Nanomaterials and Their Distinguishing Features

Swati Singh, Naveen Kumar Arkoti, Vivek Verma, and Kaushik Pal

Abstract Nanomaterials have evolved as a fascinating class of materials that encompasses a diverse variety of prototypes with at least one dimension in the 1–100 nm range. The small size and sensible design of nanoparticles can result in extremely high surface areas. As a result of this, nanoparticles have improved features such as high reactivity, strength, surface area, sensitivity, and stability. Nanomaterials can be made with mechanical, magnetic, optical, electrical, and catalytic capabilities that are vastly superior to those of their bulk counterparts. Furthermore, the size, shape, synthesis conditions, and appropriate functionalization of nanomaterials may all be precisely controlled to provide the desired qualities. This chapter gives a brief overview of nanomaterials and how they have been used to progress nanotechnology development throughout history. We discuss and establish nanomaterial classification based on dimensions and materials in particular. The chapter emphasizes the unique characteristics of nanomaterials, such as size and surface area, magnetic properties, quantum effect, and so on. This chapter also discusses nanomaterial advancements and applications in a variety of sectors, including energy harvesting and storage, structural, gas sensing, biomedical and health care, and many more. Finally, we conclude by discussing challenges and future avenues relating to nanomaterials.

Keywords Nanomaterials · Properties · Optical · Surface area · Quantum confinement

1 Introduction

Since the beginning of time, materials have piqued the attention of humans. Rocks were discovered to be capable of breaking objects that were extremely hard to shatter

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S. Singh · N. K. Arkoti · K. Pal (✉)
Center of Nanotechnology, Indian Institute of Technology Roorkee, Uttarakhand 247667, India
e-mail: aushik@me.iitr.ac.in; pl_kshk@yahoo.co.in

V. Verma · K. Pal
Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Uttarakhand 247667, India

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with human hands about a million years ago. Stones were the earliest tools, and they have been used to crush and grind food, as well as mortars and pestles, in kitchens and laboratories today. 5000–6000 years ago, it was unintentionally discovered that molten copper could be collected by placing a copper-containing rock over a fire. As a result of this finding, metal ores were reduced to make metals for manufacturing anything from plowshares to swords. New materials for toolmaking were accessible that were harder and lasted longer than stone. The evolution of metals and metallurgy has coincided with our growth and advancement (Murthy et al. 2013).

Materials with exceptional mechanical, physical, and chemical properties are required for new technologies. Materials science and engineering have created materials with diverse qualities by modifying the constituents or microstructure of materials through thermochemical and mechanical processes. As a result, microstructural engineering and structure–property connection studies have become increasingly important. The mechanism whereby the ultrafine microstructures influence the characteristics of materials was being interpreted after the development of theories of lattice distortion and misalignment and the implementation of innovative high-resolution microscopy techniques such as field ion, atomic force, and electron microscopy. These breakthroughs have aided in comprehending the relationship between the properties and structure of solids (Sadik et al. 2014).

Nanotechnology has gained extensive interest over the last century after Richard P. Feynman, the Nobel prize awardee, delivered his lecture at the annual meeting of the American Physical Society on “There’s Plenty of Room at the Bottom” in 1959 (Feynman 1992). After this, various discoveries and inventions have been made in nanoscience and technology due to the availability of new tools for the characterization and manipulation of small objects at the atomic scale. Nanotechnology is the controlled manipulation of shape and size at the nanoscale scale (1–100 nm) for the design, characterization, fabrication, and application of structures, devices, and systems having at least one novel/superior trait or characteristic. An essential feature of nanotechnology-produced materials is their higher surface-to-volume ratio, which is desired for many applications. Another essential feature is quantum physics, where nanotechnology enables everyone to create materials with one dimensional (nanowires), two dimensional (nanotubes), or three dimensional (nanoparticles), which are particularly useful in industrial applications (Baig et al. 2021).

In nanotechnology, a nanoparticle (NP) is defined as a tiny constituent array that acts as a single unit and exhibits unique features not seen in bulk materials. The confinement of photons, phonons, and electrons at the nanoscale results in the development of novel biological, physical, and chemical characteristics, making them distinct materials in their very own right. Nanoparticles’ (NPs) size, shape, and structure influence their qualities and reactivity. The lowering of dimensionality impacts a range of characteristics, including melting temperature (which is determined by the number of atoms involved in the coordination), conductivity, magnetic properties, optical properties, and reactivity, to name a few. Quantum physics is to blame for these massive shifts. The mean of all quantum forces influencing atomic molecules determines the bulk characteristics of every substance. As particles get progressively smaller, consequently, at a point of time, where averaging becomes ineffective (Yang et al. 2021).

