Introduction to Nanomaterials and Nanotechnology

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Abstract

Nanotechnology is the innovatory technology of the twenty-first century, and nanoscale materials have created a considerable amount of attention from researchers. It is an emerging interdisciplinary area of research wherever groupings of atoms as well as molecules are handled at the nanometer levels. It can be defined as the systematic study of materials that have properties critically dependent on length scales on the order of nanometers. Such novel and improved properties make nanoscale materials promising candidates to provide the best scientific as well as technological progress in a number of fields in particular communications, electronics, energy, environment, information, biology, pharmacy, health care, and medical care. This chapter first draws attention to the different definitions and classification of nanomaterials based on their origin, chemical composition, materials, and their dimensions. The fundamental properties of matter transform at the nanoscale and the most enhanced and valuable properties of manufactured nanomaterials such as confinement effects, surface effects, mechanical properties, structural properties, thermal properties, optical properties, and magnetic properties are also described. In the last section, we have discussed various methods to fabricate nanomaterials.

Keywords

Nanoscale materials · Size-dependent characteristics · Distinctive properties · Superior performance

1 Introduction

The first technological revolution, at the end of the eighteenth century, has sparked the advancement of industrial research and the attainment of novel materials (Fajardo et al. 2015). At present, the obstacles are the miniaturization of devices as well as instruments; lesser volume, lesser power consumption but superior performance. The progress relies upon searching out novel pleasing materials and the capacity to create minute structures with high accuracy. Though, the growth is not so smooth and effortless. One of the best splendid techniques created to answer such a condition is nanotechnology (Fajardo et al. 2015; Huyen 2011). Recently, the study engaging nanoscale materials has created a considerable

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amount of attention from researchers. They believe nanotechnology as the innovatory technology of the twenty-first century (The Royal Society 2004).

The word nanotechnology is taken from a Greek word "nano" stands for "dwarf" or "very small," and so it relates to materials of minute size ranges (Nikalje 2015; Rai et al. 2008). The interdisciplinary science of nanotechnology is a talented field wherever groupings of atoms as well as molecules are handled at the nanometer levels. In reality, it is the design of components, materials, devices, and/or systems at near-atomic or molecular levels. Generally, one of the dimensions of nanomaterials is between 1 and 100 nanometers (nm) length in scale. This promising technology implies to the imaging, handling, manufacturing, measuring, modification, modeling, and reduction of matter at nanoscale with characteristic properties, for example, cost-effective, definite, eco-friendly, good strength, lighter, and specific for a variety of purposes (Asmatulu et al. 2010; Taniguchi 1974; Pradeep 2007).

The definition of nanotechnology has been divided into two parts, one is the part about manufacturing at dimensions of 1–100 nm, and the other is about characteristics of materials at the nanoscale that make possible their exploit for novel applications. The size range that holding a great deal of attention is characteristically from 100 nm down to the atomic level, for the reason that it is in this range that materials have fundamentally distinct properties from their bulk counterparts. The most important justifications for this revolutionize in performance are an increased significance of surface as well as the interfacial area (Wardak et al. 2008). At the same time, nanotechnology is a new-fangled paradigm in fundamental thoughts and understanding regarding the physical universe, where the bottom-up approach is the rule and not an exception. In this novel system, one has to imagine in terms of atoms and how they act together to create valuable materials, structures, devices, and systems (Raza and Raza 2013; Rocco 2007; Rocco et al. 2011).

Nanotechnology has been moving from the laboratory surroundings into applications and customer products for quite a while now (Barakat and Jiao 2011). The nanotechnology will create new perspectives for this world and their promises have been noticed to provide the best scientific as well as technological progress in a number of fields in particular communications, electronics, energy, environment, information, health, and medical care (Daryoush and Darvish 2013).

Nanotechnology has also a widespread perspective in the areas of biology, pharmacy, physics, and material science which could merge to contribute to healthcare. Even though the perception of nanotechnology has been investigated in healthcare study for the past three decades, it is still believed to be in the early stage of development as anticipated therapeutic advantages have not been totally understood (Miyazaki and Islam 2007; Sandhiya et al. 2009). Both the educational as well as industrialized groups of people are spending time in addition to money into the development of nanotherapeutics to conquer the superficial challenges and interpret the hypothetically established advantages of nanoparticulate systems into clinical benefits. Although nanotechnology is at its early stages, however, it is expanding quick, opening plentiful perspectives for the logical minds to utilize this enhanced technology for human well-being (Daniel and Astruc 2004).

This chapter addresses to fill up-to-date understanding of manufactured nanomaterials, by providing an extensive review of current progress in the nanotechnology field. It draws attention to the different definitions, classifications, fundamental properties, and synthesis routes of nanomaterials.

2 Nanomaterials

Nanomaterials, previously called by Paul Ehrlich as "Magic Bullets" (Kreuter 2007), are one of the major investigated materials of the century that gave birth to a novel branch of science referred to as nanotechnology (Nasir Khan et al. 2017). Nanomaterials are chemical substances or materials that are created or used at a minute scale. Indeed, the word material speaks about an infinite number of components, jointly showing an averaged statistical performance. As a result, the performance of nanomaterials is affected by specific interface effects and demonstrates characteristics affected by the size and the restricted number of constituents (Guo et al. 2014).

Nanomaterials are a diverse class of substances that have structural constituents lesser than 100 nm in minimum one dimension. Nanomaterials consist of nanoparticles (NPs), which are particles, with at least two dimensions between about 1 and 100 nm (Klaine et al. 2008). Though, a single globally recognized definition for nanomaterials does not present. Diverse groups have dissimilarities in belief in defining nanomaterials (Boverhof et al. 2015). To be classified as nanomaterials, the material must be less than 100 nm in size in a minimum one direction. The International Organization for Standardization (ISO) has explained nanomaterials as a "material with any external nanoscale dimension or having the internal nanoscale surface structure" (ISO/TS 27687 2008; ISO/TS 80004-1 2010). The US Food and Drug Administration (USFDA) also denote nanomaterials as "materials that have at least one dimension in the range of approximately 1 to 100 nm and exhibit dimension-dependent phenomena". As per the European Union Commission nanomaterials means "a manufactured or natural material that acquires unbound, aggregated or agglomerated particles where external dimensions are between 1-100 nm size ranges," in accordance with Potocnik (2011).

The exploit of different definitions throughout diverse authority's referred to as the most important obstacle to regulatory efforts as it shows the way to legal uncertainty in applying regulatory approaches for indistinguishable nanomaterials. So, the requirement to convince diverging considerations is the main confront in developing a single international definition for nanomaterials.

