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Review

Nanoparticles' classification, synthesis, characterization and applications—A review

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Abstract: This review provides an overview of the importance of nanoparticles in various fields of science, their classification, synthesis, reinforcements, and applications in numerous areas of interest. Normally nanoparticles are particles having a size of 100 nm or less that would be included in the larger category of nanoparticles. Generally, these materials are either 0-D, 1-D, 2-D, or 3-D. They are classified into groups based on their composition like being organic and inorganic, shapes, and sizes. These nanomaterials are synthesized with the help of top-down bottom and bottom-up methods. In case of plant-based synthesis i.e., the synthesis using plant extracts is non-toxic, making plants the best choice for producing nanoparticles. Several physicochemical characterization techniques are available such as ultraviolet spectrophotometry, Fourier transform infrared spectroscopy, the atomic force microscopy, the scanning electron microscopy, the vibrating specimen magnetometer, the superconducting complex optical device, the energy dispersive X-ray spectrometry, and X-ray photoelectron spectroscopy to investigate the nanomaterials. In the meanwhile, there are some challenges associated with the use of nanoparticles, which need to be addressed for the sustainable environment.

Keywords: nanomaterials; nanoparticles; characterization; top-down synthesis; bottom-up synthesis

1. Introduction

Over the last few decades, nanotechnology has expanded at an incredible rate. Nanotechnology specializes in creating materials and devices at the nanoscale, allowing for precise manipulation of size, shape, and functionality. Nano has become a ubiquitous buzzword in advertising efforts. The Greek term "nano" means "dwarf," while the Latin "nanos" means "nanus.". Nanotechnology has broad potential uses across all of the technological and scientific domains. Nanoscience facilitates the investigation at atoms and molecules level that affect their fundamental properties, whereas, nanotechnology seems to be the act of manipulating substances on the atomic scale to develop unique nanomaterials with exceptional features. Richard P. Feynman first used word "nanotechnology" in his 1959 lecture, "In 1959 Capacity that at Bottom", since then, the field has made great progress. Several new types of nanoscale materials have been created, thanks to the advancements in nanotechnology. As it was found that a substance's size can affect its physiochemical properties, including its optical qualities, therefore, the importance of these materials became clear. Nanoparticles (NPs) of gold (Au), platinum (Pt), silver (Ag), and palladium (Pd) with varying size were synthesized. For instance, gold NPs of varying sizes and shapes, each with its own distinct hue and set of properties that could be put to use in biomedical, were introduced. Changes in the solution's defining properties are reflected in the color of the solution (viewing angle, nano shell width, and gold concentration). Changes from any of these variables affect the NPs' ability to absorb light and, by extension, their color [1].

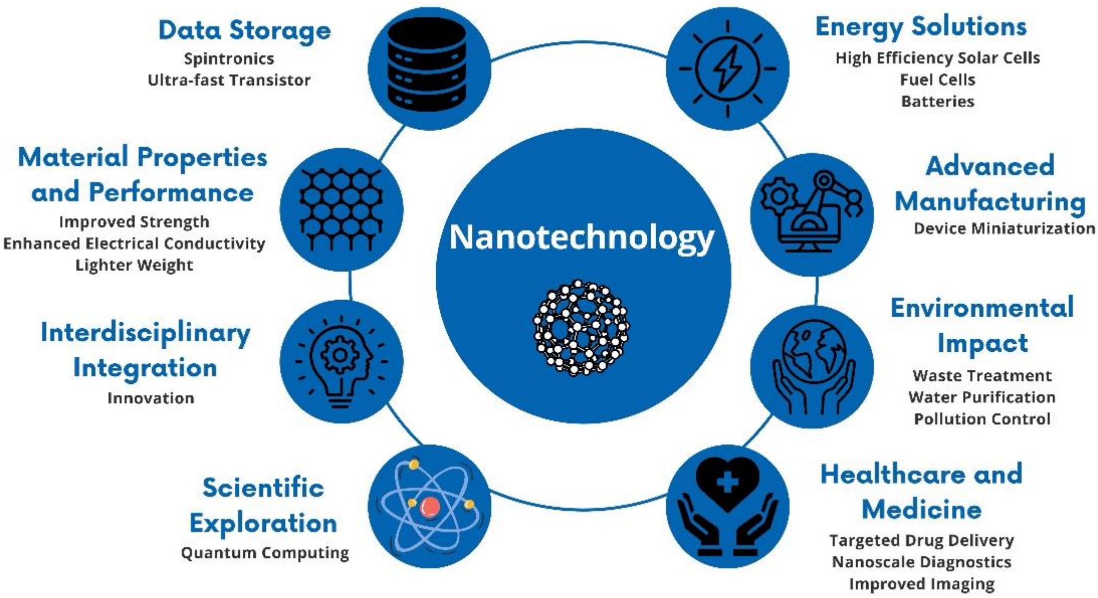

Figure 1. Significance of nanoscience and nanotechnology in fields of engineering and science.

The public is unaware of the myriad ways nanotechnology is being employed in areas such as medical, building, nature conservation, electronics, national security, and even personal safety [2–6], despite the fact that it is getting increasing attention from scientists and engineers as depicted in **Figure 1**. Even if a lot of work already has been done with this technology, there is still opportunity for generating the new unique nanomaterials in a variety of fields for the development of humanity. Scientists spend their time, effort, and resources to advancing human understanding because they are passionate about the subject. Miniaturizing equipment while keeping prices down is thus a priority in different sectors. At some point in the future, nanotechnology will be able to dictate every facet of human existence. People's curiosity in nanotechnology is piqued, and they begin discussing the field's underlying principles and innovative uses. Nanotechnology cannot exist without nanomaterials. Nanomaterials are those with lengths approximately 100 nm or less. Nanoparticles have physicochemical properties that are unique from that of bulk material because of their size and shape. Nanomaterials take on a surprise new persona with unique characteristics and abilities when their quantum structure and size are altered. Several types of nanomaterials, like nanostructures, nanoclusters, and nanosheets, can be distinguished entrenched on their extent of range. As particles interact with one another, their physical properties will evolve.

2. Classification of nanomaterials on the basis of size

- One kind of nanomaterials is called zero-dimensional (or 0-D) because its dimensions are under a nanometer.
- With a 2-D nanomaterial, both dimensions are larger than a nanometer, whereas, in a 1-D nanomaterial, only one dimension is. This category includes structures like nanorods, nanotubes, and nanowires.
- 2-D nanomaterials have just two dimensions that are tiny, whereas the remaining dimension is macroscopic. Nanofilms, nanolayers, and nanocoating's are all examples of such materials.
- Three-dimensional or large nanomaterials (3-D) have a size of >100 nm in three arbitrary dimensions. Nanowire and nanotube bundles, as well as core-shell structures, multi-nanolayers, and nanocomposites are all examples of 3-D nanomaterials [7]. **Table 1** provides classification of nanomaterials on the basis of dimensions.