Quantum effects, increased surface area, and self-assembly are among the factors that contribute to nanomaterials' distinctive features. At the nanometer range—especially at the lower end—quantum effects can influence matter's behavior, affecting material's magnetic, electrical, and optical properties (Patra et al. 2011). Second, for the same quantity of material generated in bulk, nanoparticles have a significantly higher surface area. Because the number of active sites increases as particle size decreases, the fraction of surface atoms increases, resulting in an increase in reactivity (Saleh 2020). Finally, self-assembly is a method of constructing an ordered pattern or structure through the organization of components. Supramolecular contacts (ionic, coordination, hydrophobic, hydrogen, and van der Waals bonds) are commonly used in molecular self-assembly, although kinetically labile covalent connections can also be used. When the aggregated and non-aggregated states are equilibrated, the inherent mobility leads to ordered nanostructures with various fascinating qualities, including high sensitivities, self-healing, and error correction to extrinsic stimulant. Because of their unique properties, nanomaterials have applications in multiple fields such as drugs and medication, cosmetics, food packing, biomedical, sensors for environmental stages, electronic and optical, energy harvesting and storage, structural, lubrication, and quantum computing (Foong et al. 2020).

This book gives an in-depth knowledge of how the nanomaterials came into existence and a brief introduction to their unique properties in the first chapter. The second chapter deals with nanomaterials synthesis by top-down and bottom-up methods and characterization techniques like structural, microscopic, composition, optical, magnetic, etc. Chapter 3 deals with different nanomaterials and nanostructures in 0D, 1D, 2D, 3D nanostructures and their simulations of various applications in Chap. 4. The successive chapters discuss the applications of nanomaterials in energy storage and harvesting, structural, sensors and actuators, biomedical, and other discrete areas. The final chapter discusses nanomaterials' future challenges and opportunities in new technologies.

2 Classification of Nanomaterials

Nanomaterials are generally categorized based on their dimension and materials (Fig. 1).

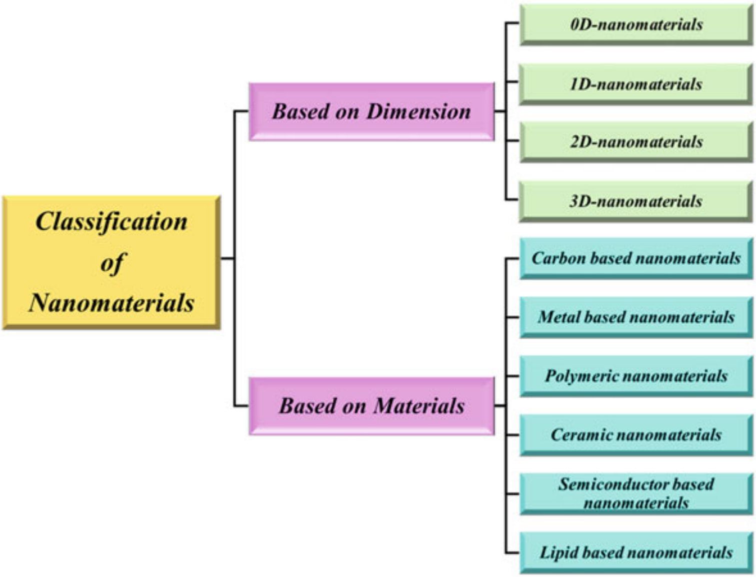

Fig. 1 Classification of nanomaterials

2.1 Based on Dimension

2.1.1 Zero Dimensional

Nanomaterials with all of their dimensions in the nanoscale, i.e., scaled below 100 nm, are known as zero-dimensional nanomaterials (0D). There seem to be no dimensions (x, y, z) greater than 100 nm (Saleh 2020). They generally include spherical nanomaterials, hollow sphere, cube, polygon, nanorod, quantum dots (QDs), as well as metal and core–shell nanomaterials.

