

NANOPARTICLES: CLASSIFICATION, SYNTHESIS, CHARACTERIZATION, AND MULTIFUNCTIONAL APPLICATIONS

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ABSTRACT

Nanoparticles (NPs) typically have dimensions of less than 100 nm. The potential applications of nanotechnology in a variety of fields, such as catalysis, gas sensing, renewable energy, electronics, medicine, diagnostics, medication delivery, cosmetics, the construction industry, and the food industry. The main factors influencing the characteristics of NPs are their shapes and sizes. The special properties of NPs could be investigated for applications in energy (oil recovery), electronics (transistors, LEDs, reusable catalysts), medical (imaging, tumour detection, drug administration), and more. The creation of NPs with the proper size, structure, monodispersion and morphology is essential for these applications. Nanotechnology has produced new methods that can consistently produce NPs and nanomaterials while being safe for the environment. The goal of this study is to demonstrate both top-down and bottom-up approaches for producing nanomaterials, as well as various characterization techniques, characteristics of NPs, and industry-specific uses of nanotechnology.

Keywords: Nanomaterials-Classification, Synthesis, Characterization; Nanotechnology applications; Multifunctional nanoparticles;

1. INTRODUCTION

The field of nanotechnology has been increasingly popular in recent years. The foundation of nanotechnology is nanoparticles (NPs). Carbon, metal, metal oxides, and organic materials can all be found in NPs, which are minuscule particles lesser 100 nm [1]. This effect is influenced by a number of factors, including increased mechanical strength, a bigger surface area in relation to volume, and increased chemical reactivity or stability. In addition to their material, NPs vary in size, shape, and dimension. One-dimensional NPs, such as nanotubes, nanorods, and nanowires, have dimensions in the nanometric range [2], while two-dimensional materials have a minimum physical dimension in the nanoscale range, such as phosphorenes and graphitic carbon nitride thin films or nanosheets. The word "three-dimensional" refers to the compact, contact-forming surfaces of the 0D, 1D, and 2D elements, if they are 3D porous nanostructures or nanoscale grains in thick polycrystals [3]. NPs can be spherical, cylindrical, or other shapes, sizes, and compositions. Surfaces can be uneven and wavy or uniform and smooth. Certain NPs are crystalline or amorphous, consisting of scattered or aggregated multi-crystal solids.

To improve characteristics and lower production costs, a variety of synthesis processes are being created or refined [4]. To enhance their capabilities, process-specific NPs are produced by modifying several techniques. Scientists are now more equipped to describe NPs and discover practical uses for technological developments. NPs are everything these days, including electronics, aerospace, renewable energy, and even kitchenware.

Emerging nanomaterials with improved photocatalytic capabilities include heterojunction architectures and hybrid semiconductor NPs. The combination of methods was first demonstrated for Au metal deposition on aqueous CdSe nanorods. Utilizing cutting-edge synthetic methods to manipulate the composition, size, shape, and location of different components. By producing hydrogen through solar-to-fuel conversion, these HNPs have demonstrated photocatalytic water splitting. In photocatalytic CO₂ reduction, it is essential. The photocatalytic characteristics of HNPs have important environmental applications, including waste treatment, water purification, and antibiotic action [5].

The environment is being severely harmed by the overuse of medications and personal hygiene products. Innovative heterojunction structures, including Cd_{0.5}Zn_{0.5} nanorods/BiOCl microspheres, are being developed as photocatalysts with effective electron-hole separation, low cost, and durable redox capability. Cd_{0.5}Zn_{0.5}S exhibits great photocatalytic potential in this structure. However, carrier recombination, low oxidative activity, and photo corrosion compromise its photocatalytic effectiveness. Strong physical stability, easy defect engineering, eco-friendliness, and special photo/electric properties are all characteristics of BiOCl photocatalytic activities [6]. Nevertheless, it suffers from rapid recombination of photogenerated electron-hole pairs and a wide band gap (3.2-3.4 eV).