Table 1. Dimension, types in different forms of occurrence, properties, and potential applications of nanomaterials [8].

Dimensionality	Type of nanomaterial	Properties	Potential Applications
Zero dimensional	Nanoparticles, carbon dots	High surface rea, isotropy, and confined electronic movement	Applications include bio imaging, electronics, drug delivery, and catalysis.
One dimensional	Nanowires, nanorods, nanotubes	High aspect ratio, anisotropy, outstanding electrical conductivity.	Application areas comprise energy storage devices, nanoelectronics, and composite materials.
Two dimensional	Graphene, MXenes	Excellent surface area, better in-plane electrical and thermal conductivity, layered structure.	Such materials have applications in catalysis, electronics, and energy storage.
Three dimensional or higher order	a bunch of nanowires, core shells, nanocubes, nanocages	Porous structure, multifunctionality, enhanced mechanical strength.	Application areas include tissue engineering, filtration, supercapacitors, and catalysis.

Many kinds of NPs exist, each with its own unique size, shape, characteristics, and synthesis. Nanomaterials may range from those based on carbon to those based on metal, semiconductors, polymers, or lipids. Different nanomaterials along with their synthesis procedure and specific examples are provided in **Table 2**.

Table 2. Nanomaterials, synthesis procedures [9], and corresponding examples [10].

Nanomaterials	Methods of synthesis	Examples
Metal nanoparticles (NPs)	Biochemical synthesis, photochemical, thermochemical process, electrochemical	ZnS, Pt, Pd, Ir, Ag, Au, Cu, Rh, Co, Fe, Ni, Cu Au, Ni, CoNi, CdTe, CdSe.
Carbon nano-materials	Arc-discharge technique, chemical vapor deposition, laser ablation method	Cylindrical carbon nanotube like single walled nanotubes (SWNT) and multi walled nanotubes (MWNT) Fullerenes
Polymer nanomaterials	Polymerization and electrochemical techniques	Nanowire of polypyrene, polyaniline, poly (3,4-ethylenedioxythiophane) dendrimers (PAMAM)
Nanocomposite	Innovative processes	Nanocomposite of polyethylene oxide and polyethyleneimine; carbon nanotubes (CNTs) epoxy composites include hydrocarbon polymer composites, polyethylene glycol, polyester polyamides, conjugated polymer composites, CNTs with polycarbonates, fluoropolymers, and so forth
Bio nanoparticles	Biological operations	Protein NPs, plasmids and viruses [11],

3. Nanoparticles and related terminologies

Nanoparticles are defined as "particles having a nanometric size of 100 nm or less would be included in the larger category of NPs". The British Standards Institution [12] officially presented the following definitions for the terminologies being used:

- Nanometer-scale refers to distances between 1 and 1,000,000 of them.
- Nanoscience, refers an extremely small range, aims to explain how different materials behave depending on their atomic or molecular composition or bulk size.
- Nanotechnology is the application of scientific knowledge to the controlling and manipulating of matter at the nanoscale.
- Nanomaterials are defined as those that include or exhibit structures on the nanometer scale.
- Nano-objects are those made of materials with at least one peripheral element on the nanometer scale.
- An item with three exterior dimensions on the nanometer scale is called a nanoparticle. When the lengths of the nanotube are varied, the term nanoparticle is replaced with nanorod or nanoplate.
- A nanomaterial is said to be a nanofiber if it has three dimensions, two of which are on the nanoscale and one of which is much bigger.
- When at least one of a multiphase structure's phases are on the nanoscale, we call it a nanocomposite.
- To put it simply, a nanostructure is a collection of tiny components that are linked together.

A brief history and recent developments of NPs is presented in **Figure 2**.

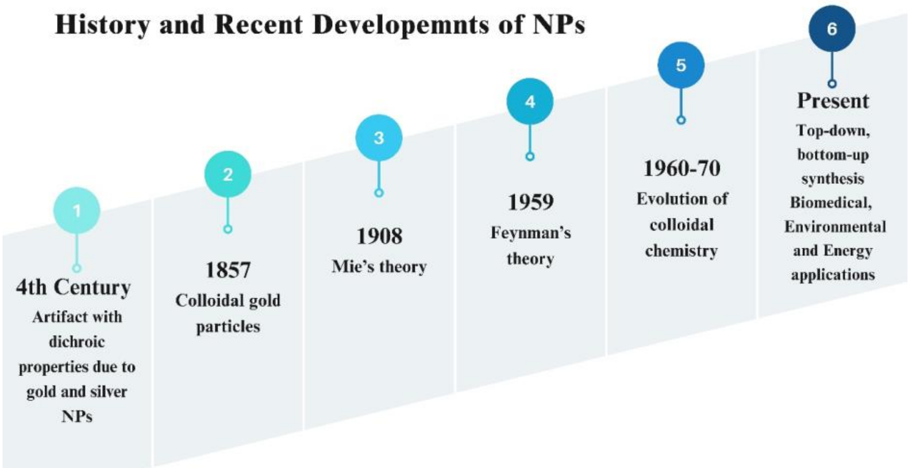

Figure 2. History and recent developments of NPs.

4. Classification of NPs

4.1. Organic NPs

Nanoparticles with composition of carbon or the one which are synthesized by organic molecules are called organic nanoparticles. Common examples of polymers or organic NPs include micelles, dendrimers, ferritin, liposomes, etc. Some of these NPs (liposomes, micelles, etc.) contain a hollow core (also called a nano capsule) and are sensitive to thermal and electromagnetic radiation (heat and light) [7]. Because of their productivity and ability to reach peculiar areas of the physical body, organic NPs are widely used in the biomedical field, for example in drug delivery systems.

4.2. Inorganic NPs

Nanoparticles without composition of carbon are called inorganic NPs. Most of inorganic NPs are made up of metals or metal oxides.

4.2.1. Metal NPs

Metal based NPs are mainly synthesized using constructive and destructive processes. These types of NPs are made from all kinds of commonly used metals. Ascribable to their effective surface to volume correlation and quantum effect, they have excellent thermal, antibacterial, catalytic, and ultraviolent sensitive properties. As there are many atoms on their surface and being small in size, they exhibit marvelous conductivity.

4.2.2. Metal Oxide NPs

Nanoparticles of metal oxides exist for nearly all metals. Some commonly used metals are aluminum (Al), copper (Cu), cobalt (Co), lead (Pb), manganese (Mn), silver (Ag), and zinc (Zn). However, NPs can be made using chemical techniques like electrochemical or photochemical ones. Metal oxide nanoparticles can be created by reducing metal-ion antecedents in solution with reducing agents. They may absorb small molecules due to their high surface energy. There are several potential applications for these NPs, including biomolecule detection and surveillance, and analytical and environmental testing. Samples are occasionally coated with gold NPs before being seen using a scanning electron microscope (SEM). This typically increases the quality of its electrical current, which in turn produces higher-resolution SEM images. Because of their remarkable optical properties, metal oxide NPs have several potential applications.