2.1.2 One Dimensional

One-dimensional nanomaterials (1D) are materials having one non-nanoscale dimension and two nanoscale dimensions (x, y). Needles-shaped nanomaterials are formed as a result of this process. Metals, polymers, ceramics, nanotubes, nanowires, and nanofibers are all examples of 1D nanomaterials.

2.1.3 Two Dimensional

Two-dimensional nanomaterials (2D) contain only one dimension (x) in nanoscale, while the remaining two dimensions are outside the nanoscale. Two-dimensional nanomaterials exhibit plate-like shape. Thin films, nanoplates, and nanocoatings with nanometer thickness are included in this 2D nanomaterials (Pokropivny et al. 2007). They can be single-layered or multilayered, crystalline, or amorphous.

2.1.4 Three Dimensional

Three-dimensional nanomaterials (3D) are materials that not constrained in any way to the nanoscale. Above 100 nm, these materials have three arbitrary dimensions. The bulk (3D) nanomaterials are made up of a variety of nanosize crystals arranged in various orientations (Aversa et al. 2018). They are classically shaped artifacts from the past. They have a length, width, and thickness that are all a few nanometers or more. Multiple nanocrystals are arranged in opposite directions in 3D nanomaterials. Bulk powders, nanoparticle dispersions, nanotubes, fullerenes, nanowire bundles, foams, fibers, polycrystals, honeycombs, and multi-nanolayers are just a few examples of 3D nanomaterials.

2.2 Based on Materials

2.2.1 Carbon-Based Nanomaterials

Carbon-based nanomaterials are primarily hollow spheres, ellipsoids, and tubes made up of carbon. Carbon nanotubes (CNTs) and fullerenes are two prominent groups of carbon-based nanomaterials. Moreover, fullerenes are spherical and ellipsoidal carbon nanomaterials, while carbon nanotubes are cylindrical (Khan et al. 2019). Fullerenes such as allotropic carbon forms are nanomaterials made up of spherical hollow cages. The carbon units in these materials are organized pentagonal and hexagonal, and each carbon is sp^2 hybridized. Electrical conductivity, electron affinity, high strength, structure, and variability all have sparked significant commercial interest.

Carbon nanotubes (CNTs) have a 1–2 nm diameter and are elongated tubular structures. According to their diameter telicity, these are classified as metallic or semiconducting. The structure is similar to that of a graphite sheet rolling on itself. They are referred to as single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs), or multi-walled carbon nanotubes (MWCNTs), depending on the rolled sheets as one, two, or multiple walls (Aqel et al. 2012). Chemical vapor deposition (CVD) technique has recently been used to create them (Elliott et al. 2013). Due to their unique chemical, physical, and mechanical properties, these materials are used to make nanoconjugates for a variety of industrial purposes, including fillers, effective gas adsorbents that work for environmental cleanup, and for different inorganic and organic catalyst’s support medium.

2.2.2 Metal-Based Nanomaterials

Metallic precursors are generally used to produce metal-based nanomaterials. Metallic nanomaterials as nanoparticles show localized surface plasmon resonance, a type of resonant electron oscillation that gives them good optoelectrical characteristics. In the visible zone of the electromagnetic spectrum, alkali and noble metal nanoparticles such as gold (Au), copper (Cu), and silver (Ag) have a large absorption band. These nanoparticles with regulated facet, size, and shape are significant in today's cutting-edge materials (Chen et al. 2018). Quantum dots and metal oxides such as copper oxide (CuO) and titanium dioxide (TiO_2) are also included among these nanomaterials. A quantum dot is a nanometer-sized semiconductor crystal that has a core–shell structure in the traditional sense. Quantum dot's optical characteristics are altered by changing their size, shape, and material composition (Hong 2019). Nowadays, metal nanoparticles are used in a wide range of research areas due to their outstanding optical characteristics. Coating of gold nanoparticles is commonly used in FESEM samples to improve the electronic stream, which aids in the acquisition of high-quality FESEM images.

2.2.3 Polymer-Based Nanomaterials

Polymeric nanomaterials are nanoscale solid particles made up of natural or manmade polymers. Dextran, gelatin, pullulan, polylactic acid, chitosan, polylactide-co-glycolide, poly ethylene glycol, and polycaprolactone are some of the polymers commonly employed to make these polymeric nanomaterials as nanocarriers (Yang et al. 2021). These polymers are frequently employed as drug release controls in pharmaceutical and medical applications. Nanocapsules and nanospheres are two main types of polymeric nanoparticles that differ in their shape. Nanocapsules have an oily core in which the chemotherapeutic agent is normally dissolved and have an outer shell of polymer that regulates the drug's release profile from core, while nanospheres are made up of a continuous polymeric network that allows chemotherapeutic agent to be maintained or adsorbed onto their surface (Mansha et al. 2017). These polymeric nanoparticles (PNPs) can be easily functionalized and focused to create new drug delivery systems (DDS) for a variety of ailments.