3 Why Are Nanoscale Materials: So Special and Unique?

Nanoscale materials, which can be either standalone solids or subcomponents in other materials, are smaller than 100 nm in one or more dimensions. Putting this dimension in standpoint, a nanometer (nm) is one-billionth of a meter and one-millionth of a millimeter, approximately four times the diameter of an atom. For our macro-oriented brains, in fact understanding the scale of the nanometer is not easy although real-life comparisons can help give us a good judgment. Such as, the twinkling of an eye is to a year is what a nanometer is to a tool for measuring (Feynman 1960).

Nanoscale materials have a higher surface area to volume ratio in addition to the number of surface atoms as well as their arrangement decides the size and properties of the nanoscale materials (Sarma et al. 2015). Size reduction of materials can bring about an entire range of novel physicochemical features and prosperity of prospective applications (Brechignac et al. 2006). These features very much rely upon size, shape, surface area as well as the structure of elements. Nanoscale materials can be present in single, compound, aggregated, or agglomerated structures with sphere-shaped, cylindrical, and asymmetrical shapes (Kumar and Kumbhat 2016). By the production of nanoscale structures, it is probable to manage the basic properties of materials, for instance, their charge capacity, magnetic properties, melting temperature, and even their color, with no altering the chemical composition of the nanoscale structures'. This will make possible novel, highly efficient materials, and nanotechnologies that were impracticable in the past. The most important benefits of nanomaterials against bulk material consist of a reduction in melting point as well as surface area, an enhancement in dielectric constant in addition to mechanical strength (Maddinedi et al. 2015; Dasgupta et al. 2016; Ranjan et al. 2016; Pulimi and Subramanian 2016). Additionally, the size of nanoscale materials facilitates them to absorb remarkably on to other materials (Dasgupta et al. 2015; Ranjan et al. 2017; Ranjan et al. 2016).

To point up the intrinsic value of influencing matter on such dimensions, Daniel Ratner, Professor of Bioengineering at the University of Washington, suggests a valuable thought experiment. Assume that we have a 3 × 3 × 3 – foot cube of pure gold. If we were to cut in half this cube in all dimensions, we would have eight smaller cubes. These newly formed cubes would show the similar inherent properties as the original cube of pure gold – each one would still be weighty, glossy, and yellow, with the similar chemical and structural features. If we were to carry on breaking in two until we have cubes dimensions about microns (10^{-6} of a meter), the intrinsic bulk properties of the material would still stay invariable. Also, this is not explicit to gold; the same retains right for ice, steel, plastic, or any pure solid. Though, if we were to get to the nanoscale, quantum effects would start to dominate, and the gold's characteristics, counting its color, intermolecular chemistry, and melting temperature, would alter. These quantum effects had been "averaged out of existence" in the bulk material (Ratner and Ratner 2003; Koo 2016). At the nanoscale, the power of gravity gives van der Waal's forces, surface tension, as well as additional quantum forces.

For differentiation of nanoscale materials from the bulk materials, it is essential to show the distinctive properties of nanoscale materials and their potential effects on science as well as technology. The size of the nanoscale materials has an enormous control on their properties (Fig. 1.1). When a particle is in its bulk state in comparison with its size in its microscale, there is not a large amount of dissimilarity in its properties. On the other hand, when the particle attains a size of smaller than 100 nm, the properties revolutionize notably in comparison with its bulk state. In 1–100 nm, quantum size effects determine the properties of particles, for example, chemical, magnetic, optical, mechanical, electrical, and thermal (Sun 2007; Brust et al. 1994; Daniel and Astruc 2004).

Over the past few decades, the size-dependent properties of gold nanoparticles (AuNPs) have been explicated well (Junk and Riess 2006; Daniel and Astruc 2004). AuNPs demonstrates the size-dependent color. At the nanoscale, the gold particle shows purple color diverse from the bulk, which was yellow-colored. This alteration in color is based on the alteration in their band type from continuous to discrete as a result of confinement effect. These quantum effects in the nanoscale are the fundamental explanations behind the "tunability" of properties. By merely changing the particle size, we can alter the material property of our interest.

Nanoscale structures have extremely higher surface-to-volume ratios as well as aspect ratios, creating them perfect for exploit in polymer nanocomposites. For the past five decades, investigators have been functioning with macrocomposites, for example, filled polymers or a fiber-reinforced polymer matrix composite, in which the length scales of the polymer fillers or the fiber diameters is in micrometer scale. The reinforcement length scale is in micrometers, and the interface of fillers is about to the bulk polymer matrix. For the past two decades, investigators have been finding out nanocomposites, where the length scale of the reinforcement (nanoparticles) is on the nanometer scale. These nanocomposites have ultra-large interfacial area per volume, and the distances between the polymer and filler components are very small.

Before talking about the properties of nanoscale substances, it may be beneficial to explain a case showing the basic effects of the minute size of nanoparticles (Koo 2006). The first and most vital effect of smaller particle size is its vast surface area, and so as to get an idea of the significance of this geometric variable, the surface-over-volume ratio should be discussed. It is assumed that a particle is sphere-shaped, the surface a of one particle with diameter D is $\alpha = \pi D^2$, and the corresponding volume v is $v = \frac{\pi D^3}{6}$. So, the surface/volume ratio is

$$R = \frac{a}{v} = \frac{6}{D} \tag{1.1}$$

This ratio is in inverse proportion to the particle size, and as a result, the surface enlarges with reducing particle size. The same is applicable for the surface per mol A, a quantity that is very important in thermodynamic considerations.

$$A = na = \frac{M}{\left(\delta\pi \mathrm{D}^3/6\right)\pi \mathrm{D}^2} = \frac{6M}{\delta \mathrm{D}} \tag{1.2}$$

In Eq. (1.2), n is the number of particles per mol, M is the molecular weight, and ϱ is the density of the material. Like the surface-over-volume

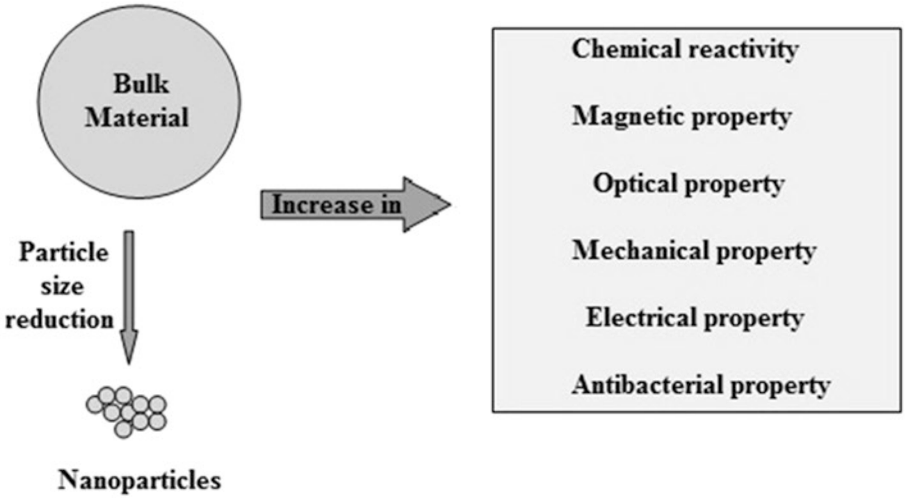


Fig. 1.1 Properties of nanoscale materials

ratio, the area per mol raises in inverse proportion to the diameter of particle. Therefore, larger values of surface area are obtained for particles that are simply a few nanometers in diameter (Koo 2016).