4.2.3. Ceramic NPs

Ceramic NPs are inorganic solids formed by heating and cooling a mixture of materials such as carbonates, oxides, carbides, carbonates, and phosphates. Forms ranging from polycrystalline to amorphous, dense to porous to hollow, are all accessible. Researchers are paying a lot of attention to these NPs due to their potential in various fields, in addition to catalysis, photocatalysis, and the photodegradation of dyes. These NPs may be employed into a drug delivery system by adjusting certain physical characteristics; this is particularly useful for treating cancers, eye diseases and some bacterial and viral infections.

4.2.4. Semiconductor NPs

Nanoparticles made of semiconductors show characteristics similar of both metals and nonmetals. These may be located in groups II–VI, III–VI, or IV–VI of the periodic table. These particles have large bandgaps, the tuning of which reveals new characteristics. Their applications range from water splitting and photocatalysis to electronics and photo-optics [13]. NPs of semiconductors include the elements such as silicon and germanium from group IV and gallium nitride (GaN), gallium phosphide (GaP), indium phosphide (InP), and indium arsenide (InAs).

4.2.5. Polymeric NPs

In the scientific literature, these particles are commonly referred to as polymer nanoparticles (PNPs) since they are often made of organic materials. They can be in the form of nanospheres or nano-capsules, depending on the method of manufacturing. The former are adsorbate molecules along the surface's periphery. These are easy to operate. PNPs provide a wide range of benefits, including controlled release, drug molecule protection, combined treatment for imaging, targeted delivery, and many more. They may be used in the medical diagnostics and medication delivery industries. PNPs used for medication delivery have excellent biodegradability and biocompatibility.

4.2.6. Lipid-based NPs

Nanoparticles made of lipids are typically round and have a diameter between 10 and 100 nm. Almost predominance of lipid-based NPs are spherical platforms, comprise minimum one lipid bilayer and encompass one internal organic and aqueous compartment. There is a lipid solid in its center and a matrix of soluble lipophilic molecules around it. Surface agents and emulsifiers stabilize the NPs' outer core. Lipid-based NPs consist of a wide range of component configurations. Lipid-based NPs have many benefits including easy formulation, conscious arrangement, renewability, high bioaccumulation, capacity for carrying massive cargo loads, and a variety of properties to modulate their characteristics. These are mainly used in the treatment of cancer including both medication delivery and RNA release.

4.3 Carbon-based NPs

Carbon nanotubes and Buckminster fullerenes are the two most common forms of these NPs. Graphene is simply rolled up into CNTs. They are widely used for reinforcing existing structures. The two most common types of CNTs are single-walled carbon nanotubes and multi-walled nanotubes. Carbon nanotubes are unique in a way that they conduct heat only in one direction, making them ideal for uses that necessitate fine-tuned regulation of temperature. Fullerenes are a type of carbon allotrope distinguished by their hollow cage structure made up of sixty or more carbon atoms. These frameworks have a polyhedral and hexagonal agreement in place of carbon units [14]. Due to their high strength, electronic configuration, and ionic properties, these have useful applications in industry. Sub (SWNTs), two-fold (DWNTs), and multi-walled carbon nanotubes are defined by the number of walls given in the rolled sheets. Deposition of starting material, notably the atomic carboxylic acids, evaporated from tungsten by laser or by electrical discharge, is a common method of polymerization for these substances. Chemical vapor deposition (CVD) is a new method for synthesizing them. Nano-composites made from some of these materials are employed as supplements, effective gas biosorbents, in pollution control, and as assist medium for multiple organic as well as inorganic catalysts [15].

Nonetheless, they are also utilized in their basic state for a wide range of commercial applications.

4.3.1. Fullerenes

Fullerenes, which are carbon-based NPs with a spherical shape, are bound through sp^2 hybridization. Depending on the number of layers, fullerenes may range in size from 4–36 nm in diameter for poly-layered fullerenes and to 8.3 nm in size for mono-layered fullerenes [16].

4.3.2. Graphene

Graphene is the name given to isomorphous type of carbon that have a hexagonal structure and two-dimensional flat surface. A single layer of graphene is just 1 nm thick [17].

4.3.3. Carbon nanotubes

Carbon monolayer nanotubes have a diameter of less than 0.7 nm. However, there is some variation in length of multilayer carbon nanotubes i.e., it may vary in micrometers to several centimeters, and their ends can be closed or hollow [18]. Carbon nanotubes are manufactured by winding the carbon atoms of micro graphene into hollow pipes.

4.3.4. Nanofibers of carbon

Most of nano-foils are coiled in cylindrical shapes of cup or cone shapes, rather than straight tubes, to create carbon nanofibers [19].

4.3.5. Carbon black

Black nanocarbon have a diameter of 20–70 nm and are amorphous in structure. When agglomerates of around 500 nm are produced, the interactions between the particles become very strong and the particles mix to create larger aggregates [19]. **Figure 3** demonstrates the classification of nanoparticles.

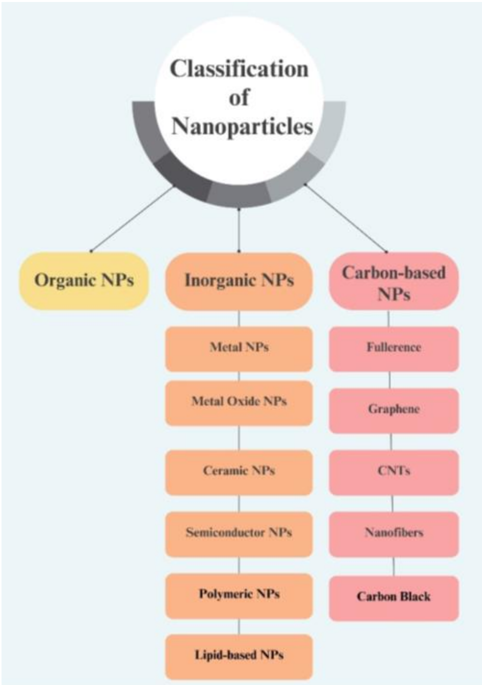

Figure 3. Overview of the classification of nanoparticles.

5. Synthesis of NPs

Nanoparticles are fabricated by different approaches i.e., bottom-up along with top-down one and biological synthesis, that have been developed on behalf of synthesizing NPs. These approaches are briefly explained in the following section.

5.1. Bottom-up methods

One example of a bottom-up or constructive approach is the construction of materials from their atomic level to the cluster or bunch of their nanoparticle level. The most commonly used prevalent bottom-up techniques for producing nanoparticles include sol-gel, spinning, chemical CVD, and pyrolysis.