2.2.4 Ceramic-Based Nanomaterials

Ceramic-based nanomaterials are generally heat-resistant inorganic nonmetallic solids that are made by heating and cooling them repeatedly. These materials have improved structural, optical, superconductive, electrical, ferromagnetic, and ferroelectric characteristics and can be manufactured utilizing physical and chemical processes. They are available in a variety of shapes and sizes, including amorphous, polycrystalline, dense, porous, and hollow. Because of their use in catalysis, photocatalysis, dye photodegradation, and imaging like applications, these nanomaterials are garnering close attention from researchers (Jung et al. 2018).

2.2.5 Semiconductor-Based Nanomaterials

Semiconductor nanomaterials have qualities that are intermediate between metals and nonmetals, allowing them to be used in a variety of applications including solar cells, light-emitting diodes, diodes, transistors, lasers, medical imaging, and quantum computing. The size and shape of these semiconductor NPs or QDs (quantum dots) have a significant impact on their characteristics. They are frequently referred to as "artificial atoms" due to their incredibly small size and the fact that they have unique, discrete, and definite electronic states, as found in naturally occurring atoms/molecules. Photocatalysis, photo-optics, and electrical devices all rely on them. Furthermore, with their acceptable bandgap and band-edge positions, a variety of semiconductor nanomaterials as nanoparticles have been used in water-splitting applications (Singh et al. 2018).

2.2.6 Lipid-Based Nanomaterials

Lipid-based nanomaterials are organic nanoparticles with a lipid unit that can be employed in a wide range of biomedical applications. The diameter of a lipid nanoparticle is 10–1000 nm, and it has a spherical shape. Similarly, to polymeric nanoparticles, lipid nanoparticles have a solid lipid core surrounded by a matrix of soluble lipophilic compounds. To stabilize the nanoparticles outer core, surfactants or emulsifiers were utilized (Rawat et al. 2011). Lipid nanotechnology is a branch of nanotechnology concerned with the design and manufacture of lipid nanoparticles for applications such as delivery of chemotherapeutic agent and release of RNA in cancer therapy.

3 Unique Properties of Nanomaterials

3.1 Size and Surface Area

According to Gleiter's theory, when the size d of a microstructure is reduced to a critical value d → d*, the scale length of physical phenomena (phonons and free path length of electrons, etc.; screening length, coherent length, etc.) becomes equal to or compatible with the characteristic size (diameter, thickness, and length) of the microstructure's building blocks.

Generally, a material's properties are defined by a certain "length scale," which is commonly measured in nanometers. If the material's physical size is dropped less than nanoscale, its characteristics alter and become the size and shape sensitive. Nanomaterials will have unique exciting features due to its size effects. The origins of the unique material properties in this size range are not explained by classical physics ideas. Furthermore, because nanocrystals have a large SA (surface area) and a considerable percentage of the atoms in a nanocrystal are on its surface, size effects in chemical and physical characteristics of nanocrystals can arise (30% for a 1 nm crystal, 15% for a 10 nm crystal). As particles and structures become smaller, surfaces and interfaces become increasingly critical (Roduner 2006).

3.2 Quantum Effect

Size effects are a unique and exciting feature of nanomaterials. Because nanomaterials are considerably closer to monomolecules and atoms than bulk counterparts, quantum mechanics is required to explain their unneling. In its most basic form, quantum mechanics is a scientific model for explaining the motion and energy of atoms and electrons. The following are the most crucial quantum phenomena, as well as other physical features, that arise in the nanoscale:

Because nanomaterials are so tiny, their mass is shallow; thus, gravitational forces are insignificant. On the other hand, electromagnetic forces play a significant role in influencing how atoms and molecules behave.

Wave-corpuscle duality: The wave-like aspect of the matter is more evident for things of very tiny mass, such as electrons. As a result, electrons behave like waves, and their location is described by a wave (probability) function.

