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# Nanomaterials, Structure modifications and their applications

**Bharat A. Makwana[1], Pooja R. Popat[2]***

[1]Department of Chemistry, Bhavan's Sheth R. A College of Science, Gujarat University, Ahmedabad, Gujarat, India
[2]Department of Chemistry, H.V.H.P. Institute of Post Graduate Studies and Research, Kadi Sarva Vishwavidyalaya, Kadi, Gujarat

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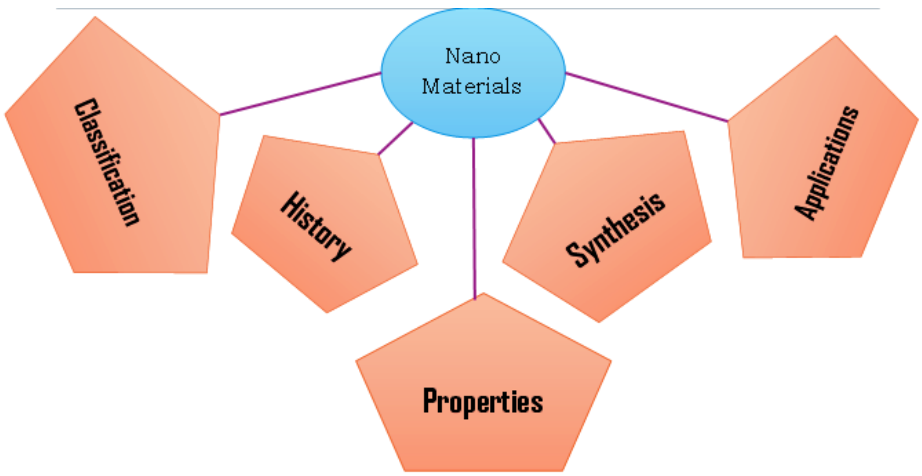
## ABSTRACT




When we bring materials down to the nanoscale, their properties change, and nanoparticles exhibit optical, magnetic, or electrical properties different from those of larger particles. Nanomaterials, because of their unique physicochemical properties at the nanoscale, have revolutionized various scientific and technological domains. This chapter provides a comprehensive overview of nanomaterials with a particular focus on their structural modifications and how these influence their functional performance. Different classes of nanomaterials, including carbon-based, metal-based, polymeric, and composite nanostructures—are discussed in the context of their synthesis, surface engineering, and morphological tuning. The emphasis is placed on strategies such as doping, core-shell structuring, surface functionalization, and defect engineering, which are employed to tailor their electrical, optical, thermal, and mechanical properties. The chapter further explores the diverse application landscape of structurally modified nanomaterials, encompassing energy storage and conversion, catalysis, biomedical engineering, environmental remediation, and nanoelectronics. Through a synthesis-structure-property-performance framework, this chapter elucidates the critical role of structural design in unlocking the full potential of nanomaterials for next-generation technologies.

**Keywords: nanomaterial, Metal nanoparticles, Applications**

## 1. INTRODUCTION

The investigation, modifications, and processing of substances, particulates, and objects at the nanoscale means one-millionth of a millimeter, or the scale of atoms and molecules—is called nanoscience. The way in which atoms and molecules come together to form bigger components on the nanoscale determines significant characteristics of the materials, including their electronic, optical, thermal, and mechanical characteristics. Furthermore, because quantum mechanical effects become significant, these features are frequently more distinct in nanoscale-length organizations than they are on a large scale. The field of technology known as nanotechnology focuses on objects with specifications and dimensions ranging from 1 to 100 nm, or, more broadly, on manipulating particular molecular and atom components. These relatively emerging fields of study are at a junction of the sciences of materials, the fields of biochemistry, electronic devices, physics, and bioengineering.

Nanotechnology is based on the manipulation, control and integration of materials on the nanoscale (1 to 100 nm) to form novel structures, devices, and systems at the macroscopic level (Figure 1). The nanoscale is defined as the lengths between 1 and 100 nm. This ratio is an approximation, what mainly matters is the special behavior of the particles and materials that appear below 100 nm.

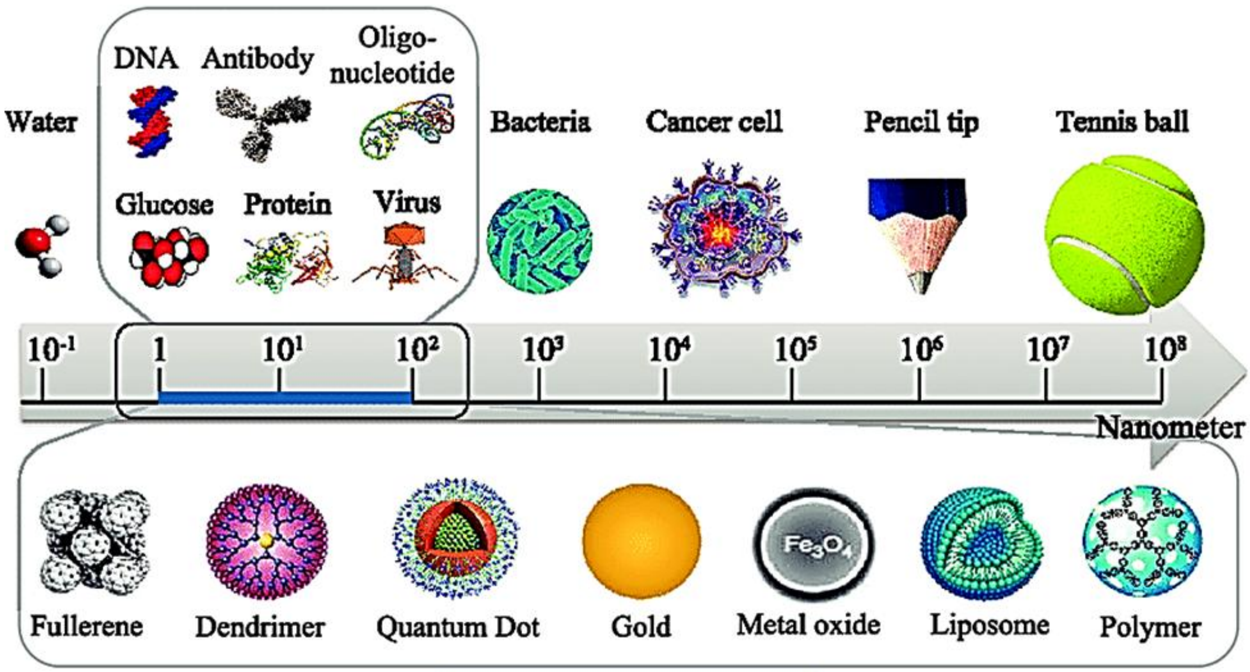



*Figure 1.* **Nanoscale (Saallah & Lenggoro, 2018)**

The world in the very bottom layer looks and works in a very different way. Very tiny man-made nanos could be the foundation of systems at the macrolevel, presenting extraordinary performance such as super sensitive electronic sensors or waterproof textiles.