5.1.1. Sol-gel

A used prevalent colloidal solution is a suspension of solids particles in a liquid. The sol-gel approach appears to be the best bottom-up method because most nanostructures can be made using it. Common precursors used in the sol-gel method include metal oxides and chlorides [20]. The precursor in host liquid can be broken up into a liquid and a solid phase by shaking or sonicating the mixture. Phase separation methods like sedimentation, filtration, and centrifugation is used to remove the nanoparticles, and then they are dried to remove any remaining moisture. **Figure 4** presents the mechanism for the synthesis of $BaTiO_3$ NPs.

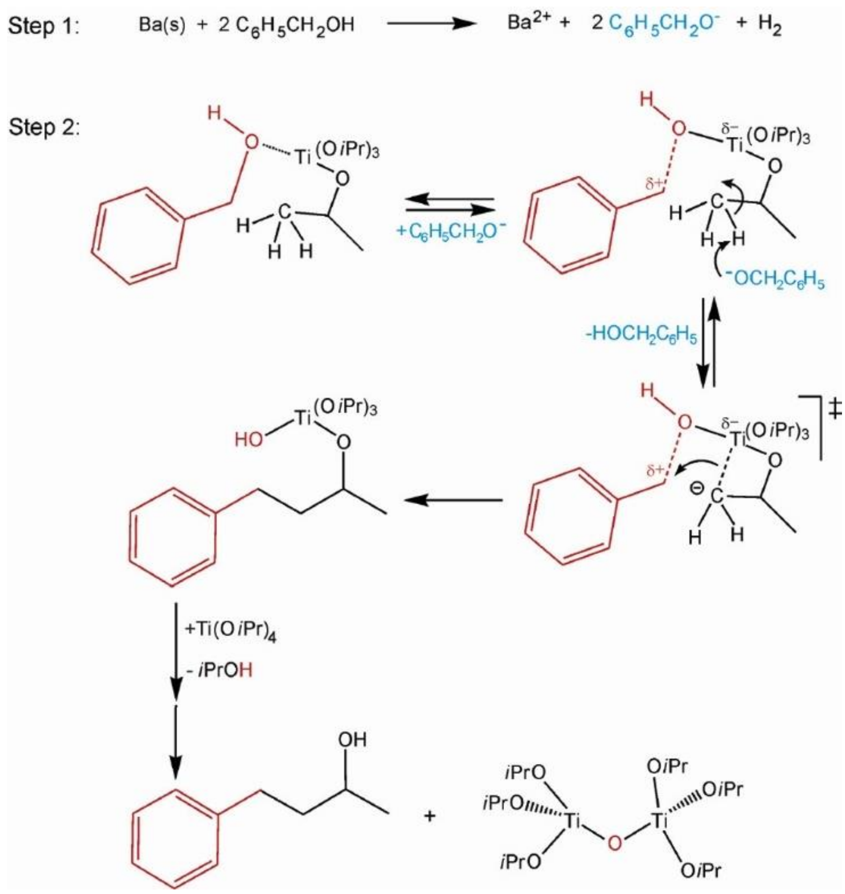

Figure 4. Suggested route for the synthesis of of BaTiO3 NPs along with byproducts (Reused with permission from WILEY - VCH Verlag GmbH & Co. KGaA, Weinheim [21]).

5.1.2. Electrodeposition

Electrodeposition is a method which involves the reduction of metal ions from a solid metal being coated on a substance or in a solution when electric current is applied. Its basic principle is use of an electrolytic cell containing a metal salt solution [22]. When current is supplied, it results in reduction of metal cations from cathode in solution and then gives a metal coated surface of the nanoparticle.

5.1.3. Hydrothermal method

Hydrothermal synthesis of NPs is chemical based which involves extraction of nanomaterials from hydrolysis reaction at high or wide range of temperatures [23]. This process is performed using a specific solvent below critical point at both pressure and temperature over wide range under supercritical conditions. However, this is convertible method for synthesis of nonorganic NPs at both extreme hot temperatures and pressures.

5.1.4. Spin-synthesized

Nanoparticles are spin-synthesized in a furnace using a spinning like disc (SDR). It uses a disc and spins inside a closed chamber/reactor to control physical parameters. Reactors are routinely purged of oxygen, to nitrogen or any other inert gases to prevent chemical reactions. The precursor or water are placed inside the disc and spun at different speeds to create the liquid. Atomic or molecular fusion can be precipitated, gathered, and dried with the use of spinning [24]. Variables in the SDR's operation, such as fluid, disc engine speed, liquid/precursor ratio, feeder position, etc., all influence the characteristics of the produced nanoparticles.

5.1.5. Deposition of Chemicals from gases

Chemical vapor deposition is a method of coating a substrate with some thin layer of gaseous reactants. Reaction causes the deposition i.e.; the joining of gas molecules takes place in a reactor at room temperature. A reaction happens when the mixed gas contacts a heated substrate [25]. The reaction product is a thin coating that is deposited on the substrate and can be removed and recycled for further use. Substrate temperature plays an important impact in chemical vapor deposition. Nanoparticles made using CVD are superior because they are pure, consistent, rigid, and robust. There are certain downsides to CVD, such as the fact that it requires specialized equipment and results in very toxic gaseous by-products. **Figure 5** represents step by step procedure for the synthesis of carbon nanofibers.

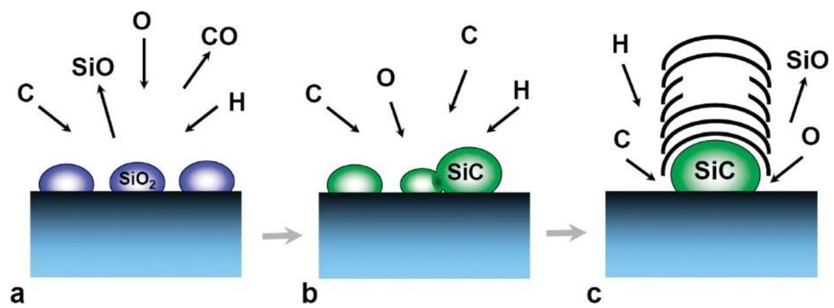

Figure 5. Step-by-step representation of synthesis route for carbon nanofibers. **(a)** Creation of SiC through reduction of SiO2 with the help of carbothermal reaction; **(b)**

coalescence of SiC NPs; **(c)** the degradation of SiC and formation of carbon caps on its surface (Reused with permission from American Chemical Society [26]).

5.1.6. Pyrolysis

As far as industrial production is concerned, pyrolysis is the standard method for making NPs. In a flame, a precursor is burned up. Precursors are introduced into the furnace through a small hole and burned under extreme heat and pressures [27]. Most of the other furnaces use lasers in place of flames to generate the extremely feverish temperatures required for spontaneous evaporation of material. Advantages of pyrolysis include its simple operation, high throughput, minimal material and labor costs, and scalability.

5.2. Top-down methods

The top-down also known as destructive method is breaking down a substance into smaller pieces until it reaches nanometer size. Some of the most common ways to create NPs are by mechanical milling, nanolithography, laser ablation, sputtering, and thermal breakdown.