The distinctive properties and superior performance of nanoscale materials are established by their sizes, surface structures, and inter-particle interactions. The role played by particle size is very similar to the role of the particle's chemical composition, adding one more parameter for designing and managing behavior of the particle. To entirely know the impacts of nanoscale materials in nanoscale science and technology, one requires to study why nanoscale materials are so special! (Koo 2016).

The excitation surrounding nanoscale science and technology presents inimitable opportunities to buildup innovatory materials. Nanoscale science and technology is a comparatively young field that includes almost all disciplines of science and engineering. Nanoscale structures are a novel branch of materials study drawing an immense deal of attention due to its impending appliances in chemical catalysis, computing, imaging, material synthesis, medicine, printing, and many other fields (Koo 2016).

On account of all these inimitable behavior and properties, nanoscale materials have greater applications in cosmetics, electronics, and pharmaceutical industries. In addition, they are commonly employed for the advance of health care products and restoration of the polluted environments (Pulimi and Subramanian 2016). Nanoscale materials stand for areas of scientific study and industrialized applications in full expansion (Gaffet 2011). Nanoscale materials in addition play a very important role in drug delivery, imaging, and even in surgical procedure as they have a size range comparable to that of biological molecules for example proteins, receptors, deoxyribonucleic acid (DNA), and ribonucleic acid (RNA) (Gendelman et al. 2015; Pillai 2014; Wang et al. 2013; Wang and Thanou 2010; Torchilin 2005). Nanoparticulate systems are moderately small in size in comparison with cells but are larger than the majority "small molecule" – type drugs, which could get better their residence time in circulation with no risk of clogging the blood vessels, which sequentially can enhance the bioavailability and pharmacokinetic profile of a variety of drugs. Nanoparticles can make use of a natural process called endocytosis to go through cells, which offers a specific benefit in circumstances where normal penetration into cells would be difficult for a particular molecule (Liu et al. 2012). This characteristic is also useful for the targeting of particular organelles within the cells like nuclei with gene knockdown by tiny interfering RNAs (siRNAs) (Torchilin 2011;

Huang et al. 2011a, b; Vander Heiden 2011). Higher surface-area-to-volume ratio is an additional interesting characteristic of nanoparticulate systems, which gives a huge substrate for adherence of definite moieties for active targeting (Moghimi et al. 2005). Surface modification has been done to nanoparticles with specific antibodies or peptides to attain tissue targeting, which lessens the probability of distracted off-target toxicity (Yokoyama 2005; Bae and Park 2011). Consistent with therapeutic and diagnostic requirements, the surface features of nanotherapeutics can be customized with imparting stealth properties to avoid elimination by the reticuloendothelial system, which gets better the circulation time and raises drug concentration at the site of action (Wang and Thanou 2010; Gamucci et al. 2014).

Nanoparticulate technology has opened up new opportunities in the early detection as well as management of different cancers, bio-detection of pathogens, and in the formulation of fluorescent biological labels as they take in both imaging and therapeutic abilities. Nanoparticulate technology is also beneficial in addressing solubility as well as stability problems of poorly soluble drugs and in modifying their pharmacokinetic profiles to get extended plasma half-life. Since the 1980s, the healthcare group of people has met clinical challenges where resistance has developed against antibiotics and chooses other conventional therapeutics. It is feasible that these problems can be tackled with nanoscale materials (Wang et al. 2013; Salata 2004). As of 2014, more than 1800 consumer products containing nanoscale materials are on the market (Vance et al. 2015).

4 Classification of Nanoscale Materials

The manufacturing of traditional products at the nanoscale presently helps and will keep on helping the economic growth of various countries. Till date, a variety of nanoscale products have been documented and lots of other varieties of products are expected to come out in the future. Consequently, the requirement for their categorization has ripened. The first suggestion for nanoscale material classification was specified by Gleiter in 2000 (Gleiter 2000). A nanomaterial is a broad name provided to each kind of material existing at the nanoscale. Several names have been given to these new materials; nanostructured, nanometer-sized, ultrafine-grained, etc. Nanoscale materials can be formed from one or more species of atoms or molecules and can demonstrate a broad range of size-dependent characteristics. In this range of size, nanoscale materials link the gap among tiny molecules and bulk materials in terms of energy states (Johnston and Wilcoxon 2012; Smith and Nie 2010). They can be found naturally or manufactured chemically, mechanically, physically, or biologically with a variety of structures (Saleh 2016). Nanoscale materials can be categorized on the basis of special parameters counting their origin (natural or synthetic); chemical composition; material-based (Carbon-based nanomaterials, Inorganic-based nanomaterials; Organic-based nanomaterials; Composite-based nanomaterials); and on the basis of their dimensions (Saleh and Gupta 2016; Buzea et al. 2007).

4.1 Classification of Nanomaterials Based on Their Origin

Based on their origin, the nanoscale materials can be divided into two categories (Filipponi and Sutherland 2013):

(a) *Natural nanomaterials or nonintentionally made nanomaterials*

These types of materials speak about nanosized materials that belonged naturally to the environment (e.g., proteins, viruses, nanoparticles produced during volcanic eruptions, etc.) or that are formed by individual activity with no plan (e.g., nano-particles produced from diesel combustion). They are formed in nature either by organic species or during human-induced activities. The manufacturing of simulated surfaces with elite micro as well as nanoscale patterns and properties for industrial appliances are easily obtainable from natural origins. Naturally, generated nanomaterials are present through the Earth's spheres to be precise in the atmosphere, hydrosphere, and lithosphere which are comprised of rocks, soils, magma, or lava at particular stages of evolution and even in the biosphere which covers microorganisms and higher organisms, including humans, apart from anthropogenic activities. Globe is made-up of nanomaterials that are naturally formed and are also present in the oceans, lakes, rivers, groundwater, and hydrothermal vents (Hochella et al. 2015; Sharma et al. 2015; Jordan et al. 2014).