A different term for nanotechnology is “an enormous change from the small world,” and can be used to great effect wherever it is needed. It is not easy to reveal the actual history of the nanoworld. However, the use of nanomaterials has a long history, and humans have unintentionally employed them for a variety of purposes for a very long time. Optical variation in the Lycurgus cup made by Roman reveals the proof of silver nanoparticles and gold nanoparticles. The unintended trapping of various nanoparticles in the glass matrix of medieval stained glass from Europe, a metallic glaze of copper and silver nanoparticles in Deruta ceramics from Italy, is the primogenital model of the nano technique (Jose Varghese et al., 2019). The 1925 chemistry Nobel Laureate Richard Zsigmondy was the one who first proposed the idea of a “nanometer” by measuring the size of gold nanoparticles using a microscope. Although Richard Feynman is acknowledged as the inventor of contemporary nanotechnology, it is unclear who was the first developer in the fields of nanoscience and nanotechnology? An inspiring and notable theory entitled “There is plenty of room at the bottom” was put forward by Richard Feynman during the meeting of the American Physical Society at California Institute of Technology (Caltech) in December 1959: “Why can’t we write the entire 24 volumes of Encyclopedia Britannica on the head of a pin? There is a lot of space at the Bottom.” This ground-breaking, thought-provoking and widely accepted concept opened our eyes to a completely new realm of science and technology (Bayda et al., 2019; Rafique et al., 2020), and that is why Feynman is reflected as a father of modern nanotechnology. *Nanotechnology* term coined by Norio Taniguchi in 1974.

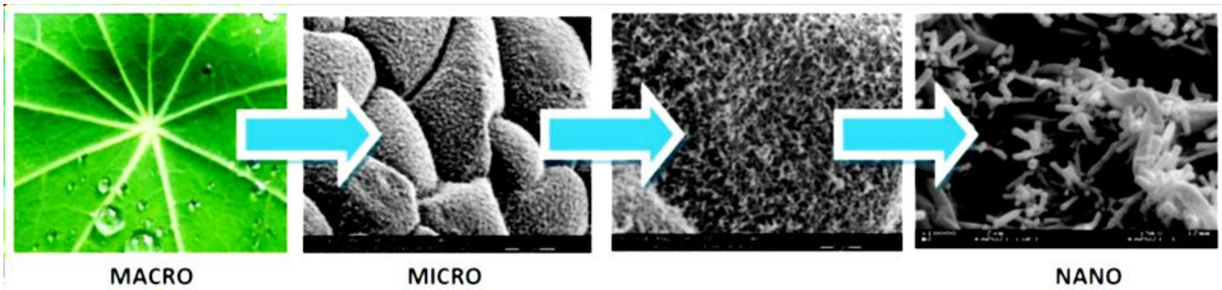



*Figure 2.* **Macro to Nano**

In recent studies, nanoscience and nanotechnology are at the cutting edge. Experts with exceptional knowledge of nanoscience and the ability to apply that knowledge to new technologies are needed in this rapidly expanding field because of the economy. To provide businesses and educational institutions with top-notch professionals who are researchers in their own field and have a general background in various subdisciplines such as electronics, physics, chemistry, material science, and biotechnology, a multidisciplinary technological education is essential. This is what the master's program offers. However, we oscillate between two boundary instances in nanoscience and nanotechnology: endless life and complete annihilation. Even if this might be overstated a little, all of these scenarios are plausible. The explanation is clear: We are capable of performing simple tasks. This is the stage at which biological individuality emerges, allowing us to alter extremely basic processes. Before we begin such major modifications, we need a trustworthy theoretical explanation for maintaining things under control. The fundamental physical framework must be equally advanced as the models (Ali et al., 2016; Deepa & Rajendran, 2018). (Figure 3) shows the timeline of nanoscience and nanotechnology.

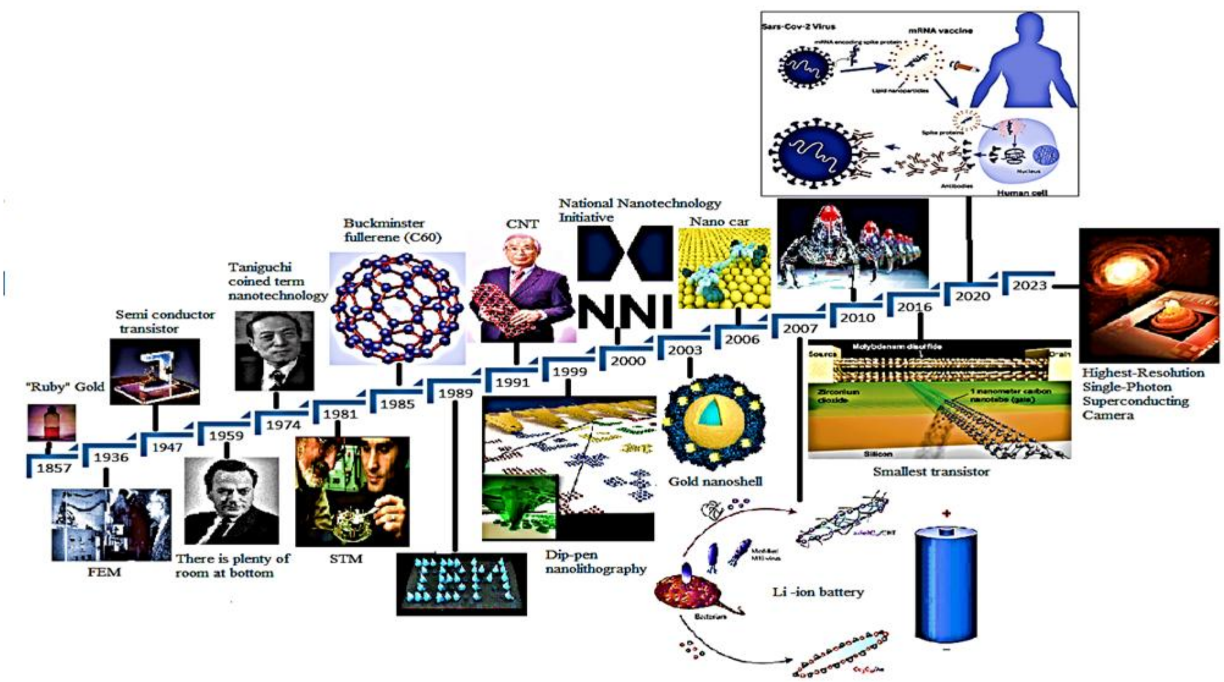



*Figure 3.* **Time line of nanotechnology {Arif et al., 2024)**

## Nanomaterials and Their Types

Substances that have a minimum of one exterior dimension of 100 nm or less, or inside structures of 100 nm, are typically referred to as nanomaterials. They could take the shape of fibers, tubes, rods, or granules. When nanomaterials of the same composition as known materials in bulk form are introduced into the body, they may exhibit distinct physicochemical characteristics and respond accordingly. As such, they might offer various risks. Nanostructures sometimes have extremely broad surfaces for a particular quantity of substance; they should also be evaluated in this context because they can show features that are reminiscent of individual nanoparticles. Depending on their size, origin, structural design, pore size, and possible toxicity, nanomaterials can be categorized into four clusters. (Figure 4) represents the classification of Nanomaterials.