5.2.1. Mechanical milling

The most common top-down method for creating NPs is milling. Mechanical milling is used for milling, following annealing of nanostructures during synthesis, with each component milled inside an inert environment [28]. Particle shape is affected by ductile materials during mechanical milling, while particle size is affected by fracture and cold-welding.

5.2.2. Nanolithography

Nanolithography is the study of making things that are often on a scale from 1 to 100 nm. It encompasses a wide range of techniques, including but not limited to nanoimprint lithographic technique, scanning probe photoresistor, and electron-beam lithography. In lithography, a light-sensitive substance is combined with a printing procedure that selectively removes material to create the desired shape and structure. The main benefit of nanolithography is that it can scale up the production of nanoparticles of a specific shape and size. There is a prohibitive cost associated with the complicated machinery.

5.2.3. Etching

Etching is a chemical process of layers separation from some substance like wafer. It is mainly used for micro or nanofabrication. However, to protect other parts of the wafers from etching, special masks are used which provides resistance from this process. These masks are made of photoresist material which is contrived from photolithography [29].

5.2.4. Laser ablation

Laser ablation is a popular method for fabricating nanoparticles in a wide range of materials. Nanoparticles can be created by concentrating a plume from plasma created by irradiating a metal coated in a fluid medium with a laser. It is reliable top-down method that can be used instead of the conventional method of chemically degrading metals to produce metal-based NPs. In water emulsion solvents, LASIS (laser ablation in liquids) might be called a "green" approach for manufacturing nanoparticles because no chemical or bonding agent is required.

5.2.5. Sputtering

This process includes the deposition of some nanostructures on surface as a consequence of wrenching with ions. A covering of NPs is first deposited through sputtering and then it is annealed to harden. Layer thickness, processing temperature and surface texture, etc. are important parameters to be considered while using this method.

5.2.6. Thermal decomposition

When anything is broken down by heat, it undergoes an endothermic chemical reaction. When an element reaches its breakdown temperature, it completely disintegrates chemically [30]. The NPs are the product of a chemical reaction triggered by the metal's breakdown at specific temperatures.

5.3. Biological synthesis of nanoparticles

The following procedures are used in the biological production of NPs:

5.3.1. Plant-based synthesis

The synthesis using plant extract is non-toxic, making plants the best choice for producing NPs. Plant extracts such as geranium, sun-dried cinnamon menthol, Azadi Acta indica, etc., may be used to create gold and silver NPs [25]. In the meanwhile, plant-based synthesis poses some challenges as well, such as inconsistency in yield, size, and shape of the NPs due to the variation in the nature of plant extracts which is further related to the change in geographical locations, seasons, and species.

5.3.2. Synthesis by bacteria

The vast potential for synthesis of zinc oxide nanoparticles in the past has led to a dramatic expansion of the field. The capacity of Bacillus species to produce extracellularly has made them popular in the synthesis of metal nanoparticles. The dimensions are between 10 and 20 nm. Furthermore, gold NPs may be synthesized [27].

5.3.3. Synthesis by fungi

Aspergillus nagger, aspergillus orizae, and fusarium solan are just a few examples of the types of fungus that may be used to create the NPs. The effectiveness of silver NPs against scherichia coli, staphylococcus aureus, and pseudomonas aeruginosa has been evaluated [31].

5.3.4. Synthesis by yeast

Here, cadmium NPs are synthesized using the yeasts Candida glabrata and Schizosaccharomyce pombe. Extremophilic yeast strain obtained from acid mine drainage is also used to study silver and gold NPs. Stable lead sulfur NPs have been synthesized using the marine fungi rode sporidium diazoate [32].

5.3.5. Synthesis by biological compounds

Nanoparticles may be synthesized using biological compounds such as proteins, peptides, viruses, and enzymes [23]. The mineralization of sulfides is aided by the tobacco mosaic virus. Viruses cause cowpea chlorotic mottle which is also present on the M13 like bacteriophage's outer membrane. **Figure 6** provides different routes for the synthesis of NPs.

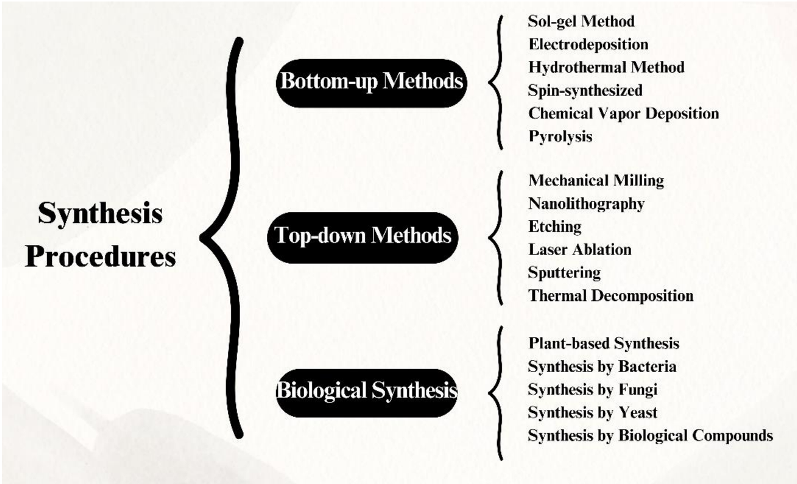

Figure 6. Synthesis routes for nanoparticles.

The advantages, disadvantages, and practical applications of top-down and bottom-up synthesis of NPs are provided in the **Table 3**.

Table 3. Pros and cons of different synthesis approaches for NPs.

Methods	Advantages	Disadvantages	Practical Applications
Top-down Synthesis	These methods offer large scale production e.g., milling. The synthesis procedures are simpler one realized through mechanical and chemical processes. There is precise control over the shape and size of the NPs. Usually, no complex chemicals are employed	The surface defects may lead to roughness thus affecting the characteristics of the NPs. There is requirement of higher amounts of energy. There may be a lot of waste associated with these processes.	Different electronic components such as microchips, thin films, and nanoscale circuits can be produced using these methods. Catalysts can be synthesized using these methods. Optical devices can be manufactured using these methods.
Bottom-up Synthesis	There is a better control over the structure. There is less likelihood towards the defects. Uniform size distribution can be achieved. These methods are versatile and energy efficient.	Comparatively, these methods are time consuming and complex. They require costly chemicals. The scalability is limited. There is tendency towards the incorporation of impurities.	These methods are employed to produce NPs for fuel cells, drug delivery, catalysis, batteries, and supercapacitors. Environmental remediation is also key area of application for these methods.

6. Characterization of NPs

Several physicochemical characteristics are shown by the NPs. Changing even a single nanometer in size causes a noticeable shift in behavior. Nanoparticles need to be characterized using a variety of tools so that their characteristics may be studied. A few examples are the ultraviolet (UV), spectrophotometer, the Fourier transform infrared spectroscopy (FTIR), dispersive energy X-ray spectrometry (EDS), SEM, atomic force microscopy (AFM), vibrating sample magnetometry (VSM), and superconducting quantum interference device (SQUID).