(b) *Synthetic (engineered) nanomaterials or intentionally made nanomaterials*

These types of nanomaterials manufactured with intent by means of a defined production procedure like mechanical grinding, engine exhaust, and smoke or are synthesized by physical, chemical, biological, or hybrid techniques. Synthetic nanomaterials cover up a wide range of materials, counting both inorganic (elemental metals, metal oxides, metal salts, and aluminosilicates) as well as organic (fullerenes, micelle-like amphiphilic polyurethane particles, and dendrimers) materials (Filella 2012). The issue of risk assessment approach has come into existence recently as there is increased manufacturing and succeeding release of engineered nanomaterials in addition to their utilization in consumer products and industrial appliances. This risk assessment approach is very much cooperative in the prediction of the behavior and fate of engineered nanomaterials in different environmental media. The most important confront among engineered nanomaterials is whether existing information is adequate to predict their behavior or if they show a distinctive environment-related performance, diverse from natural nanomaterials. At present, different sources concerned possible applications are employed for the fabrication of engineered nanomaterials (Wagner et al. 2014).

4.2 Classification of Nanomaterials Based on the Chemical Composition

According to their chemical composition, nanomaterials can be categorized as metal-based materials are mainly made-up of metals like silver, gold, and copper. And metal oxide nanomaterials which are made of metal and oxygen, for example, titanium, silica, and alumina (Saleh and Gupta 2016).

4.3 Material-Based Classification

Most recent nanoscale materials can be classified into four material- based categories:

(a) *Carbon-based nanomaterials*

Generally, these carbon-based nanomaterials cover up a wide range of compounds, counting fullerenes (C60), carbon nanotubes (CNTs), carbon nanofibers, carbon black, graphene (Gr), and carbon onions (Filella 2012). For manufacturing these carbon-based nanomaterials different methods are used like laser ablation, arc discharge, and chemical vapor deposition (CVD) (except carbon black) (Kumar and Kumbhat 2016).

(b) *Inorganic-based nanomaterials*

These inorganic-based nanomaterials include metal and metal oxide nanoparticles. These nanomaterials can be synthesized into metals like Au NPs or silver nanoparticles (Ag NPs), metal oxides like titanium dioxide (TiO_2), and Zinc oxide (ZnO) NPs, and semiconductors such as silicon and ceramics (Jeevanandam et al. 2018).

(c) *Organic-based nanomaterials*

Organic-based nanomaterials consist of nanomaterials prepared generally from organic matter, exclusive of carbon-based or inorganic-based nanomaterials. The exploitation of noncovalent interactions for the self-assembly and blueprint of molecules assists to renovate the organic nanomaterials into most wanted structures for instance dendrimers, micelles, liposomes, and polymeric NPs (Jeevanandam et al. 2018).

(d) *Composite-based nanomaterials.*

Composite nanomaterials are multiphase NPs with one phase on the nanoscale dimension that can either join NPs with other NPs or NPs attached with bigger or with bulk-type materials (e.g., hybrid nanofibers) or very complex structures, for example, metalorganic frameworks. The composites may be any combinations of carbon-based, metal-based, or organic-based nanomaterials with any form of metal, or polymer bulk materials. Nanomaterials are fabricated in diverse morphologies contingent on the essential properties for the desired application (Jeevanandam et al. 2018).

4.4 Classification of Nanomaterials Based on Their Dimensions

Nanomaterials with structural characteristics at the nanoscale can be created in various forms. In 2007, Pokropivny and Skorokhod formed a new idea of classification for nanomaterials which listed the newly developed composites, for example, zero-dimensional (0-D), one-dimensional (1-D), two-dimensional (2-D), and three-dimensional (3-D) nanomaterials shown in Table 1.1 (Pokropivny and Skorokhod 2007). This classification is greatly reliant on the electron association along the dimensions in the nanomaterials. For instance, electrons in 0-D nanomaterials are captured in a dimensionless space while 1-D nanomaterials have electrons that can shift along the x-axis, which is less than 100 nm. Similarly, 2D and 3D nanomaterials have electron associations along the x, y-axis, and x, y, z-axis in that order. The ability to forecast the properties of nanomaterials decides the classification value of the nanomaterials. The categorization of nanomaterials given by researchers suggested that the features of nanomaterials are ascribing to the particle shape as well as dimensionality, as per the "surface engineering" conception, and thereby class of nanomaterials (Pokropivny and Skorokhod 2007; Tiwari et al. 2012).

In accordance with this conception, nanomaterials can be classified as follows:

(a) *Zero-dimensional (0-D)*

They are crystalline bunches of a few hundred to a few thousand atoms with sizes ranging from 2 to 100 nm (Wani 2015). All the dimensions of the materials present in the nanometer scale are called 0-D nanomaterials. Nanoclusters are forms that are 1 to 100 nm in all space-based dimensions. These are in general sphere-shaped nanostructures, length, breadth, and heights are restricted at a single point. They can be amorphous or crystalline in nature. 0-D nanomaterials play an incredibly vital role in electronics, engineering, and technology. In recent times, the widespread investigation is in development to fabricate nanoparticles for a variety of applications (Cao 2004).

(b) *One-dimensional (1-D)*

The second class of nanoscale materials, subjected as 1-D nanomaterials, is held in reserve for those materials that have nanoscale dimensions that are equal in all but one direction (Balaz 2008). The nanomaterials have one of the dimensions, which are exterior, the nanoscale and are called 1-D-nanomaterials. It has just one parameter whichever length (or) breadth (or) height. These are commonly needle-like nanostructures that include nanotubes, nanowire, nanofibers, and nanorods having a diameter between 1 and 100 nm and a length that could be much larger are classified as 1-D nanostructures. These are also amorphous or crystalline in nature. These nanoscale materials present momentous benefits over bulk or thin-film planar devices (Abdelsalam and Abdelaziz 2014). Nanofibers are to some extent bigger in diameter than the characteristic

Table 1.1 Classification of nanomaterials on the basis of their dimensions

Sr. No.	Class of nanomaterials based on their dimensions	Nature of nanomaterials	Examples of nanomaterials
1	Zero-dimensional (0-D)	Amorphous or crystalline	Single crystalline or polycrystalline nanoparticles
2	One-dimensional (1-D)	Amorphous or crystalline	Nanotubes, nanowires, nanofibers, nanorods
3	Two-dimensional (2-D)	Amorphous or crystalline	Nanofilms, dendrimers, nanolayers, nanotextured surfaces or thin films, nanocoatings, etc.
4	Three-dimensional (3-D)	Crystalline	Quantum dots, fullerenes, nanoparticles, nanocrystals, colloids, nanoshells, nanorings, etc.

nanomaterials definition, though still too small to see to the naked eye. They are generally manufactured by electrospinning technique in the case of inorganic nanofibers or catalytic synthesis method for carbon nanotubes and exhibit size ranges between 50 and 300 nm in diameter. Nanofibers can be aligned biochemically and electrostatically (Kumar and Kumbhat 2016). Nanowires are similar to nanofibers. In these systems, one dimension surpasses by an order of magnitude the other two dimensions, which are in the nano-range (Gubin 2009). Thin films or surface coating also comes under the materials with one dimension in the nanometer scale which have been produced and employed for decades in different areas counting antireflecting coating on sunglasses, chemical and biological sensors, chips of computer memories, electronics, information storage systems, optical devices, and solar cell application. Thin films can be deposited by a range of techniques and can be grown-up controllably at the atomic level (Seshan 2002; Liu et al. 2003).