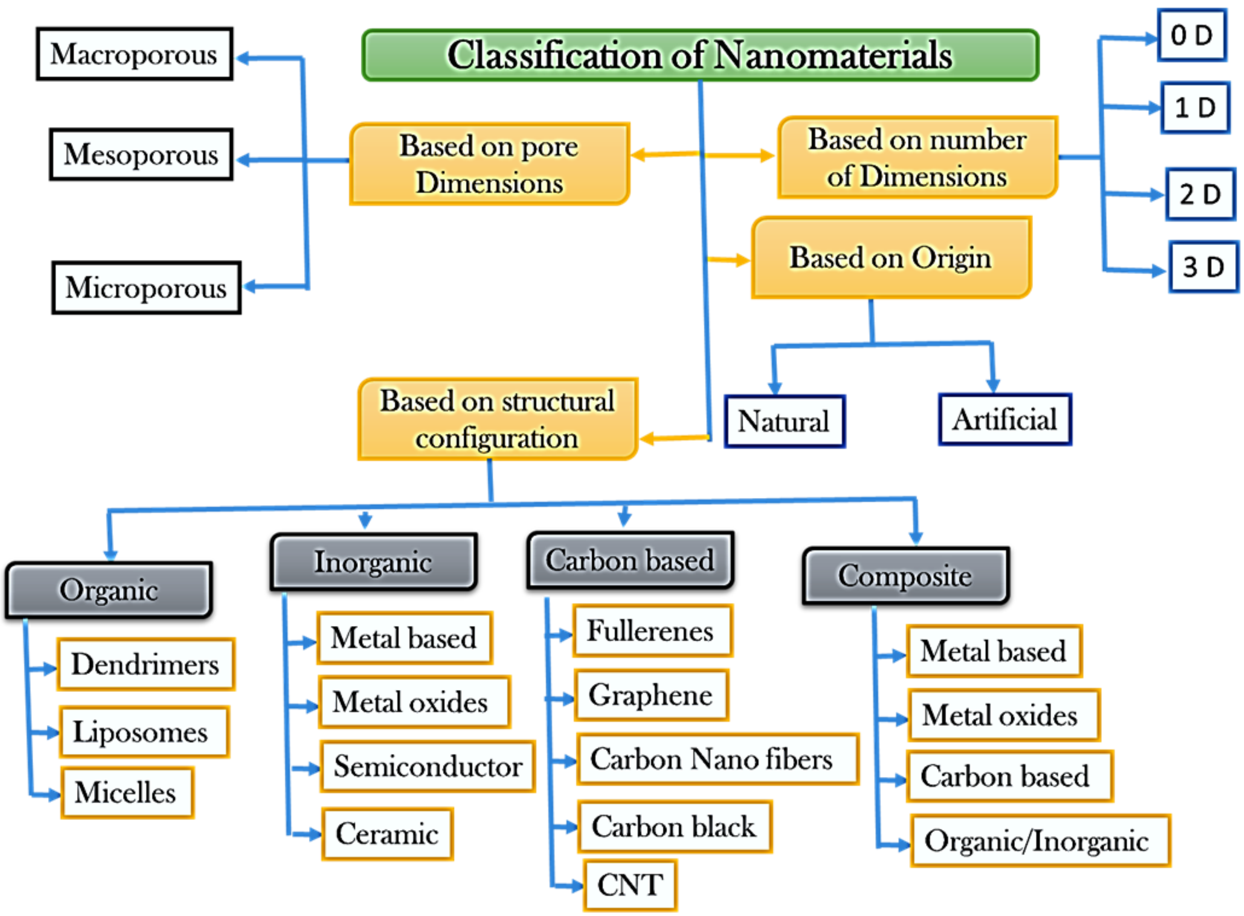



*Figure 4.* **Classification of nanomaterials (Mekuye & Abera, 2023)**

### Based on Dimension

Nanomaterials can be divided on the basis of dimensions that come under the nanoscale, so the main classes for the nanomaterials could be; Zero-dimensional (0 D), One-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) nanomaterials.

***(I) Zero-dimensional nanomaterials (0 D): In this case, all dimensions (X, Y, and Z) are on the nanoscale, which means that none of them is greater than 10 nm; for example, nanoparticles, fullerenes, quantum dots, nanospheres, and nanoclusters are part of it***

These materials can have many forms and shapes, be metallic or ceramic, and be amorphous or crystalline, single or polycrystalline (Khan & Hossain, 2022).

*(II) One-dimensional nanomaterials (1D)*

In this case, two dimensions (x, y) out of three are at the nanoscale, while the third dimension is not in the nanometric range. This produces nanomaterials in the form of needles. It includes nanowires, nanorods, nanofibers, nanohorns, thin films, and nanotubes. They can be metallic, ceramic, or polymeric and can exhibit in the form of amorphous or crystalline (Cho et al., 2019).

*(III) Two-dimensional nanomaterials (2D)*

Under this category, only one dimension is considered as nanoscale while the other two are outside the nanometric range. For example, nanofilms, nanotubes, nanolayers, nanosheets, nanowalls, or plate-like structures. Various nanostructures such as MoS2, CdS, ZnS, and others were formed under this class of materials. They can exhibit metallic or polymeric form and can be crystalline or amorphous (Joudeh & Linke, 2022).

*(IV) Three-dimensional nanomaterials (3D)*

However, this class includes all three dimensions outside the nanometric range, which is above 100 nm. The structures look like bulk objects that are formed by multiple nanosized objects in different arrays. As an example of such a 3D structure, it can include nanoparticles such as clusters, a bunch of nanowires or nanotubes, colloids, atomic scale porous thin film, etc. (Alharthi, 2023).

## Based on Structural Composition

According to structural composition, nanomaterials can also be classified as Carbon-based nanomaterials, Inorganic based nanomaterials, and Organic based nanomaterials and nanocomposites:

I. Carbon-based nanomaterials are composed mostly of carbon material that includes graphene, fullerene, single-walled carbon nanotubes, multiwalled carbon nanotubes, carbon fiber, activated carbon, and carbon black. (Figure 5) shows the various forms of carbon based nanoparticles.

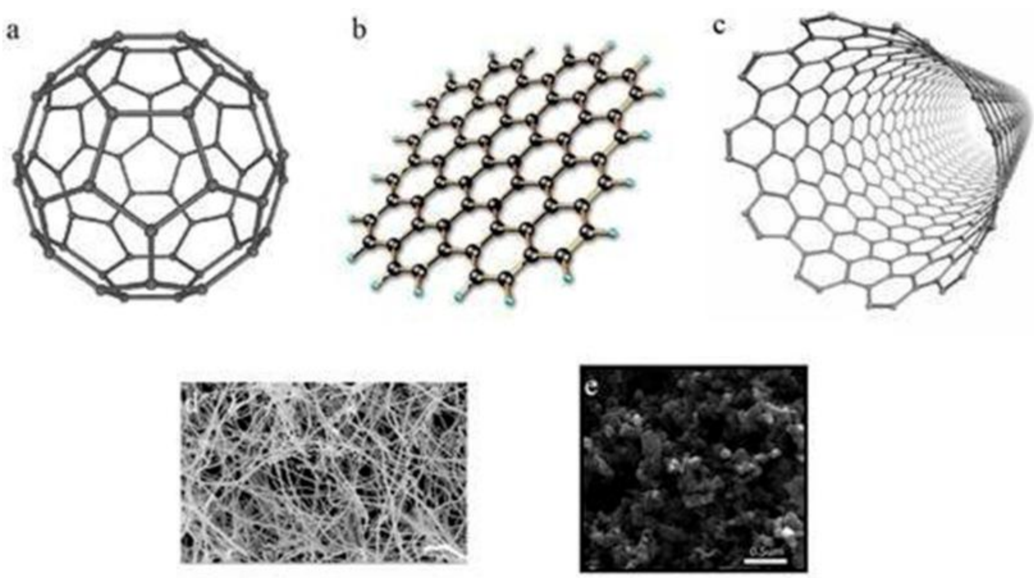



*Figure 5.* **Carbon based nanoparticles: (A) fullerenes, (B) graphene, (C) carbon nanotubes, (D) carbon nanofibers and (E) carbon black (Ealia & Saravanakumar, 2017)**