6.1. Structural arrangement, morphology, surface area, size, and shape of NPs

The size and shape of NPs are key determinants of their unique physical and chemical properties. You may examine the surface morphology using an AFM, field emission scanning electron microscopy (FESEM) or transmission electron microscope (TEM). The results obtained from these methods will help to determine whether the NPs are spherical, rod-shaped, or porous. Nanoparticle diameter may also be calculated. When put next to SEM and TEM, ability to reveal NPs' composition, morphology, and crystallinity stands out. Signals are generated when an electron beam strikes atoms in a sample. These signals will reveal the structure and content of the sample's surface. Thus, the samples' exterior needs to have some degree of electrical conductivity. Surface coating with ultrathin electrically charged material may be used for nonconductive samples. AFM examines materials that are dry ones. High resolution transmission electron microscopy (HRTEM) and FESEM are commonly utilized for subsequent processes of nanoscale. TEM's image resolution is superior to that of light microscopes. This will allow a comprehensive understanding of NPs. TEM is a simple method for determining the nanoparticle's size [33]. Scherrer's equation may be used to determine the particle size using X-ray diffraction (XRD) spectroscopy. Nanoparticle size may be easily determined using the distinct XRD peaks. Nevertheless, the XRD peaks are wide and it is more difficult to identify the size of non-crystalline NPs as compared with TEM. The size of NPs is too tiny to be determined by XRD. Dynamic light scattering (DLS), Mossbauer spectroscopy (MS), and photon correlation spectroscopy (PCS) may be used to determine particle sizes and distributions. The surface area on NPs may be calculated using the Brunauer Emmett Teller (BET) technique. In addition to determining crystal orientation and aggregation section, electronic morphology, lattice structural spacing and particle phase shift all may be attained.

6.2. Determination of elemental and mineral conformation

Elemental composition and surface interrelation may be determined using EDS in conjunction with SEM and TEM devices. Elemental percentages may be determined with the use of the methods like atomic spectrometry and inductively coupled plasma mass spectroscopy (ICP-MS). Nevertheless, hard NPs will not directly used for these spectroscopic applications. They need proper dissolution with acids or strong bases compounds. Mineral detection is achieved using X-rays diffraction which results in making up the nanoparticle's aggregated crystalline form [34]. Elemental composition data may also be obtained using XPS.

6.3. Investigation of structural arrangement and nodes in nanoparticles

There are a number of techniques to produce the coveted structure with bonding qualities. Standard procedures such as FTIR, X-ray photoelectron spectroscopy (XPS), thermogravimetric analysis (TGA), and Raman spectroscopy (RS) might be helpful. The XPS and FT-IR can verify the presence of oxygen bonding in the metal. Nanoparticle's surface arrangement may also be studied using XPS. It has the potential to keep track of statistics like the oxidation number in addition to their elemental composition. Spinel symmetry and structure may be determined by Raman spectroscopy. X-ray absorption spectroscopy (XAS) will provide a wealth of data, including calcination states, adjacent molecules, collaboration numbers, length of bond, and the electronic formation of the necessitate element [35].

6.4. Analyzing the intrinsic attributes of nanoparticles

It is possible to learn more about the magnetic characteristics of nanoparticles by using VSM, Electron paramagnetic resonance (EPR) and SQUID. The EPR method can identify paramagnetic facilities along with unbound alkyl. The SQUID instrument will be accustomed to evaluating distinct varieties of samples like translucent, emaciated films, particles, moisture, and vaporish. It is an overly sensitive piece of equipment. The Hs, magnetic partial pressure, and residual magnetic polarity can be measured with SQUID and VSM, at a persistent extrinsic load magnetic flux density [36]. Mossbauer technique of spectroscopy provides access against wealth of features. Electronegativity, oxidation states, spin, and covalent character can be determined, as well as bonding, structural, and magnetic characters. **Table 4** exhibiting the advantages, limitations, and specific uses of different characterization techniques is presented below.

Table 4. Pros, cons and specific applications of different characterization techniques for NPs.

Technique	Advantages	Limitations	Specific Uses
TEM	Surface topography images of ultra-high resolution, crystallographic information, atomic scale imaging.	Difficult sample preparation methods, expensive setup.	Determination of atomic structure, imaging of NPs, investigation of microstructure.
SEM	Images of surface characteristics, provision of analysis of wide range of materials, ease of sample preparation.	Internal structure cannot be examined, low resolution, require conductive samples.	Analysis of surface morphology, inspection of surface defects including cracks and fractures.
FTIR	Identification of functional groups and chemical bonds, agile analysis, provision of quantitative and qualitative analysis.	Low sensitivity, not appropriate for metals, provides surface attributes only.	Identification of functional groups and compositions.
XRD	No destructive approach, analysis of material phases.	Usually limited to crystalline materials.	Determination of phases and crystal attributes.
SQUID	Detection of magnetic behavior at low temperatures.	Expensive due to the use of cryogenic conditions, only for magnetic materials	Specific uses include paramagnets, ferromagnets, and superconductors.

7. Applications of NPs

Nanomaterials are practically amazing due to their magneto strictive, electronic, luminescence, and electrochemical properties. Their usage is present in almost every field from medical to advanced manufacturing. They are being used in the fields of medicine [37], water purification, catalysis, mechanical engineering, and computer science as well as in fields like electrochemistry, luminescence, piezoelectric, and magneto strictive ones [38]. They can be used as electrodes in batteries and supercapacitors, two common types of energy storage devices [39–45]. They can also be used in recording media, like voice/video tapes. Additionally, they also find some applications in isolators, sprockets, and circulators. They have applications inside the dyeing industry and the treatment of wastewater [46].

7.1. Mechanical engineering

Nanoparticles play a vital role in mechanical engineering due to their inimitable properties and their corresponding effects. Nanotechnology shows remarkable results in materials by enhancing their strength, flexibility, mobility, elasticity, resistivity to environmental concerns and toughness. Reinforcement of composites materials, for example, graphene or nanotubes in metals or polymers ultimately results in improving the mechanical strength and stiffness of newly formed or advanced materials which gives extraordinary durability in terms of structural and wear resistance to environment. With the advancement of technology and evolution of NPs, the conventional measures of manufacturing have been evolved and nano-manufacturing has been adopted to increase output by escalating technical performance, and, excessively shows reduction in production cost. Automobiles being fabricated with help of nanotechnology have observed lower rate of failure and self-degrading properties. Thus, on basis of CO_2 free nanotechnology, environment friendly and sustainable transport, which might call as nano cars, where safe, clean and quiet driving is possible with less or no emission of harmful substances in atmosphere, is possible. In a lucid way, these additives improve efficiency and lifespan of machinery. Moreover, oxides of aluminum and boron nitride are being used to incorporate heat dissipation in mechanical systems. Now a days, additive manufacturing is one of the most advanced methods for manufacturing of 3-D mechanical parts with advanced nanomaterials along with complex geometries in an efficient way [37].