One of the outcomes is a condition known as "unneling." A particle can only enter in via a boundary (potential barrier) provided if there is enough energy to "jump" over it, according to classical physics. If the particle contains less energy than that necessary to leap over the energy barrier, the chances of finding it on the other side of the barrier are nil in classical physics (the "obstacle"). Due to the unneling effect, a particle with less energy than that required to leap the barrier has a finite probability of being positioned on the opposite side of the barrier (Narendra Kumar et al. 2016).

3.3 Magnetic Properties

Generally, a material's magnetic behavior is determined by its structure and its temperature. A substance must have a nonzero net spin to experience a magnetic field (transition metals). The size of a traditionally predicted domain is typically approximately 1 m. These materials take on new characteristics at nanometer level. Because of the huge surface-to-volume ratio, a large percentage of molecules have varied magnetic coupling with surrounding molecules, resulting in variable magnetic characteristics (Lu et al. 2007).

Platinum and gold are non-magnetic in bulk; however, they become magnetic at the nanoscale. When Au nanoparticles are coated with the suitable chemical substances, such as thiol, they become ferromagnetic. Magnetic nanoparticles are utilized in imaging, bioprocessing, cooling, and high-density magnetic storage medium, among other uses.

3.4 Thermal Properties

Electrons are the main thermal energy carriers in bulk metals, and nanostructuring can affect their distribution. The free electron density in metallic-type carbon nanotubes, for instance, is low due to spatial confinement, and phonons control their thermal transport behavior. By modifying the accessible energy levels, quantum confinement changes the distribution of carriers. As a result, electrons are now more probable in smaller energy bands that could be used to manipulate thermal properties such as phase transition, melting point (mp), heat capacity, and thermal conductivity (Roduner 2006).

3.5 Mechanical Properties

Planar dislocations in a solid's crystalline structure, such as dislocations, are crucial in defining a material's mechanical characteristics. Because of the supremacy of crystal interfaces and surfaces, it is envisaged that dislocations would play a more diminutive role in explaining nanocrystal qualities compared to the description of microcrystal qualities. A dislocation's free energy is composed of three terms: (1) the free energy deriving from entropy contributions; (2) the elastic strain energy outside the core and extending to the crystal borders; and (3) the core energy (within a radius of around three lattice planes from the dislocation core) (Kumar et al. 2003).

3.6 Electronic and Electrical Properties

The discrete aspect of the energy levels becomes apparent once again when the system size approaches the de Broglie wavelength of the electrons, yet a truly discrete energy spectrum is only found in systems that are confined in all (x, y, z) three dimensions.

Materials that are conducting in nature can become insulators below a threshold length scale when their energy bands stop overlapping. Electrons can tunnel quantum mechanically between two nanostructures that are near together due to their inherent wave-like nature, and if a voltage is applied between two nanostructures that aligns the discrete energy states in the DOS, resonant unneling occurs, dramatically increasing the unneling current.

The quantum confinement effect causes the bandgap to rise as particle's size decreases in the nanoscale regime, causing metal to become a semiconductor as its size decreases. Some nanomaterials' electrical qualities are linked to their distinctive structures and have completely extraordinary electrical properties. Carbon nanotubes, for example, can be either conductors or semiconductors, depending on their nanostructure (Yurkov et al. 2007).

3.7 Catalytic Properties

The active surface, where the reaction occurs, is among the most important elements of a catalyst. The active surface increases whenever the catalyst particle size is lowered; the smaller the catalyst particles, the greater the surface-to-volume ratio. Higher the active surface of catalyst, higher the reactivity of surface. It has been appeared that spatial organization of active sites in a catalyst is critical. Both the properties, notably nanoparticle size and molecular structure/distribution, may be controlled via nanotechnology. As a consequence, this method can help the automotive, chemical, petroleum, pharmaceutical, and food industries enhance the design of their catalysts (Bhandari and Knecht 2011).

3.8 Antimicrobial Activity

Nanomaterials, particularly metal and metal oxide nanoparticles, offer unique antimicrobial capabilities such as antibacterial, antifungal, and antiviral properties, which make them ideal for application in medical and pharmaceutical devices to combat deadly infections. Furthermore, antimicrobial characteristics of metallic nanoparticles are widely recognized, with many, particularly silver and gold, currently being employed in medical devices to help clean equipment and reduce the transmission of infectious diseases and also in cancer therapy (Bankier et al. 2019). Furthermore, the formation of reactive oxygen species (ROS) by these metallic nanoparticles suppresses the antioxidant defense mechanism and damages the cell membrane, ultimately resulting in cell death (Fig. 2).