Because carbon-based nanomaterials can occasionally be stronger than steel, they are used primarily for structural reinforcement. Carbon-based thermally conductive nanomaterials are nonconductive in the tube and thermally conductive along its length (Gu et al., 2022).

***(II) Inorganic nanomaterials composed of inorganic metals and metal oxides with nonexistence of carbon***

Nanomaterials that are synthesized from metals to nanometric sizes either by destructive or constructive methods are metal-based nanomaterials.

***(a) Metal-based inorganic nanomaterial includes various metals such as silver (Ag), gold (Au), aluminum (Al), cadmium (Cd), copper (Cu), iron (Fe), zinc (Zn), and lead (Pb) nanomaterials***

As small as 10–100 nm in size. They can be synthesized by destructive or constructive processes. These nanoparticles exhibit unique features such as high surface area-to-volume ratio, pore size, surface charge, and surface charge density, spherical and cylindrical shapes, crystalline and amorphous structures, reactivity, color, and sensitivity to different environmental factors such as sunlight, heat, air, and moisture. Because of their excellent optical properties, they can be used in various fields of research.

b. Metal oxide-based nanomaterials are self-possessed of a metal cation and negative oxygen. They are synthesized to modify the properties of their respective metal-based nanomaterial, for example, when exposed to oxygen at normal temperature, iron nanoparticles (Fe) quickly oxidize to iron oxide ($Fe_2O_3$), which enhances their reactivity in contrast to iron nanoparticles. Metal oxide nanoparticles are synthesized mainly as a result of their increased reactivity and efficiency. Examples of metal oxide nanomaterials are zinc oxide (ZnO), copper oxide (CuO), magnesium aluminum oxide (MgAl2O4), titanium dioxide (TiO2), cerium oxide (Ceo2), iron oxide (Fe2O3), silica (SiO2), iron oxide (Fe3O4), etc. (Khan et al., 2022; Tadesse, 2006).desse, 2006). In contrast to their metal counterparts, these nanoparticles have remarkable properties.

c. *Semiconductor-based nanomaterials* exhibit unique features when their size is decreased to the nanoscale. Due to their enormous surface area or quantum size effect, semiconductor materials result in significant changes in their physical and chemical properties. Although still in the research stage, semiconductor nanomaterials and devices show promise for use in a variety of sectors, including solar cells, waveguides, chemicals, biosensors, laser technology, light-emitting nanodevices, and nanoscale electronics.

d. *Ceramic-based nanomaterials* Inorganic solids known as ceramic nanoparticles are composed of oxides, carbides, carbonates, and phosphates that are produced by heating and then cooling. The use of ceramic nanoparticles in drug delivery systems is particularly useful for treating bacterial infections, glaucoma, and tumors. Researchers are also very interested in nanomaterials because of their potential applications in photocatalysis, catalysis, photodegradation of dyes, and imaging. Various Metal based Nanomaterials described in (Figure 6)

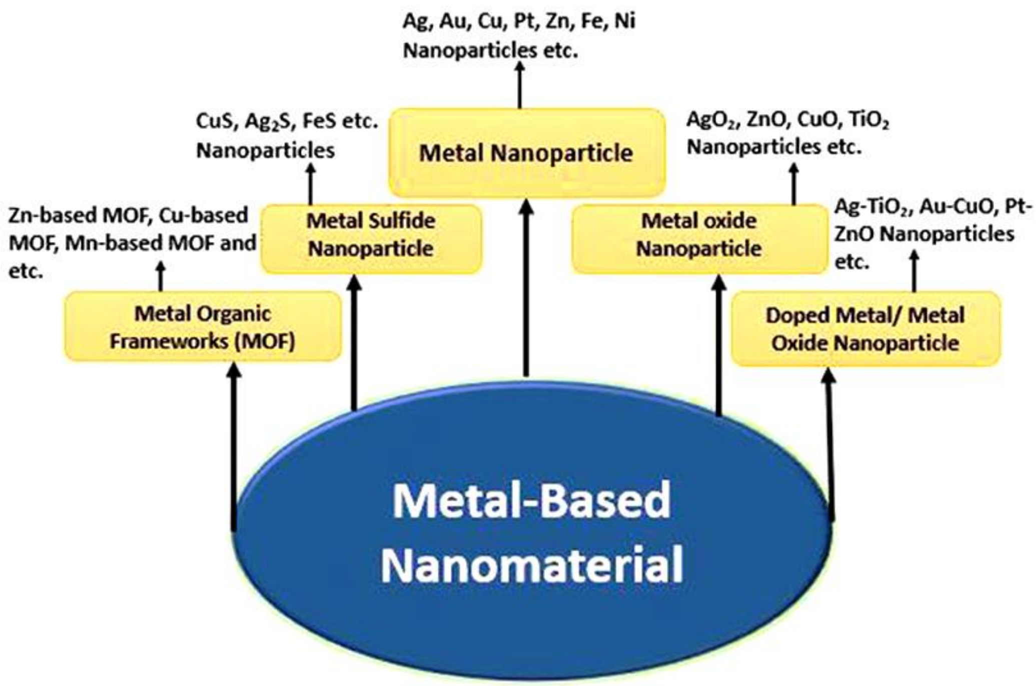



*Figure 6.* **Metal based nanomaterial (Yaqoob et al., 2020)**

III Organic nanomaterials are formed from organic materials that exclude carbon materials, for example, dendrimers, cyclodextrin, liposomes, and micelles (Figure 7).

These nanoparticles are biodegradable and nontoxic, and some particles such as micelles and liposomes have a hollow core, also known as nanocapsules, and are sensitive to thermal and electromagnetic radiation such as heat and light. They are the perfect drug delivery option because of these special characteristics. In addition to their typical characteristics such as size, composition, surface shape, etc., the drug's carrying capacity, stability, and delivery systems, either the entrapped drug or the adsorbed drug system, determine their range of uses and efficiency. Organic nanoparticles are effective and may be injected into particular body parts; they are most commonly utilized in the biomedical industry, such as in drug delivery systems. This technique is referred to as targeted drug delivery. The dendrimer surface is covered by many chain ends that are capable of performing particular chemical reactions. Molecular recognition, nanosensing, optoelectrochemical, and light harvesting systems all make use of dendrimers. In addition, three-dimensional (3D) dendrimers may be helpful for drug administration since they have interior holes that can hold extra molecules (Gu et al., 2022; Siregar et al., 2018).