(c) *Two-dimensional (2-D)*

In this class of nanomaterials, only one dimension is in the nanometer scale, while another two are out of the nanoscale (Gubin 2009). It has simply length and breadth. 2-D nanostructures display plate-like shape (Thomas et al. 2014). The examples of 2-D nanostructures are nanotubes, dendrimers, nanowires, nanofibers, nanofilms, nanolayers, nanotextured surfaces or thin films, and nanocoatings. 2-D nanomaterials can be amorphous or crystalline. They are fabricated from different chemical compositions. They are utilized as a single layer or multilayer structure (Koski and Cui 2013). The properties of 2-D systems are not as much understood and their manufacturing capabilities are less advanced. 2-D systems are applied to structural bulk materials for the purpose of improving the desired properties of the surface, for example, corrosion resistance, wear resistance, friction, and holding the bulk properties of the material unchanged (Koch et al. 2007).

(d) *Three-dimensional (3-D)*

Three-dimensional (3-D) structures are materials having three random dimensions beyond the nanoscale (Saleh and Gupta 2016). It has all parameters of length, breadth, and height. These materials acquire a nanocrystalline nature (Law et al. 2004). These consist of quantum dots or nanocrystals, fullerenes, particles, precipitates, and colloids. A number of 3D systems, for example, natural nanomaterials, metallic oxides, carbon black, TiO_2, and ZnO are widely known, whereas others, for example, dendrimers, fullerenes, and quantum dots portray the maximum confronts in terms of fabrication and understanding of properties. Bulk nanomaterials are composed of multiple arranged nanosized crystals. 3-D nanomaterials include the dispersion of nanoparticles, bundles of nanowires, and nanotubes as well as multinanolayers (Lin et al. 2013; Tiwari et al. 2012).

5 Properties: The Physics at the Nanoscale

In recent times, the material science investigation is paying attention to the discovery of novel materials with new and superior properties and novel synthesis methods to deal with the augmented technological requirement. Nanomaterials are the center of the interest attributable to their remarkable applications and fascinating properties (West and Halas 2003; Sozer and Kokini 2009).

In reality, the fundamental properties of matter transform at the nanoscale and nanomaterials manifested interesting and valuable properties. The physical, as well as chemical properties of nanoparticles can be fairly diverse from those of larger particles of the same substance. They are nearer in size to single atoms and particles over bulk materials, and to clarify their performance, it is essential to make use of quantum mechanics (Kumar and Kumbhat 2016). While nearly all microstructured materials have alike properties to the corresponding bulk materials. This is mostly attributable to the nanometer size of the materials which make them: (a) large fraction of surface atoms; (b) high surface to volume ratio and quantum confinement effects; (c) spatial confinement; (d) reduced imperfections, which do not exist in the corresponding bulk materials (Roduner 2006). Changed properties can comprise but are not restricted to color, solubility, material strength, electrical conductivity, magnetic performance, mobility, biological activity, and chemical reactivity (Fig. 1.2) (Blackwelder 2007).

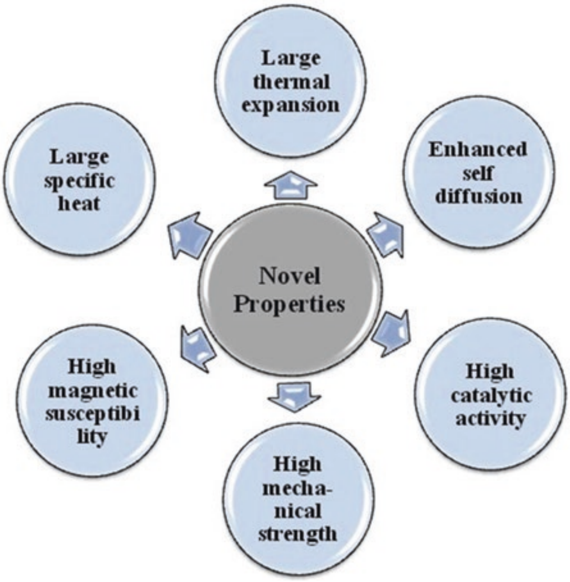
Size effects make up a peculiar and attractive aspect of nanomaterials. The effects are taken into consideration by size pertaining to the advancement of chemical, electronic, electromagnetic, spectroscopic, structural, and thermodynamic properties of these predetermined systems with varying sizes (Henry 2008). The properties of a material depend upon the type of motion, its electrons can execute, which relies upon on the gap available for them. Thus, the properties of a material are characterized by an explicit length scale, usually on the nanometer dimension. If the physical size of the substance is lowered under this length scale, its properties transform and turn out to be sensitive to size along with shape. Attributable to our capacity of atom manipulation, we can formulate nanomaterials suitable for specific applications (Sugimoto et al. 2008).

In any matter, the considerable variation of basic electrical and optical properties with decreased size will be seen when the energy spacing between the electronic levels goes beyond the thermal energy. In tiny nanocrystals, the electronic energy levels are not constant as in the bulk but are discrete (limited density of states), on account of the captivity of the electronic gesture function to the physical lengths of the particles. This observable fact is called quantum confinement and consequently, nanocrystals are also referred to as quantum dots (Stucky and Mac Dougall 1990). Furthermore, nanocrystals attain a higher surface area and a great fraction of the atoms in nanocrystals are on its surface. As, this part relies mostly on the size of the particle (30% for a 1 nm crystal, 15% for a 10 nm crystal); it can present go up to size effects in the chemical and physical properties of the nanocrystals.

5.1 Confinement Effect

Quantum size effects are correlated to the "dimensionality" of a system in the nanometer range (Richards and Bonnemann 2005). The quantum effects are an outcome of quantum mechanics and of the particle-wave duplicity. These happen in the case where the size of the system is commensurate with the de Broglie wavelengths of the electrons, phonons, or excitons circulating in them (Naseri and Saion 2012).