7.2. Photocatalysis

Photocatalysis is a method which involve use of photon (light) to actuate the chemical reaction by means of some particles or substance. This process actually leads to initiating a redox reaction along with the electron hole pairs. It is an encouraging approach for sustainable green environment [47]. It is a non-hazardous, safe and reliable technique for deteriorating a large number of pollutants from the environment. NPs act as catalyst to absorb substantial number of pollutants due to their large surface area. It is observed that NPs of gold and aluminum have higher reaction rates of eliminating the organic dyes from environment. Moreover, NPs of platinum are used in most of the catalytic converters of automobiles, which significantly reduces the cost and speed up the reaction by improving its overall mechanical performance [38].

7.3. Waste treatment

Environmental pollutants are one of the major concerns along with gradual increase of urbanization and industrialization. However, some preventive measures have been taken along with the passage of time to solve this problem like sedimentation, activated sludge process, chlorination, aerobic digestion, and chemical treatment etc. Meanwhile, with some advancement of technology, NPs and their composites are used due to their extraordinary physiochemical properties to counter aforesaid issues [48]. They are well known in waste treatment processes as they have adsorption properties like activated carbon NPs act as adsorbents to eliminate maximum pollutants. For removal of heavy metals, this adsorption mechanism is adaptable due to their surface energy and affinity of surrounding atoms present in the outer most shells [45]. Photocatalysis technology, adsorption, nanomembrane technology, and disinfection are some of the methods which help in treatment of wastewater and NPs play a pivotal role in that.

7.4. Water purification

Water purification is one of the common challenges for most of the developed and developing countries. Some of the traditional methods for purification of water are ultrafiltration, microfiltration, biological treatments, distillation, UV treatment, and reverse osmosis (RO). But these methods have some limitations as they will purify the water up to some extent. There comes the need of NPs for water purification. This technology mainly contains oxides of metals and nonmetals and efficacious membranes for hindering and filtering of microbes and harmful pollutants in water. Meanwhile zeolite-based nanomaterials are also used for water purification. Almost 40 morphological kinds of this materials are found naturally and can also be made in laboratory as per requirement. It has a 3-dimensional structure in which Si^{4+} can be replaced with Al^{3+}. These ceramics have special membrane like structure which made it special to filter up to ultra range of soluble particles. Meanwhile carbon nanotubes, graphene and nano absorbent with metals, Ag, ZnO and TiO_2 nanoparticles are most frequently used for water purification [46]. Particularly, titania-based materials have been reported for extraction of antibiotics, dye contaminants along with oxidative sterilization [49].

7.5. Medicine and health care

The use of nanotechnology in healthcare dates back to 1965. Their versatile properties make them useful in medical imaging. Targeted pharmaceuticals, tissue engineering, molecular engineering, biosensors, and diagnosis are the primary areas of application [50–54]. Nanoparticles are used in the field of targeted pharmaceuticals, where they are administered directly to the disease sites like cancer tumors. The smallest possible size of the NPs is required for this method of delivering the drug to the desired location via the bloodstream. When stimulated, the nanoparticles might release their cargo of drug at the site of action. Physical-chemical, biological, temperature and electrical-based materials are all examples of the many types of stimuli that exist. The drug’s release will be triggered by these stimuli. Gold, titanium, magnetic NPs, and quantum dots are commonly used for drug delivery and targeting. Good and enhanced output is what you can expect when you mix these NPs with polymers. Metal NPs are by far the most effective ones for targeting drugs. Gold NPs’ special spectroscopic properties have a significant impact on photothermal therapy in diagnosis of cancer. Nanoparticles of gold, silver, or magnetite ones, all work well as nanocarriers [55]. Nanocarriers are built to transport cancer drugs to the affected area. Nanoparticles are small enough to penetrate deeply but not so small that they disrupt the body’s healthy tissues. That way, healthy cells will not be harmed. Drug delivery is facilitated in part by silver NPs. Some of these NPs are enriched with rare earth elements, including Fe, Ni, Co, and their oxides.

Magnetic dipole-dipole interactions can also lead to their clustering. Both organic and inorganic coatings, as well as magnetic core-shell NPs find widespread applications. Nanoparticles of the quantum dots (QD) have been found to be effective tumor targeting agents. Magnetic resonance imaging (MRI) makes use of the electrical properties of QDs. Diagnosis and treatment are two areas where mesoporous silica NPs shine [56]. This technology can also be used to precisely administer medication for cardiovascular conditions.

7.6. Nanoparticles as catalysts

Reducing the acceleration, binding to reagents to antagonize bonds, getting effective collisions by attempting to bring the superoxide radicals close together, and increasing the percentage yield are some of predominate mechanisms in which catalysis come. Stimulus helps in reducing the reaction heat because they cut down unwanted byproducts. Surface area per unit mass is increased because they seem to be so small in size. Because of this, catalytic chemical reactions can take advantage of a larger surface area. When compared to conventional catalytic reactions, which use bulk materials, nano catalytic reactions are more reactive [57–63]. There are many different types of nano catalysts, including those based on metals, carbon, and ceramics [64]. Cobalt ferrites, coin ferrites, copper terbium, zinc ferrites, alloys, and core-shell ferrites are all examples of metal-based catalysts. For example, copper-based nano-catalysts can be used to improve the selectivity, catalytic performance, and stability while treating the wastewater. They are preferable due to reusability and ease of the recovery in wastewater treatment [65]. In the recent years, CO_2 reduction reactions (CO_2-RR) are in the limelight due to the environmental concerns. In this backdrop, NPs of noble and other transition metals are being employed for CO_2-RR. For instance, NPs of gold and copper have been reported as electrocatalysts for CO_2-RR. It was observed that reduction efficiency and stability tremendously increased which was ascribed to the heterometallic interactions between the two metals and MWCNTs [66].

7.7. Fuel cell application

A fuel cell is an electrochemical device that uses two redox reactions to transform the chemical energy of fuel and oxidizing agent into electricity. An oxygen/hydrogen fuel cell produces electricity with zero emissions of carbon monoxide. Every type of vehicle and instrument, from airplanes to cars, ships, submarines, and weapons now features fuel cells. Fuel cells come in many forms, including the fuel cell using proton exchange membranes (PEMFC), direct methanol fuel cells (DMFCs), alkaline fuel cell (AFC), phosphoric acid (PA) fuel cell (PAFC), the molten carbonate fuel cell (MCFC), and a solid- oxide fuel cell (SOFC) [67]. One major problem with using fuel cells is platinum (Pt) dependent catalysts that are prohibitively expensive. Researchers have not yet succeeded in fully substituting another metal for platinum. Pt-Co, Pt-Mn, Pt-Ru, Pt-Ir, Pt-Cu, and Pt-Fe, are platinum-dependent catalysts that have been introduced. Catalysts based on carbon, iron, and transition metal oxides are also used. For instance, the use of doped titanium oxide as Pt catalyst support has been reported. Traditionally, carbon-based supports are employed which are prone to corrosion, degrading overall performance of the PEMFCs, however, titania NPs-based support exhibited superior durability as compared to the commercially available catalyst Pt/C [68]. Carbon-based catalysts make extensive use of graphene, carbon nanotubes [69], and carbon nanofibers.