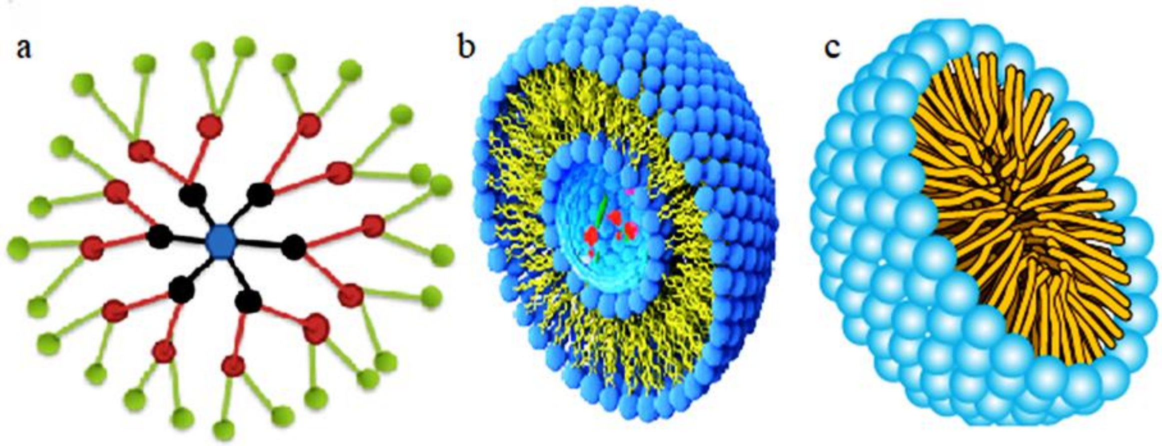


*Figure 7. Organic nanoparticles: (A) Dendrimers, (b) liposomes, and (C) Micelles (Ealia & Saravanakumar, 2017; Zahoor et al., 2021)*

(IV) Composite nanomaterials are any combination of metal-based, metal oxide-based, carbon-based, and/or organic-based nanomaterials, and these nanomaterials have complicated structures such as a metal–organic framework. It has applications as adsorbents and also as sensors and can also be used to improve the mechanical and thermal properties of auto parts of the product (Mekuye & Abera, 2023).

### Based on Pore Dimensions

According to pore dimensions, nanomaterials are classified as

Microporous materials: Porous materials having a pore size of more than 50 nm are known as macroporous materials. Examples of macroporous materials are porous glass, porous gels, and Carbon microtubes. Their pore widths, comparable to optical wavelengths, are projected to have unique and extremely valuable optical features including photonic band gaps and optical stopbands, but they have garnered little attention in the literature, mostly because of their complexity. They can be used as guest material to host large and small molecules (Lal et al., 2022).

mesoporous materials: A mesoporous material, often referred to as nanoporous, is a type of nanoporous material that has pores with widths ranging from 2 to 50 nm. Mesoporous oxides include titanium, zirconium, cerium, niobium, tin, and many more. MCM-41 and N-OMC are the best examples of mesoporous materials. Meso-porous carbon has direct application in energy storage devices. The surface area of these materials increases because of the porosity within the mesoporous range. It can be utilized as liquid or vapor adsorbing systems or as nanoreactors for polymerization (Lal et al., 2022; Li et al., 2016).

#### *Microporous materials*

A material containing pores with a diameter less than 2 nm is termed microporous material. It includes MOF, zeolite framework, and clay materials. They are used in membrane reactors, sensors, gas purification, as an adsorbent, etc. (Lal et al., 2022; Stöcker et al., 1994)

### Based on Origin

Rendering to the origin nanomaterial classified as natural nanomaterials and artificial nanomaterials. Natural nanomaterials: Natural nanomaterials molded from natural sources that include ocean spray, volcanic ash, forest fires, radioactive decay, acid mine drainage, etc. Natural organic nanomaterial includes virus, proteins, milk and blood, spider silk, and gecko feet, while natural inorganic nanomaterials include clays, opals, and fumed silica (Hochella et al., 2019; Khan & Hossain, 2022).

Artificial nanomaterials: Artificial nanomaterials designed by humans for certain revolutions. Carbon black, quantum dots, dendrimers, metal-based nanomaterials and semiconductor nanoparticles are examples of artificial nanomaterials (Hochella et al., 2019; Mekuye & Abera, 2023).

## Unique Properties of Nanomaterials

Interest in nanomaterials with critical sizes less than 100 nm has been sparked by their intriguing and distinct characteristics. The properties of materials with nanoscale dimensions are significantly different from those of atoms and bulk materials, even though most macro- and microstructured materials share similarities with their bulk materials, which leads to main changes in the Optical, Electrical, Mechanical, Chemical, Physical, and Magnetic properties of nanomaterials. This is caused by nanoscale size effects, composition, crystallography, surface charge/interaction, and surface area (Baig et al., 2021; Kolahalam et al., 2019).

### Physical Properties

#### *Optical property*

Due to their nanoscale size and their localized surface plasmon resonance (LSPR) nature, the' optical properties of nanomaterials make them highly attractive to investigate. However, a variety of parameters, including size, shape, doping, surface functionalization, and interactions with other materials, among others, have a significant influence on these properties. Their size-dependent optical characteristic results from a shift in the optical energy band gap, which in turn affects the ' surface plasmon resonance of the nanomaterials. The reduction in particle size causes an increase in the optical band gap, particularly in semiconductor nanomaterials (Karak, 2019). Silver nanoparticles show the SPR band at 410 nm and produce a yellow color that can turn orange at 200 nm and blue at 40 nm (Horikoshi & Serpone, 2013). Nanoparticles have the potential to become photoluminescent and lose their LSPR due to their minuscule size (Huynh et al., 2020).

### *Electrical property*

The quantum effect takes control when the scale is lowered to the nanoscale; electron delocalization occurs along the axis of nanotubes, nanorods, and nanowires. Conducting materials exhibit semiconductor and insulator behavior as a result of the replacement of discrete energy states by energy bands because of electron confinement. This outcome suggests that the metal is transitioning into a semiconductor (Mekuye & Abera, 2023). Certain conductive metal nanoparticles can become nonconductive when exposed to a specific voltage because of the quantization of electron energy. When the size of a material is reduced to a few nanometers, for example, the metals used as conductors, such as copper, will lose their conductivity; conversely, the insulators, such as silicon dioxide, will lose their insulating qualities and become conductive (Narain, 2020).

### *Magnetic property*

At the nanoscale, elements can exhibit different magnetic behaviors due to size, electronic environment, symmetry disturbance, and surface-interface effect. The acute particle size can enhance superparamagnetic behavior and coactivity. For example, despite the ferromagnetic nature of bulk iron oxide's ($Fe3O4$), $Fe3O4$ nanoparticles exhibited super paramagnetic-like characteristics (Karak, 2019). At the nanoscale, a nonmagnetic element like gold and platinum can turn into a magnetic element (Khalid et al., 2020; Roduner, 2006). Magnetic nanoparticles find applications in biomedical fields, including magnetic resonance imaging, magnetic fluid hyperthermia, and medication administration (Flores-Rojas et al., 2022; Xu et al., 2014).