Fig. 1.2 Size-dependent properties



In fact, electrons act at the same time as particles and as waves. Since waves, they travel around the whole space in which they are gratis to move about. The nanograin acts similar to a type of box, in which a definite property may or may not be present. Beneath a particular critical size, characteristics of the property straightforwardly and exactingly rely upon the size of the grain. This is known as the confinement effect (Rezaie et al. 2013). Quantum size effects play a fundamental role in deciding the physical and chemical properties, e.g., charge-transport mechanisms and electronic structure. Optical as well as electron-tunneling spectroscopies are crucial for learning these systems (Roduner 2006; Aznan and Johan 2012).

5.2 Surface Effects

Atoms at surfaces have lesser neighbors than atoms in the bulk. As a consequence of this lesser coordination and unsatisfied bonds, surface atoms are little stabilized compared with bulk atoms (Roduner 2006). If the particle is tiny it has a large fraction of atoms at the surface and the great average binding energy per atom. The surface-to-volume proportion scales with the contrary size, and as a result, there are plentiful properties that comply with the identical scaling law. Edge and corner atoms have even lesser coordination and attach foreign atoms and molecules more strongly. The coordination number is also restricted in small pores (Lokhande and Pathak 2014).

The influence of size reduction is not exclusive of outcomes for the atomic arrangement and the physical properties of substances. In fact, if the structure of the superficial region of a particle is exaggerated over the range of the particle size, a surface layer cannot be specified precisely (De Rogatis et al. 2008). It is acknowledged that the composition or the structure of the crystal is customized at the free surface of the material. The volume of this surface layer turns out to be noteworthy in nanoscale materials. The surface layer of nanomaterials, in that case, can be specified as the outer region where the composition or the structure of the crystal is diverse from those of the particle interior (Wang et al. 2008).

5.3 Mechanical Properties

Nanostructures demonstrate advanced mechanical properties than the bulk materials, for example, mechanical hardness, elastic modulus, tensile stress, fatigue strength, scratch resistance, fracture toughness, etc. (Meyers et al. 2006). The aforementioned augmentation in the mechanical properties of nanomaterial is ascribing to the structural flawlessness of the material. The minute-sized materials acquire free of internal structural deficiencies, for example, dislocations, micro-twins, as well as impurity precipitations. Repeatedly mechanical failure is caused by multiplying imperfections in the nanomaterials, which are more lively and move to the surface, under annealing, purifying the material. This repositioning of defects to the surface departs perfect material structures within the nanomaterials. The exterior surface of nanostructures is very little or free from imperfections than bulk materials. Materials with fewer defects will give out the superior mechanical properties (Eletskii 2007).

In a lot of nanomaterials, hardness is noticed as the most common mechanical property. An actuality of super hard nanocomposites manufactured with borides, carbides, and nitrides (Zhang et al. 2002). Extraordinary production methods were employed to produce such nanocomposites in particular plasma-induced chemical technique and physical vapor deposition technique (Chen et al. 2013; Diserens et al. 1999). The nanomaterials are created containing excellent mechanical properties for impending applications in macro, micro, and nanoscales. Nanocrystalline copper is three times more resistant as compared to usual copper; they are also more flexible (Lu et al. 2004). Carbon nanotubes and nanowires are employed to make high-frequency electromechanical resonators that can be utilized as nanoprobes, or nanotwizzers to control nanomaterials in a nanometer scale (Nguyen et al. 2005; Dequesnes et al. 2002).

Elasticity conception takes up the little, continue, and reversible deformations of isotropic elastic materials (Muskhelishvili 2013). An elastic material exhibits the following three properties: It distorts under stress and comes back to its original shape when the stress withdraws. It is uniform, isotropic, and homogeneously distributed in its occupied volume. Materials are normally not isotropic as they are polycrystalline, with grains having diverse shapes and orientations. Conversely, as the lengths of the materials are very big to correspond to the mean grain, homogeneity, and isotropy hypothesis are occasionally more or less satisfied. Therefore, the elasticity hypothesis is as well employed for polycrystalline materials (Wong et al. 1997; Juve et al. 2010).

5.4 Structural Properties

The reduction in particle size of material results in the transform in interatomic spacing and so, surface and surface energy increase (Sun 2007). The structural alterations are noticed when the particle size reduces predominantly in the nanoscale range. Au NPs can accept a polyhedral shape, for example, cuboctahedral, multiply twinned decahedra (Eguchi et al. 2012). Aforesaid shapes can be explored and understood by the enlargement of crystalline along with a variety of crystallographic directions and energies of different crystallographic planes. Crystalline solid acquires long-range episodic structure of atoms and distinct prototypes. Quasiperiodic crystals do not acquire such long-range episodic structure. A quasiperiodic crystal is an arrangement that is prearranged but not periodic (Yamamoto 1996). The fundamental factor of nanostructured materials is their shape, size, and morphological constitution. The surface morphology of nanostructured materials can be adjusted by means of a chemical agent named surfactant. The morphologies of nanoparticles are adjustable and by scheming them, we can investigate their properties (Ariga et al. 2011).

5.5 Thermal Properties

Several properties of materials can be customized by managing their nanoscale dimensions. Such customized nanostructures can be employed to meet the demands of various applications. The thermodynamics of nanosystem is different from the thermodynamics of macroscopic systems, where the number of particles has a tendency to perpetuity (Labastie and Calvo 2008). Higher surface energy will change monotonically with size and can be taken care of within the structure of thermodynamics (Niepce and Pizzagalli 2008). Among them are the melting and other phase transition temperatures exemplifies the common experimental difference of melting point of gallium nitride spherical nanoparticles aligned with the size of the particles (Antoniammal and Arivuoli 2012). Its physical starting point is the raise of surface energy, the augment of the amplitude of atomic vibrations, and the supplementary surface growth of thermal vibration energy in the consequence (Pokropivny et al. 2007). It has been stated that the specific heat raised with the reduction in particle size, while the melting entropy, as well as enthalpy diminished as the particle size, reduces (Singh et al. 2017).

The exploit of nanofluid to improve the thermal transfer is a hopeful application of the thermal properties of nanomaterials (Murty et al. 2013). Nanofluids are, in general, said to be the solid–liquid composite materials, which contain nanomaterials of size in the range 1–100 nm suspended in a liquid (Obaid et al. 2013). Nanofluids grasp greater than ever interests in both investigate as well as practical appliances because of their very much superior thermal properties in comparison with their base fluids. A great deal of nanomaterials can be employed in nanofluids counting nanoparticles of oxides, nitrides, metals, metal carbides, and nanofibers such as single-wall and multi-wall carbon nanotubes, which can be discrete into different base liquid dependent on the potential applications, for example, water, ethylene glycol, and oils (Gorji and Ranjbar 2017).