4 Applications of Nanomaterials

The presence of unique characteristics of materials at atomic or molecular scale (approximately between 1 and 100 nm) has attracted very much attention and been widely utilized in medicine; targeting drug delivery; artificial implants; sensing

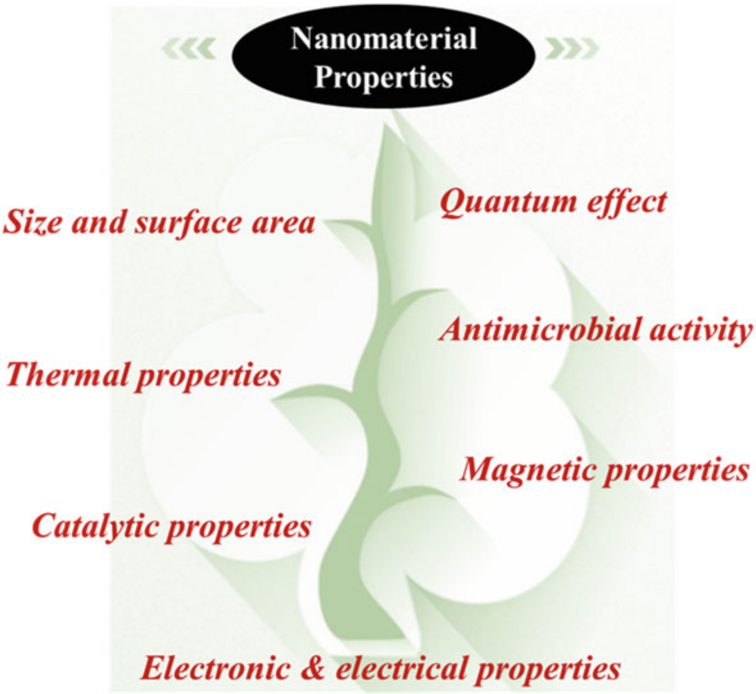

Fig. 2 Properties of nanomaterials

devices for of gas, humidity and biosensors; cancer diagnosis; energy harvesting and storage, environment management, etc. (Barreto et al. 2011); (Yang et al. 2015). With the advancements in technologies, the researchers are able to obtain insights of the chemical, physical characteristics of the nanomaterials, consequently using their potential in various fields. At the one billionth scale of meter, the materials have shown attractive chemical, physical, electrical, and mechanical properties. The nanomaterials usually differ from their bulk forms at this scale. The atoms present at the surface of the materials have different characteristics than the atoms inside the material surrounded with their similar counterparts. When the material is lesser than a critical size, their different characteristics are governed by the principles of quantum physics (Bréchignac et al. 2008).

Nanomaterials are now having multiple applications in every day's life, ranging from cosmetic products to dyes and paints, nutrition, and sports industries (Mehmood 2018). They have their use as antimicrobial and anticancer agents, therapeutic advantages, and nanoparticle-based imaging of central nervous system.

The most predominant applications and technologies based on the use of nanomaterials are categorized as follows: (i) energy storage and harvesting systems (use of