### *Mechanical property*

The higher density of defects such as grain boundaries, dislocations, triple junctions, and so on is a result of the increased number of surface atoms and interfaces in nanomaterials, which gives them their distinct mechanical properties. The mechanical properties of nanomaterials include increased strength, plasticity, increased toughness, and decreased elasticity, rigidity, and increased hardness. The volume, surface, and quantum effects of nanomaterials give them superior mechanical properties. When added to a common material, nanoparticles will somewhat fine-tune the grain, creating an intragranular or intergranular structure that will strengthen the grain boundary and improve the mechanical properties of the material (Baig et al., 2021; Cho et al., 2019; Wu et al., 2020). Tensile strength, break elongation, and impact strength of kenaf epoxy composites can be significantly increased by adding 3% nano oil palm empty fruit string filler (Saba et al., 2016).

### *Melting point*

Compared with the melting point of materials in bulk form, the melting point of nanoparticles is lower because of the unbounded surface atoms. It is the surface energy that increases as the material's size decreases. A surface layer oxidizes because of increased surface reactivity. When the surface of a particle interacts with its surrounding environment, the composition of the surface of the particle changes, and eventually the melting temperature drops (Peng et al., 2015).

### Chemical Properties

The energy of the surface atoms increases as the material size decreases at the nanoscale. The length of the bond on the surface is altered by the atoms of the surface, and as the size of the material is lowered to the nanoscale, this variation of the length of the bond becomes noticeable (Goldstein et al., 1992).

At low temperatures, the oxidation process is not observed in the case of metal nanoparticles. The process of oxidation is seen at high temperatures. For example, oxidation of iron nanopowder does not occur at 200 °C. Beyond 200 °C, oxidation increases and reaches its maximum at 400 °C. Moreover, it drops at high temperatures because a thin coating of adsorbed gasses forms on the surface of the nanoparticles when they are exposed to air. The oxidation process of the nanoparticles will not occur until the gas is desorbed. The temperature of oxidation, or threshold temperature, is determined by the characteristics of the gas and the surface bonding between the gas and the nanoparticles (Patil & Burungale, 2020).

In comparison with bulk counterparts, nanomaterials exhibit much better or improved catalytic features such as reactivity and selectivity. Due to the large surface area of the porous structure of nanomaterials, catalytic activity is enhanced (Cademartiri & Ozin, 2009). To improve performance, catalysts have recently been atomically distributed on 2D nanomaterial sheets (Zhu et al., 2020a).

## Synthesis Approaches for Nanomaterials

Various synthesis techniques or processes were applied to synthesize and design nanoscopic materials using physical, chemical, and biological methods (Vetrone et al., 2004; Zhang et al., 2007). The targeted nanocatalysts or nanoparticles were modified by the changing experimental parameters under a particular laboratory setup. The overall surface engineering and structural changes depend on particular applications such as biomedical or optoelectronics. The changes in concentration ratios, solvents used in experiments, and the kinetics of the reactions influence the morphologies of the nanoparticles. Hence, the various geometries of metallic, multimetallic, or metal-oxides were prepared under such significant concepts. Even 2D supported nanomaterials also have their strongest impact on catalytic actions in the field of catalysis and processing for particular applications. these are several chemical routes are processed to fabricate modified nanomaterials such as sol–gel, coprecipitations, hydrothermal, and solvothermal, and so on (Malik et al., 2013; Modi et al., 2021).). The controlled shape and size of the nanomaterials were obtained by these methods which are found to be most suitable for higher yield, cost-effectiveness, and sustainability. However, physical routes also carry such as pulse laser deposition, electron beam deposition, thermal deposition, electric arch, and others but these methods are costly as well the setup needs more precautions and space as compared to chemical routes. Thus, in our research work, we have employed the chemical combustion method, which is regulated by the temperature and time applied. The pure host and doped nanocatalysts were made by using a furnace at a particular temperature and then annealed for a particular time.

The synthesis approaches are categorized into two main processes known as top-down and bottom-up methods. Several concepts have been reported for these approaches; in short, we can understand as follows; the top-down process, commonly referred to as the destructive approach, breaking down large amounts of material into tiny components that eventually turn into nanoscale objects. Such as lithography, mechanical or ball milling, ablation with lasers, sputtering, electron explosion, arc discharge, and thermal decompositions. (Figure 8) indicates the different approaches for the fabrication of the various types of nanomaterials.