The most significant attributes of nanofluids are the momentous increase of thermal conductivity proportionate to liquids exclusive of nanomaterials, which have been proven by numerous investigational works (Keblinski et al. 2005). Nanofluid based devices will facilitate the expansion of real-time, plainly invasive medical diagnostic systems to observe astronaut health and assist in diagnosing and treating sickness (Berger 2012).

As a result, investigators are facing problems for the hypothetical analysis of thermal transport in nanomaterials (Cahill et al. 2003). The thermal properties of nanomaterials can be tailored by numerous factors like the small size of particles, the shape of the particle and huge interface area, etc. Hence, the thermal properties of nanomaterials are fairly diverse in comparison to the bulk materials. As the length of the material lessens to the nanometer range, it is quite similar to the wavelength and means a free path of phonon, which results in the noteworthy transform in phonon transport in the material. As a consequence of the transform in phonon confinement and quantization of phonon transport, thermal properties without human intervention get customized (Balandin 2011).

5.6 Optical Properties

The optical properties are based on electronic structure, an alteration in zone structure results in an alteration in absorption and luminescence spectra. Their distinctiveness such as spectral width and position, and sensitivity to light polarization, rely not only on the inherent properties of the nano-objects (e.g., composition, structure, size, shape) but also on their surroundings (Rezaie et al. 2013).

The diminution of material dimension as well has an effect on the optical properties of the materials. The optical properties powerfully depend upon the size of particles, which are clarified in two ways. One is attributable to the additional confined structure, energy level spacing augmented and a further is concerned to surface plasmon resonance. The optical properties of metallic nanoparticles are measured by the surface plasmon resonance (SPR) phenomenon (Pattnaik 2005). The SPR is resulting from the consistent motion of the conduction band electrons from one surface of the particle to the other, upon communication with an electromagnetic field. The reduction in size beneath the electron mean free path (distance the electron moves between scattering collisions with the lattice centers) brings about intense absorption in the UV-visible range. Optical excitation of the SPR causes the surface plasmon absorption (Homola et al. 1999).

For the semiconducting materials, quantum size consequence is mostly premeditated. Lessening the particle size of semiconducting material, inter-band transition is transferred to the higher frequency, which results in the rise in the bandgap (Schmitt-Rink et al. 1987). The bandgap of semiconducting materials is within a few electron volts, which rises quickly with reducing particle size. Quantum confinement turns out a blue shift in the bandgap (Lin et al. 2005). The optical properties of nanostructured semiconductor powerfully rely upon the particle size. Therefore, the optical properties of such materials are effortlessly adjustable by changing the size of particles. The nanostructured semiconducting materials acquire excellent transporter confinement and energy density states, which assemble it most appropriate and resourceful for laser devices (Huang et al. 2001). When the particle size of metal nanostructures is lesser than the wavelength of incident radiation, a surface plasmon resonance is created. Commencing the above discussion, it is obvious that the optical properties of materials are very much affected by the particle dimension. By changing the dimension of materials in nanometer, we can modify sophisticated optical materials for devices (Sanchez et al. 2011).

5.7 Magnetic Properties

Nanomagnetism is a vibrant and very interesting topic of current solid-state magnetism and nanotechnology (Petracic 2010). It is of foremost scientific attention and high technological importance. Ferromagnetic nanomaterials encompass prospective benefits over present materials in various appliances in hard magnets, soft magnets, magnetic recording, etc. (Schwarz et al. 2004). It is well recognized, that the coercivity of magnetic substances has an outstanding reliance on their size. Magnetic coercivity rises with the decrease in particle size in the nanometer range going through a highest at the solitary domain size, and afterward reduces one more time for very tiny particles on account of thermal effects and turns into zero at the superparamagnetic particle size. An iron, which is a soft magnetic material with coercivity about 20 Oersted (Oe) at room temperature, could be formed "hard" with a coercivity of 540 Oe (Schwarz et al. 2004). An additional example is the amazing phenomenon of giant magnetoresistance (GMR) of magnetic multilayers that has been developed to enhance the capability of hard discs by over a factor of a hundred in a few years (Mills and Bland 2006).

The magnetic properties are exploited in different appliances like ferrofluids (Hiergeist et al. 1999), and drug delivery (Wu et al. 2011). The magnetic characteristics of the nanoparticles can also be different from those of the related bulk material. Attributable to a smaller size of the particle, the surface area raises and magnetic coupling with neighboring atoms also raises, which leads to the varied magnetic properties.

Ferromagnetism takes place even for the smallest dimensions. The magnetic torques are improved atom-like for clusters with not more than around 100–200 atoms. The magnetic torque diminishes and moves toward the bulk limit, as the size is raised up to 700 atoms, with vibrations probably resulting from surface-induced spin-density waves or structural alterations. Ferromagnetism is referred to a worldwide aspect of nanoparticles of the nonmagnetic oxides (Sundaresan et al. 2006). When the particle size diminishes beneath a definite size, ferromagnetic particles turn out to be unstable. Such instability is as a result of the spontaneous polarization of domains and the adequately elevated surface energy. Owing to this property, ferromagnetic grows to be paramagnetic at the nanometer scale, but it acts in a different way from the conventional paramagnetic and therefore it is named superparamagnetism (Sato et al. 2007).

A bulk ferromagnetic substance generally includes multiple magnetic domains, while nanostructured ferromagnetic substances have minute magnetic nanoparticles and have simply one domain. These domains of different particles are arbitrarily dispersed as a result of thermal fluctuation and develop into aligned in the presence of an externally applied magnetic field (McHenry and Laughlin 2000).

6 Nanomaterials Synthesis Strategies

Nanomaterials fabrication is a tremendous contest and the subject of many kinds of research (Rosei 2004). It is a multidisciplinary domain covering biology, chemistry, engineering, materials science, and physics. The communication among researchers with varied fields will without a doubt give rise to the fabrication of novel materials with customized features. The likelihood of success of nano-manufacturing is dependent on the powerful teamwork among academia and industry with a view to being aware of existing demands and future issues, to develop products straightforwardly transferred into the industrial segment (Charitidis et al. 2014). The production of nanomaterials can adapt solid, liquid, and/or gaseous precursor materials. There are large numbers of production procedures existing to produce different types of nanomaterials organized as buckyballs, clusters, colloids, powders, rods, thin films, tubes, wires, etc. (Chen and Mao 2007; Aruna and Mukasyan 2008). Employing different techniques, synthesized materials can be designed into favorable shapes so that at last, the material can be functional to a definite application. A few of the previously available conventional methods to manufacture diverse types of materials are optimized to acquire novel nanomaterials and a number of new techniques are urbanized (Gilmore et al. 2008; Zhao et al. 2002).