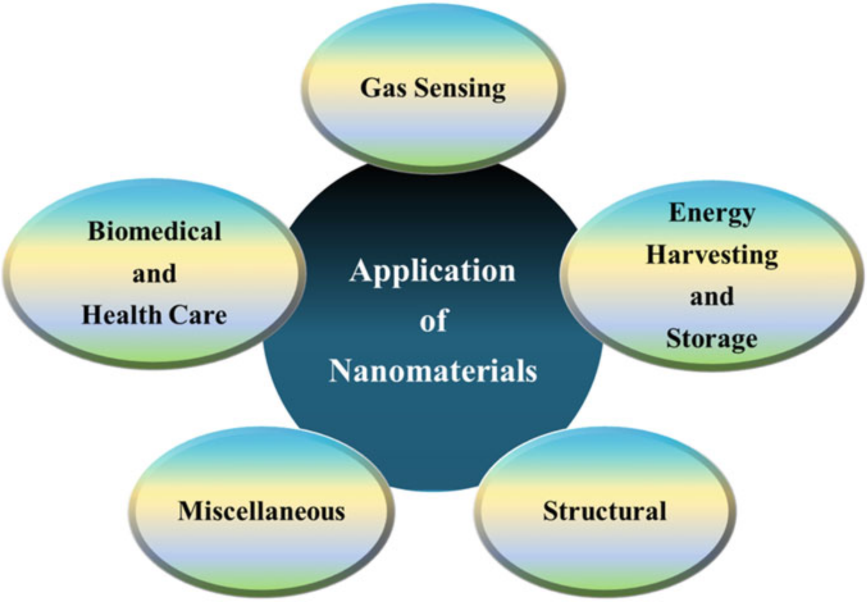

Fig. 3 Applications of nanomaterials in different fields

nanotubes to store hydrogen for different purposes), (ii) nanomaterials and nanocomposites for structural applications (in aerospace and automobile industry), (iii) gas-sensing devices. (iv) biomedical and health care, and (v) other miscellaneous sectors such as environmental management and nanoelectronics (Fig. 3).

The following sections provide an overview of a range of nanomaterials for their effective use in mentioned fields.

4.1 Energy Harvesting and Storage Applications

Energy is the most important part of survival for us human beings on earth. The energy is required for accomplishing the various tasks to meet our needs varying from our food to performing daily activities of our lifestyle. With the increasing demand of energy with the human population, the energy management is need of the hour. Use of fossil fuels as energy sources is one of the major causes of climate change and global warming (Hoel and Kverndokk 1996). The search for green and renewable sources of energy should be a prime focus for sustainable development. The nanomaterials have provided a way to power small electronic products in effective way. The cellulose-based nanostructures (cellulose nanofibrils, i.e., CNFs or nanocrystals), mesoporous structures, thin films, fibers, and their three-dimensional networks are successfully developed for solar cells and photo-electrochemical electrodes (Moon et al. 2011). Cellulose offers its self-assembling feature to attain a wide range of nanoscale configurations suitable for design of energy devices due to its unique structural and chemical characteristics (Wang et al. 2017). Yinhua Zhou et al. developed efficient and recyclable polymer solar cells on optically transparent cellulose nanocrystal substrates for renewable and sustainable energy production (Zhou et al. 2013). The development of nanomaterials has offered an elegant and effective bottom-up approach to take full advantage of tailored chemical composition, structural, electronic, and morphological characteristics in the design of energy devices (Kaur and Pal 2020). It will also enable the production of high efficiency organic photovoltaic materials.

4.2 Structural Applications

With the increased interaction between the nanostructures, having larger surface area employed with ceramic and metal-based materials helps in creating a new generation of lightweight, ultra-high strength, and tough structural nanocomposite materials. The nanostructured tough and hard materials typically used are cobalt/tungsten carbide and iron/titanium carbide-based nanocomposites. Nanoparticles/whiskers/fibers-reinforced polymers are being considered for automobile components. Besides high-strength materials, nanofluids and powders, as well as a wide range of unique morphologies, are being explored. Nanoparticles-based coatings with significantly improved features are being developed. Light structures are the demand of automotive and aerospace applications. Nanostructured metals/alloys are found to exhibit excellent mechanical properties. Nanostructuring of metallic materials helps them achieving superior strength with high ductility (Kumar et al. 2003). The use of severe plastic deformation-based techniques takes the control of nanotwins, grain boundary structures along with the grain size to achieve the concurrence of high strength as well as ductility (Singh and Pal 2021). Nanomaterials have their role in environment control and life support system development space platforms and international space station. The high-performance thermal interface materials with the use of highly conductive carbon nanotubes and metal nanowires are being developed to overcome the thermal management challenges in future aerospace electronics (Qian et al. 2018). The nanoparticle/fiber-reinforced polymer nanocomposites showing high modulus-to-weight and strength-to-weight ratio are in-line of research for their use in aerospace components owing to their multifunctional performance (Panwar and Pal 2020). The carbon-based nanomaterials have been recently investigated for their use as lubricant modifiers and improving the functionality of break pad in automobiles (Ali et al. 2019). The use of nanoparticles, nanofibers, and nanofilms along with the ultrafine-grained nanocrystalline metals has great potential to be used in aerospace and automotive industry. Their employment would help in solving the issue of energy crisis in these sectors.