7.8. Electronics

Researchers have been interested in discovering new uses of NPs for their amazing magneto strictive, electronic, luminescence, and electrochemical capabilities. Memory devices, like biosensors, CPU systems, transmitter cores, high storage capacity system, optical data storage, transformer cores etc. are all familiar places to find them. They will only be successful if they exhibit a set of characteristics [70,71]. High-Hs ferrite NPs, for instance, have practical use in magnetic recording [72]. That highly magnetized Hs can be shielded from demagnetization and has been investigated. Low Hs is preferred in transformers. High Ms and Hs with minimal residual magnetization are necessary for use in recording medium like audio and video cassettes. Nanoparticles with magnetic properties have several applications in fluids, data analysis circuits in digital computers, and digital recorders. Their magnetic ferrites reveal high electrical conductivities, thus, can be pertinent to the biomedical fields. The magnetic and electrical characteristics of cobalt ferrites are very impressive [73]. The electrifying and magnetic properties of the polymers were escalated by the incorporation of pearlites. **Figure 7** demonstrates the application of nanoparticles in different fields.

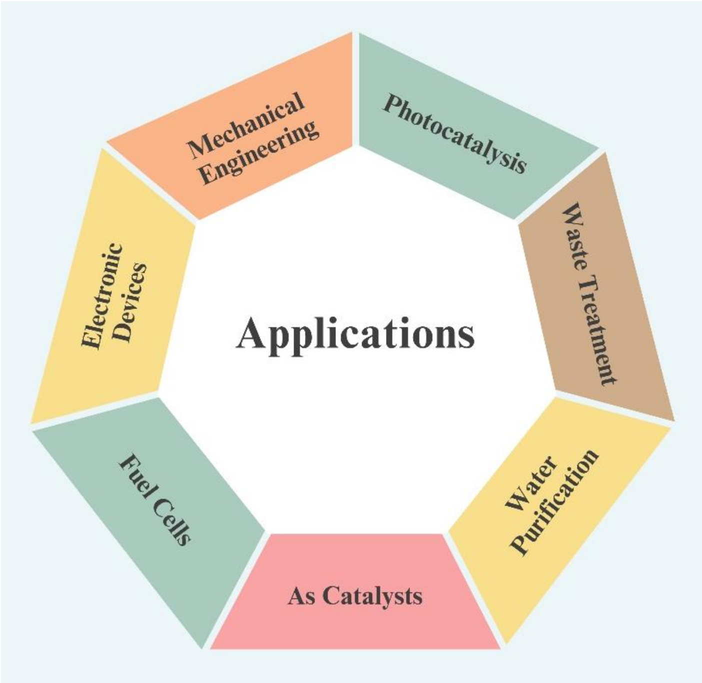

Figure 7. Applications of NPs.

8. Issues and challenges

Apart from its advantages, that have been achieved by use of nanotechnology in various fields of life, there are a number of issues in different areas which need to be resolved [74]. Some of the challenges are given below as:

- Synthesis of NPs is a vital challenge. Normally high-quality NPs are manufactured using diverse instruments under extreme conditions which results in controlled production at large scale. The scalability is challenging as processes like vapor chemical deposition, laser ablation, and hydrothermal synthesis is difficult to scale up. In the meanwhile, scalability requires more energy, costly materials, more sensitive equipment, thus adding up to the overall cost of processing.
- The change in starting material and process parameters can lead to the inconsistencies, ultimately affecting the reproducibility.
- Although NPs are remarkably effective and useful in cancer and drug delivery, however, presence of impurities, defects and discontinuity in their length suppress their strength.
- Nanoparticles have been found to be harmful for the humans as they can penetrate the human body and cause severe health issues. There is likelihood of entering in the respiratory system and other important organs of the human body. For instance, metallic nanoparticles like Au are toxic and reactive in nature, which might cause skin and lungs' cancer. Under certain conditions, it shows phototoxic effect which leads to health problems. Additionally, most of cosmetic and beauty products contain titanium dioxide NPs, long term use may cause cell damage and respiratory issues. Prolong interaction of carbon nanotubes causes inflammation and fibrosis as it has potential of toxicity. There are regulatory challenges as well as they are evolving at the moment. Stable revelation of zinc oxide NPs may raise challenges of skin and eye irritation [75].
- Another challenge which needs to be addressed is environmental impact of NPs during their synthesis, utilization, and disposal. Their accumulation in the environment may have drastic effect on aquatic life. In addition to that, sustainability is another factor which needs to be kept in mind. Use of toxic and expensive chemicals and energy-intensive methods, proliferation of NPs in the fresh water, and utilization of larger amounts of water raises sustainability concerns. There is little understanding of their end-of -life disposal as well.

9. Conclusion and future prospects

In this review, a brief overview of NPs, their types based upon their dimensions, synthesis routes, and emerging applications in various fields of science and technology have been discussed. Several physicochemical characteristics of the NPs are characterized using a variety of tools like ultraviolet, spectrophotometer, the FT-IR, AFM, SEM, TEM, which reveal that these particles exhibit distinct properties. The synthesis using plant extracts is non-toxic, making plants the best choice for producing nanoparticles. Due to small size and large surface area or volume, ability to absorb and scatter rays of light in visible and infrared region is possible. These properties make it ideal for early diagnosis and treatment of neuro-degenerative diseases. Besides its advantages, substantial number of health, environmental and safety issues rise due to the refractory use of these particles. It has the potential to cause detrimental effect like asthma, urticaria, hypertension, Parkinson, dermatitis, Alzheimer, and many other cancers in human body. Thus, there should be a controlled use and discharge of the particles in the environment.

There is dire need to divert the future research direction towards the improvement of homogeneity during the synthesis and control over shape and size, while keeping in view the consistency and scalability especially for the green approaches such as plant-based ones. The priority should be given to addressing the toxicity concerns by introducing biodegradable and non-toxic nanoparticles. The innovation will be driven by the advancement in functionalization techniques and introduction of hybrid nanoparticles with applications in energy storage devices and drug delivery. There should be emphasis on introducing proper guidelines regarding the use of NPs, providing testing frameworks, and labelling the information about the NPs. Last, but not the least, the concepts of circular economy and sustainability should be further explored to improve the yield and reusability, thus minimizing the environmental impacts.

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