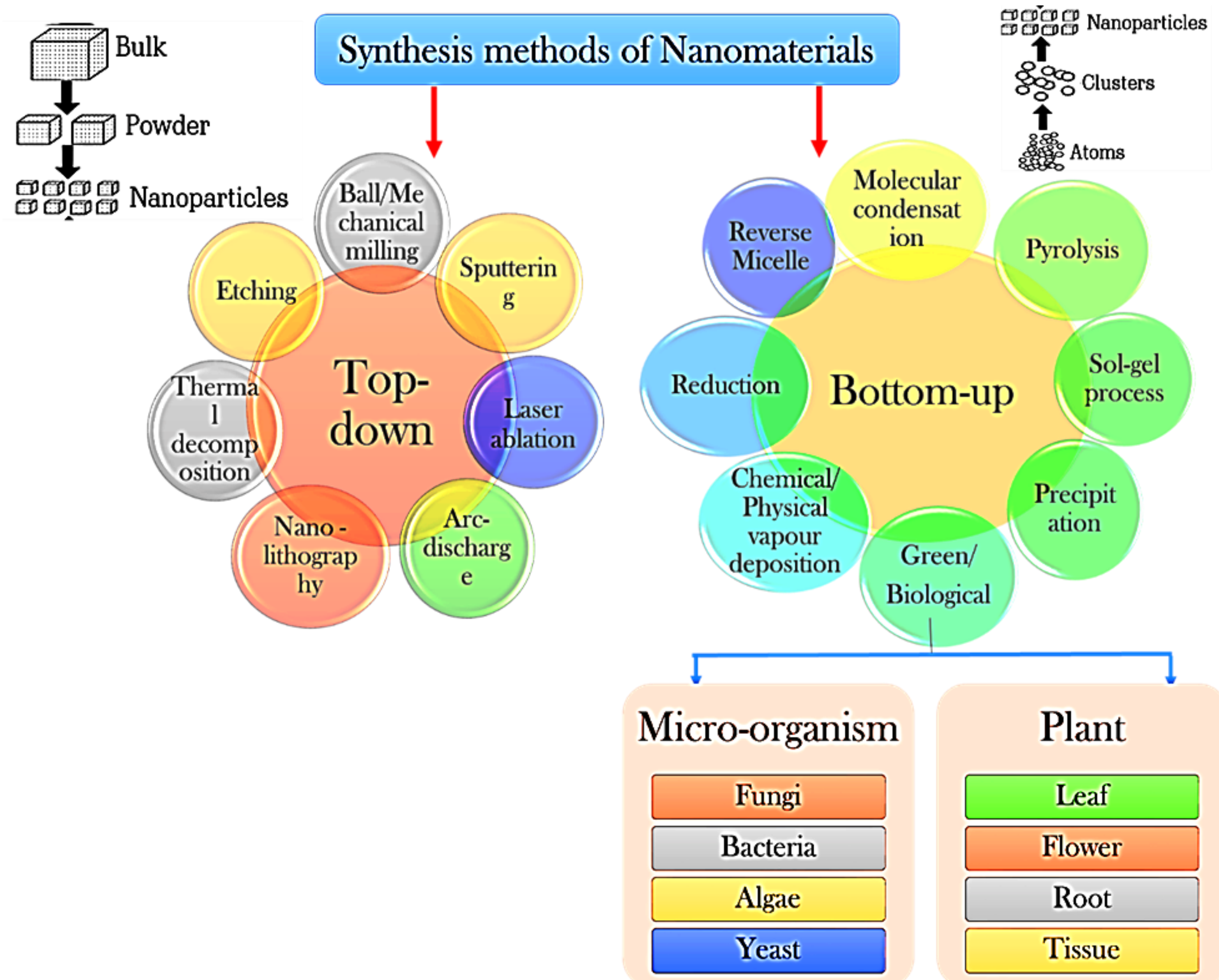



*Figure 8.* **Various synthesis routes under top-down and Bottom-up methods for nanomaterials**

## Role of Techniques to Characterize Nanomaterials

The structural and morphological analysis of the nanoscopic objects is a fundamental and most required task after preparing the nanomaterials under different routes. Because confirmations of shape, size, and band structure directly affect the application actions (Piccirillo & L Castro, 2017; Santos et al., 2015). Therefore, several spectral and microscopic techniques have been developed and explored to determine the phases and geometries of the material along the different sizes. The fundamental prior technique is UV–vis spectroscopy to identify the formation of nanoparticles or nanomaterials. The particular absorbance wavelength is responsible for the particular metallic or metal-oxide nanoparticles such as Ag, Au, Pt, ZnO, CuO, and so on. However, crystal phases and structural confirmation could be understood by XRD (XRD) techniques (Kumar et al., 2020a; Payne et al., 2011) where the nature of the materials (crystalline or amorphous), the purity, and the mixed states of the synthesized materials at the nanoscale could be determined. The peak intensity and shifting are also useful for understanding the various doped and modified nanocrystal structures. So, this diffraction pattern is an important tool for characterizing the solid sample in materials science and nanotechnology. Another vital technique is the High-Resolution Tunneling Electron microscope, which determines the size distribution, shape, and sizes of the fabricated particles; it also gives the diffraction pattern (SAED; Selected Area Energy Diffraction) and elemental composition with the atomic percentages under Energy Dispersive Spectroscopy. In addition to these, some other techniques, such as Raman, photoluminescence, SEM, Atomic Force Microscopy, BET, XPS (X-ray Electron Spectroscopy), FTIR (Chastain & King, 1992; Chávez et al., 2016; Kumar Inwati et al., 2020), and others are used in nanomaterials research and development. In general, the role of the techniques and their output is highly useful in characterizing the nanomaterials at discrete levels.

Creating material from atoms to nanoscopic particles/nanoclusters is mainly known as the bottom-up approach which is a productive method of building nanomaterials. Many examples that could be coated with these techniques include biological synthesis, sol–gel, pyrolysis, spinning, and chemical vapor deposition. In addition, over the past decade, a variety of plant species and ingredients derived from plants have been explored for the environmentally friendly manufacturing of various nanomaterials. Many plants involve a range of physiologically useful substances, such as alkaloids, phenols, flavonoids, ascorbic acid, citric acid, polyphenols, terpenes, and reductase, which act as reducing substances for metallic salts. The plant components involved in these phytosynthesis processes can act as reducing and surface-directing objects, giving them enormous potential. Plant phytonanoparticles can be synthesized either extracellularly or intracellularly.

Different types of nanoparticles were created under hydro-solvent-containing metal salts by using organisms such as fungi, algae, and bacteria. As an example, on the ocean floor, photosynthetic microbes such as Rhodopseudomonas capsulate Au nanoparticles outside the cell; the Fusarium oxysporum fungus is used to produce extracellular Ag nanoparticles; and Sargassum wightii algae is used to create extracellular Au nanoparticles. This procedure has the drawback that extra precautions need to be applied because particular algae, fungi, and bacterial species are hazardous.

## Structural Modification in Nanomaterials

For the enhancement of the catalytic activity and stability of the nanomaterials, it is an important feature that we have to modify the surfaces, shape, and dimension of the nanoparticles. Such modifications need to change experimental inputs in terms of concentration change, incorporation of metal ions, supported 2D materials such as graphene, carbon nanotubes, MoS2, carbon nitrides, etc. (Liu et al., 2021; Xie et al., 2013). The functionalization of the nanomaterials also approaches the band gap modifications which allow for control of the recombination rate of the particular semiconducting nanomaterials, which is an important character in semiconductor nanocrystals especially for improving the environmental, biomedical, and optoelectronic applications. However, supported 2D materials are also associated with improving the surface functionalities and stability of the nanocatalysts. The numbers of semiconductor materials such as TiO2, ZnO, Fe2O3/Fe3O4, CDO, Mn2O3 (Ahn et al., 2009; Pan et al., 2013; Volnianska et al., 2009) and others have been structurally modified by adding fixed concentrations of dopants. Inorganic transitional metal ions, alkali, and lanthanide were inserted to tune the band gaps and surface structures of these host materials. In our work, we have also modified the $Mn_2O_4$ band structures and modified the structural features to enhance the catalytic function of the bare $Mn_2O_4$ nanomaterials. For example, Promod Kumar et al. (2021) have tuned the electronic bands and surface sites of CuO metal oxides by incorporating the different amounts of Zn ions. A temperature-induced chemical combustion technique was employed to introduce the ionic dopants into the crystal structures of the semiconducting CuO nanoparticles on thermal annealing.

## Role of Dopants to Change the Catalytic Actions of Nanocatalysts

Metal-oxides or semiconductors were engineered in terms of their surface site and band structures to enhance the work quality of the catalysts. Various methods have been performed to modify the internal and external structures of the nanocatalysts; even the doped crystalline structures were found to be more perfect to increase the work utility of the nanocatalysts. The optical, spectral, and surface changes of the host/pure semiconducting nanomaterials could be altered by the insertion of suitable metal ions. Crystal defects and oxygen vacancy inside the bare sample control the electron-hole pair recombination, and thus the semiconductor's catalytic functions are regulated under such doping mechanisms (Kumar et al., 2020b; Kumar et al., 2023). The catalysis chemistry of such doped metal-oxides is mostly useful for biomedical, environmental, and photonic uses, as the various levels of defects in crystal arrays regulate the recombination rates of electrons. In this regard, Rb ions were added to ZnO to improve the catalytic actions by Kumar Inwati et al. (2020). The bandgap energy was identified by using UV-vis spectra (using a Tauc Plot), which revealed the particular order of energy change with respect to the doped amounts. The detailed concepts regarding the change in bandgap values were deeply understood by crystal field theory along with the energy level spectral schemes. For example, the doped Rb2+ ions merged with the Zn-3d bands by substituting Zn2 + in the crystal lattices in terms of surface impurities and oxygen vacancies. In most metal oxides, such related concepts were reported and explained in the case of doped semiconducting nanomaterials. Therefore, in our studies, the host semiconducting nanoparticles were also doped with the transitional metal ions to increase the catalytic actions. The created multiple defect levels merged with the electronic bands of the host metal-oxides and altered the band structures. Therefore, spectroscopic analysis was found to be a more accurate technique to study such bandgap values, especially UV–vis and photoluminescence spectroscopy.