4.3 Gas-Sensing Applications

The evolution of Internet of Things (IoT) technology having interconnected devices communicating each other raises the need of various sensors. The gas sensors have their use building automation, health care, industrial, and security and public safety-based IoT systems. The use of sensing devices to monitor the presence of gases for environmental control/monitoring, medical diagnosis, etc., is one of the sectors making the use of nanotechnology. The two-dimensional nanomaterials have gained very much attention due to their ultra-high surface-to-volume ratios, excellent semi-conducting performance, thickness dependent chemical and physical properties, and tunable surface activity toward selective gases (Lee et al. 2018); (Rathi et al. 2020). Others having potential in this field are as follows: metal oxide-based nanostructures, metal–organic framework-based nanomaterials, carbons-based nanomaterials, etc.

4.4 Biomedical and Health Care

The increased use of nanomaterials in biomedical application is due to their reduced size in the range of nanometers allowing them their movement into the cells of the living organisms such as human body. The use of nanotechnology and self-assembled nanomaterials in DNA chips and microarrays offers its applications in diagnostics and genetic research. The DNA chips and microarrays-related nanoelectronic devices accompanying thousands of DNA sequences arrayed on a solid substrate are very much useful to various biomedical researchers involved in forensics, drug, and gene discovery studies.

The use of fluorescent polymer-coated nanostructures is very promising in nanobiotechnological research. It has its potential use in development of new biological assays. The nanomaterials offer their targeted treating ability to treat cancer cells without affecting the surrounding cells/tissues. The biocompatible nature of cellulose nanocrystals and carbon-based nanomaterials and the electrospun nanofibers have their potential to be used in tissue engineering and food packaging applications (Pal et al. 2019).

The use of nanomaterials in various health problems is unmatched. Their use as disinfectant and treatment of viral diseases is also prominent. There have been various experimental studies to control severe acute respiratory syndrome coronavirus (Nikaeen et al. 2020). The viral infection is one of the serious concerns because of their ability to mutate and evolve over the time and their fast spreading nature. The viruses have been the cause of many epidemics in the world (Koh and Sng 2010). The use of golds nanoparticles for immunization has been evaluated and led to a significant increment of the peritoneal macrophages respiratory activity in immunized animals (Staroverov et al. 2011). These nanoparticles offer their capability to be engineered for timely and reproducible vaccines. In orthopedics, the use of nanoparticles offers greater control over release of the drug to treat prosthetic joint infections and osteomyelitis and nanotextured implant surfaces and helps to achieve implant osseointegration (Smith et al. 2018).

4.5 Miscellaneous Applications

The multidisciplinary field of nanoelectronics offers its use as either single nanostructure (e.g., nanocrystal, nanotube, and quantum dot) for processing optical, chemical, or electrical signals or as assemblies made up of these nanostructures involving their integration for electronic, chemical, biological, optoelectronic, and other applications. It paves a way through for the miniaturization in electronic industry. Nanoparticles-based coatings with highly improved features are being developed for water repellant, antifouling, and flame-retardant applications.

The ultra-small size of nanomaterials is of great interest from the point of view of analytical chemistry and is used at different stages of analytical processes. The CNTs, NPs, and MOFs are used as extraction sorbents, for their good sorption kinetics and for the determination of pollutants in food samples (Socas-Rodríguez et al. 2017).

5 Conclusion

In this chapter, we focused on nanoparticles with major emphasis on their properties, classification, and its applications in various fields. Nanomaterials are classified according to their dimensions and the materials incorporated in their fabrication. Nanomaterials, as a nanoparticle, hold number of desirable properties including optical, catalytic, thermal, magnetic, and electric properties and are between 1 and 100 nm in size. These nanoparticles possess different applications in the field of energy harvesting and storage, structural, biomedical science, gas sensing, and more. It contributes to a healthy environment by delivering cleaner air and water, nanomedicine as well as clean renewable energy for a long-term future. Nowadays, nanotechnology has gotten a lot of attention, and major institutions and organizations are investing more in research and development. Nanotechnology has established itself as a cutting-edge branch of study in which substantial research is being conducted in order to put the technology into practice. It is being tested for a variety of different applications in order to improve the object's efficiency and performance while also lowering the cost so that it is affordable to everyone. This chapter contains a summary of nanomaterials as nanoparticles as well as current information on nanoscience and nanotechnology, which has a bright future because of its efficiency and environmental benefits.

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