polymeric nanomaterials

Polymeric NMs are dense particles composed of synthetic or natural polymers that are nanosized. In medical and pharmaceutical applications, these materials are commonly used as drug-release controllers in the human body [57]. NMs based on the polymer include the following:

- (1) Polymeric NPs, which typically consist of polymers that are biodegradable and biocompatible with a size of approximately between 10 and 1000 nm. They are commonly used to distribute medications to particular targets [58].
- (2) Polymeric nanocomposites, a mixture of polymers and other nanofillers used to develop [59].
- (3) Polymeric micelles, produced in a specified solvent through the self-assembly of amphiphilic block copolymers. Due to their special characteristics, they can be used in drug delivery [57].
- (4) Dendrimers, with 3D macromolecules that are less than 15 nm in size. These materials are commonly produced for pharmaceutical and medical applications due to their characteristics [60].

To render nanoobjects, nanospheres (including nanoporous membranes and nanofibers), thermosets, thermoplastics, and elastomers can be used. Reinforcement for structural composite materials, barrier membranes, fuel cell membranes, filtration membranes, fire-resistant optical components, versatile electrical elements, and antibacterial textiles are used in their applications [61].

2.3.1.7 Core-shell nanomaterials

Single-component NMs have been widely studied, and various properties have been discovered, including easy processing and higher surface atom ratio. Researchers have concluded that the combination of multicomponent NMs could achieve much better properties with the rapid evaluation of characterization and synthesis techniques, and the diversity of their structure and composition could enrich their applications in various fields. Thus, standardized core-shell NMs have become a prominent research subject in recent years [62]. Several metals can be used for the core particles, such as Au, Ag, Pt, Pd, Zn, and Ni, while TiO_2 , ZnO, Cu_2O , SiO_2 , Fe_2O_3 , and SnO_2 metal oxide semiconductors can be developed as shells. They can play a role in catalysis, photocatalysis, and solar photovoltaics [63].

NPs formed by encapsulation of shell material can be investigated mainly in two categories: (1) inorganic-organic, organic-inorganic, and inorganic-inorganic types; and (2) chemical coating and physical coating of the shell are used to improve the activity of crust and maintain the chemical integrity of the core. Coated main particles are designed to have magnetic, optical, and catalytic properties [64].

2.3.2 Organic-based NMs

Organic materials can be used to develop organic-based NMs. By using noncovalent interactions, organic NMs can be converted into liposomes, micelles, polymers and dendrimers [3].

2.3.3 Composite-based NMs

Composite NMs can consist of the mixture of different NPs, or they can be more complex, like organic metal frames. A composite can be a combination of metal, organic NMs or carbon. Composite-based NMs are synthesized in a number of morphologies based on the properties needed for their desired uses [3].

Composites are solid materials composed of multiple phases with dimensions less than 100 nm in a structure or phase with a nanoscale repetition gap between phases [65, 66]. In the process of constructing composite structures, physical measurements on the nanometer scale range are often used. The combination of several composite-forming materials can produce various properties, such as optical properties, flexural strength, wear of gloss, and water sorption and retention [67–69]. Composite materials allow the adsorption potential of the material to be enhanced by multiple types of interactions, such as Yoshida H-bonding and bonding of dipole-dipole hydrogen [70].

2.3.4 Silicates, carbonates, and nitrides

Silicates, carbonates, and nitrides are important NM groups. Clay (magnesium aluminum silicate) is a unique nanosilicate that can take shape of nanoplates and nanotubes [21]. For improvement of mechanical strength, electrical conductivity, and barrier properties, clay is used as a filler in composites. Zeolite can be used as a molecular hydrocarbon sieve, a catalyst, and a germ to produce a separation membrane [71]. In the case of calcium carbonate, if its function as a microscale composite filler is primarily aimed at lowering costs, calcium carbonate increases its resistance to effects, its barrier properties, environmental creep and aging, dimensional stability, surface finish, nanoscale modulus, and thermal conductivity. It also decreases processing contraction [72].

3 Conclusion

Due to advances in technology and discoveries during the last 40 years, a great deal of progress has been made in understanding the production and properties of NMs. They vary in size, natural or anthropogenic origin, chemical and physical properties, and

production techniques such as bottom-up, top-down, or bottom-to-bottom. On a day-to-day basis, physical chemistry features are added to NMs with high diversity and usage areas, and the number of scientific and field areas is steadily increasing. Because of their excellent properties and diversity, NMs are used in many industries. In this respect, the classification of NMs will obviously require revision in the coming years.

We hope that this chapter has given a general overview of the knowledge and perspective on NMs.

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