## Multiple Applications of Nanomaterials

Due to compositional, surface, and electronic band engineering, nanomaterials were used in multiple applications including the healthcare sector, catalysis, food sciences, environmental purifications and preservations, cosmetics, mineral, coating production, and powder industries, military, sports, aerospace, and optical devices, etc. (Deepa & Rajendran, 2018; Patra et al., 2003; Zhu et al., 2020b).). Metallic, multimetallic, or hybrid phases including organic, inorganic, and polymer composites were explored by improving the mechanical, optical, magnetic, and physicochemical properties at the nanoscale (Xie et al., 2013; Zhu et al., 2014).

The wider fields of advanced catalytic functions were searched by researchers and academics, especially in the domain of physics, chemistry, and material sciences (Gaur et al., 2021; Jang et al., 2009). These nanomaterials are used as the strongest candidates in optoelectronics such as in digital computing, active electronic components such as p-n junction, logic gates, high-density data, and storage. Metal/ions or polymer-supported metal-oxides (semiconductors) nanomaterials are explored in photocatalysis chemistry for photocatalysts to degrade organic molecules that exist in polluted water (environmental uses) (Nakayama & Sakamoto, 2016; Patra et al., 2003). Additionally, the quality of detection was studied in the fields of biotechnology, biochemistry, and pharmacology. However, there are potential uses in macro and microelectronics, fast telecommunications, transducers, electroluminescent displays, etc. (Inwati et al., 2020; Vennerberg & Lin, 2011). So, these are some of the main parts of the applications as nanomaterials were used and explored by several scientists and researchers on global platforms (Figure 9).

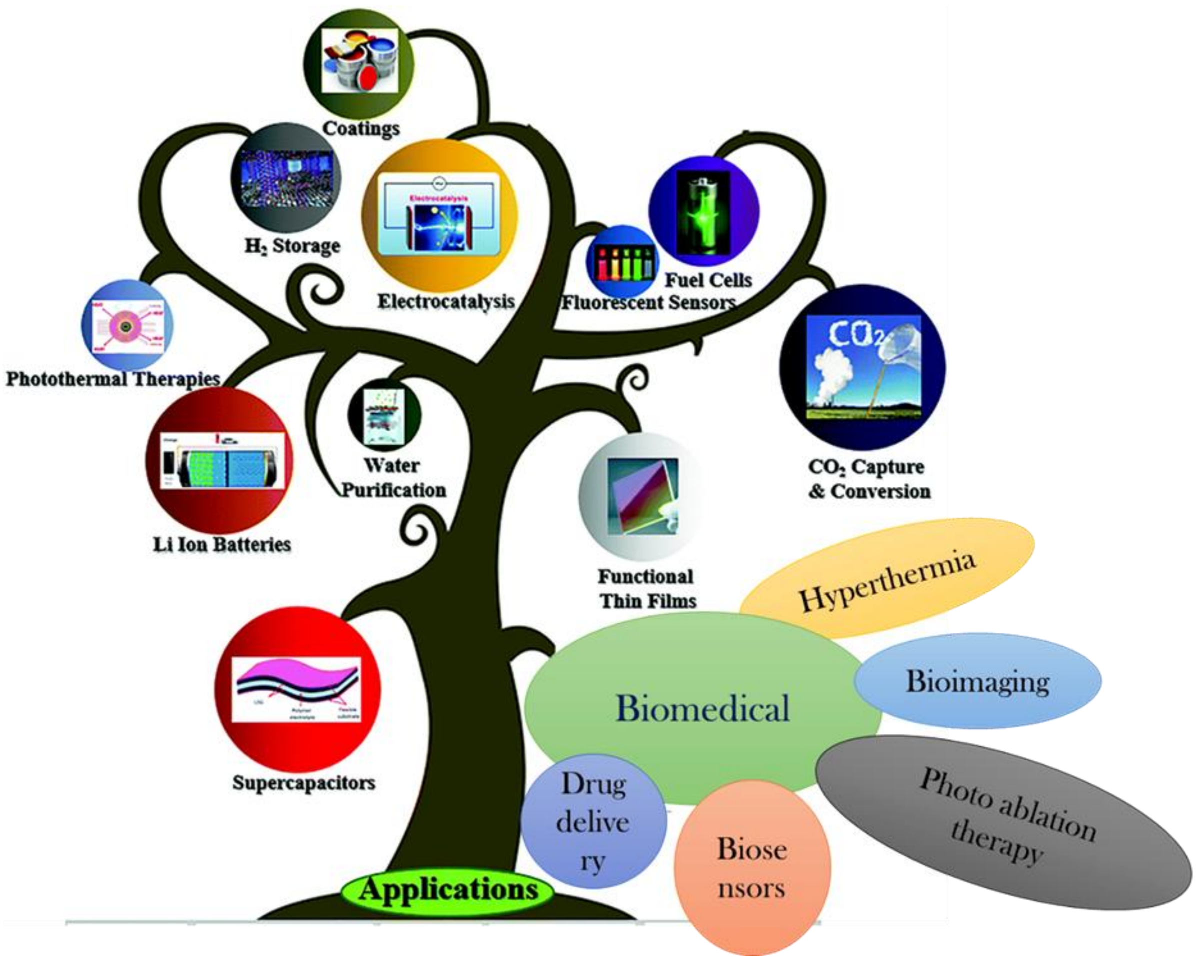



*Figure 9. Various applications of nanomaterials (Baig et al., 2021)*

In line with the research work, we have focused on the biomedical uses of the as-synthesized nanocatalysts. Antibacterial, antifungal, antioxidant, or pharmaceutical problems were resolved using these structurally tuned nanoparticles (Bai et al., 2010; Ciobanu et al., 2012). Due to their nontoxic potential catalytic work and easy fabrications, these nanocrystals are highly explored for such medicinal applications (Esmaeili & Ghobadianpour, 2016; Joshi et al., 2018).

## Conclusions

Nanomaterials represent a transformative frontier in science and engineering, offering unique physical, chemical, and mechanical properties because of their nanoscale dimensions. Through deliberate structural modifications—such as doping, surface functionalization, and morphological control—these materials can be tailored for enhanced performance in diverse applications. Whether in medicine (e.g., targeted drug delivery, imaging), electronics (e.g., nanoscale transistors, sensors), energy (e.g., solar cells, batteries) or environmental remediation, the potential of nanomaterials continues to expand.

However, while their benefits are immense, the integration of nanomaterials into commercial and industrial applications must also consider toxicity, environmental impact, and long-term stability. Future research should focus not only on the advancement of material properties but also on the development of safe, scalable, and sustainable nanotechnologies.

The combination of nanomaterials with intelligent structural modifications holds vast promise for revolutionizing technology and addressing global challenges across multiple sectors.

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