A range of techniques can be utilized for the fabrication of nanoscale materials, but these techniques are broadly divided into two main classes, i.e., (1) Bottom-up approach and (2) Top-down approach (Wang and Xia 2004) as shown in Fig. 1.3 (Iravani 2011). The manufacturing of nanomaterials by producing things smaller that are by downsizing and by constructing things from smaller building blocks that is by up-scaling. The first approach is referred to as the "top-down" and the second as the "bottom-up" approach (Ozin et al. 2009). These approaches supplementary divide into a variety of subclasses based on the adopted protocols, operation, and reaction condition. Nonetheless, a few writers proposed effective fabrication (computer simulations), as a third approach (Bader et al. 2007).

6.1 Bottom-Up Procedures

This approach is utilized in reverse as nanomaterials are produced from comparatively simple substances; so this approach is also known as building-up approach. Examples of this case are reduction and sedimentation systems. It comprises biochemical production, green production, sol-gel, and spinning (Iravani, 2011).

In this approach, a complex structure is created from small building blocks. These building blocks have precise binding capacities – commonly called molecular recognition properties which permit them to assemble automatically in the proper way. Self-assembly is an indispensable part of bottom-up approaches (Blum et al. 2005).

Bottom-up approaches imitate nature through initiating at the atomic or molecular level and building up via nucleation and/or growth from solid, liquid, or gas precursors as a result of chemical reactions or else physical processes (Dhingra et al. 2010). Colloidal dispersions like microemulsions are an excellent example of the bottom-up conception of nanomaterials manufacturing (Yaya et al. 2012). In general, bottom-up products possess high purity, improved particle size, as well as surface chemistry control. However, the bottom-up concept is in its early stage of development, it guarantees comprehensive alters to up to date techniques of manufacture (Dhingra et al. 2010).

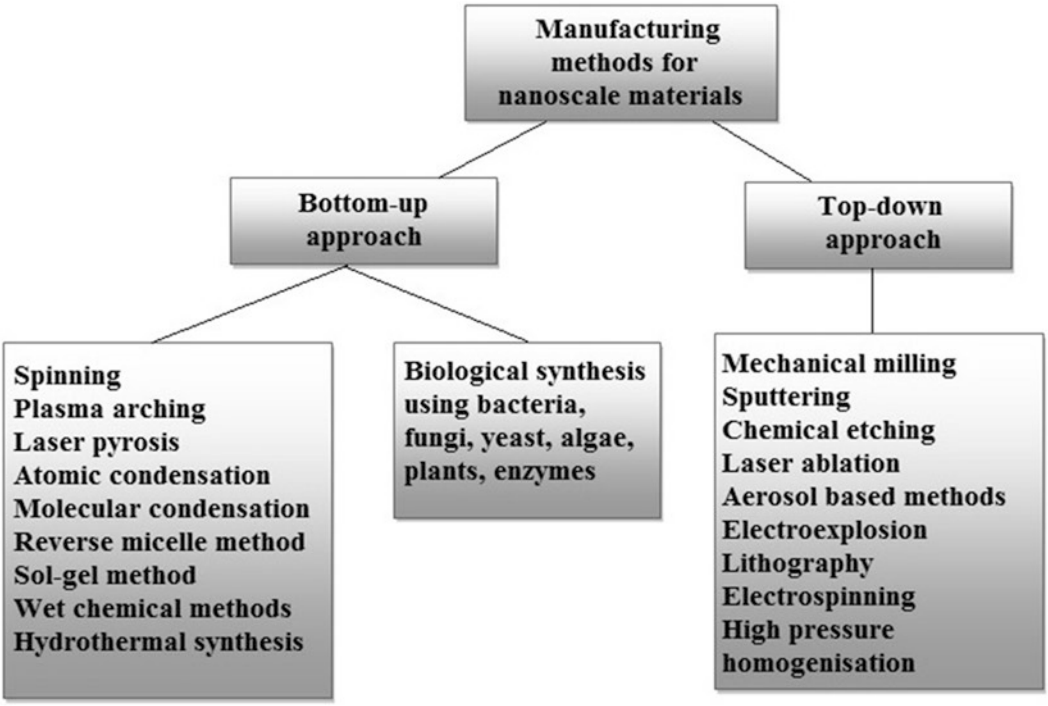


Fig. 1.3 Typical synthesis methods for nanoscale materials

6.2 Top-Down Procedures

The thought of top-down conception is to acquire procedures identified from the macroscopic world and to implement them in a manner that they can be employed for doing a similar thing on a smaller scale. Bulk particles are broken down into smaller and smaller particles. This method is generally carried out on solids or dispersed solids. From prehistoric times, human beings have formed artwork and devices by constructing materials. The characteristic example is the sculpture of stone which is the result of creating 3-D visibly attractive entities from stone. It is a prehistoric work where pieces of irregular natural stone are shaped by the controlled exclusion of stone to present in its most wanted shape (Bashir and Liu 2015).

Briefly, in this conception, a destructive approach is exploited. Starting from the large-sized molecule, which destructed into small-sized units and then these units are transformed into appropriate nanomaterials. Examples of this approach are grinding/milling, physical vapor deposition, and other decomposition techniques (Iravani, 2011).

This method, in general, depends upon physical processes or a combination of physical and/or chemical, electrical, or thermal processes for their manufacturing (Yaya et al. 2012). This is the best established of each and every one form of nanotechnology but it is normally considered that top-down approaches produce a lot more waste (Dhingra et al. 2010).

7 Conclusion

Nanotechnology can be characterized as the understanding, control, and manipulation of materials, having dimensions approximately within the 1–100 nm range, where conventional physics breaks down. Scientists consider nanotechnology as the innovatory technology of the twenty-first century. Nanomaterials refer to natural, incidental, or manufactured materials containing particles in unbound or agglomerated/aggregated states. They are materials with fundamental structural units, particles, fibers, or other essential components smaller than 100 nm in at least one dimension. It has been seen that nanomaterials are diverse from their bulk moieties and cannot be examined as same as bulk or small molecules because of their distinctive properties in nanoscale. The properties of nanomaterials rely upon the composition, chemistry, particle dimension, and interactions with other materials. The manufacturing of nanomaterials is accomplished mostly through two approaches identified as top-down and bottom-up approaches. The first way stands for breaking down the bulk material into smaller and smaller dimensions while the second one is based on consolidating the small clusters. Nanoscience and nanotechnology have the potential to deal with lot of the universal challenges facing society today and improving the quality of life. The appliance of nanotechnology continues to make momentous endowments to inventive and advantageous products across wide areas. In fact, nanotechnology aims to design novel functional smart materials and devices with a broad range of appliances, and it is important to put emphasis on the emergence of new topics like nano energy, nanomedicine, nanoelectronics, nanofood, etc.

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