2. CLASSIFICATION OF NANOPARTICLES

2.1. Organic Nanoparticles

Organic molecules smaller than 100 nm make up the class of NPs known as organic nanoparticles (ONPs) [7]. Common examples include ferritin, micelles, dendrimers, and liposomes. These include liposomes and micelles, which are biodegradable, non-toxic NPs with a hollow centre that are susceptible to heat and electromagnetic radiation. They are especially appropriate for drug-delivery applications because of these special qualities. Although variables such as particle size, content, and surface shape are significant, the drug-loading capacity, stability, and delivery method, whether the drug is entrapped or adsorbed, largely impact their performance, efficiency, and application breadth [8]. Consequently, ONPs are widely employed in biomedical fields, especially in drug-delivery systems, due to their effectiveness and ability to be administered to specific target sites within the body, a process referred to as targeted drug delivery [9]

2.2. Inorganic Nanoparticles

Inorganic NPs are those that do not contain carbon atoms. Generally speaking, inorganic NPs are those made of metals or metal oxides.

2.2.1. Metal-Based Nanoparticles

Destructive or constructive methods are used to create metal-based NPs in nanometric sizes [10]. Metal NPs exhibit exceptional ultraviolet-visible (UV-Vis) sensitivity, as well as enhanced electrical, catalytic, thermal, and antibacterial properties, owing to their quantum effects and large surface-to-volume ratio [11]. As particle size decreases, a greater proportion of atoms reside on the surface. The size and shape of NPs strongly influence their surface-area-to-volume ratio, which in turn affects properties such as electrical conductivity and UV-Vis sensitivity. Variations in surface area lead to significant changes in multiple

characteristics, including electronic energy levels, electron affinity, electronic transitions, magnetic behavior, phase transition temperatures, melting points, and interactions with polymeric, biological, and organic compounds. Furthermore, the charge properties of NPs arise from the combined effects of Coulomb charging and quantum size mechanisms [12]. Combining the quantum size with the Coulomb charge effect yields a variety of interesting features that are not observed in bulk material. Particles with spherical forms and sharp edges are especially vulnerable to quantum processes. Because of their size-dependent properties, NPs are widely used in imaging, sensing, and catalysis.

2.2.2. Metal Oxide Nanoparticles

Metal oxides (MO) are ionic compounds composed of positively charged metal ions and negatively charged oxygen ions. Strong and stable ionic bonds are formed through electrostatic interactions between the metal cations and oxygen anions [13]. Iron NPs easily transform into iron oxide NPs, which significantly increases their reactivity compared to iron NPs. The purpose of creating these oxide-based NPs is to alter the characteristics of their metal-based equivalents. MONPs are frequently created to benefit from their increased reactivity and efficiency [14]. The most frequently produced oxides are silicon dioxide, titanium oxide, zinc oxide, and aluminium oxide. These NPs exhibit exceptional properties when compared to their metal counterparts.

2.3. Carbon-Based Nanoparticles

Carbon, which is essential to biological life, energy systems, and technological advancement, has had a major impact on the evolution of social civilization on our planet. It forms bonds that are unparalleled in strength when mixed with other materials. A diverse range of carbon-based nanomaterials using various synthesis techniques. The numerous industries have a unique form and diverse characteristics. Carbon-based nanomaterials offer a number of possible uses, such as energy production, storage, and wastewater treatment, and biological applications. Graphene sheets are layered to form graphite. Graphene is a novel carbon material made of a single layer of atoms arranged in a honeycomb pattern. Because of its great strength, it can be used as a building block to create various types of carbon NPs [15]. Although NMs are all synthesized differently, their chemical and physical characteristics are related. Since fullerenes are compounds, the production of composites based on them is the most improbable. Despite this, graphene and CNTs offer enormous potential for future research and as workable substitutes for industries [16].

2.3.1. Fullerenes

Buckminsterfullerene (C_{60}) is among the most extensively studied and commonly used fullerenes. It has the shape of a football cage-like arrangement of its sixty carbon atoms, each of which has three bonds. Twelve pentagons and twenty hexagons are utilized in the C_{60} structure. Two well-established characteristics of this structure are icosahedral symmetry. It is used in material science because of its unique set of physicochemical characteristics. Nanorods, nanotubes, and nanosheets are examples of C_{60} -based nanostructures that have recently found extensive application in numerous areas of nanoscience and nanotechnology. Owing to its structural versatility, C_{60} is capable of accelerating chemical reactions across a broad range of compounds [17]. It can be incorporated into systems to enhance particular behaviors due to its special characteristics. C_{60} can be molecularly manipulated via covalent, endohedral, and supramolecular transformations to produce polymeric materials for environmental use.

2.3.2. Graphene and Graphene Oxide (GO)

Graphene has proven to be a helpful addition to polymers in the creation of polymer-based nanocomposites. However, pure graphene has drawbacks, such as its difficult bottom-up production, poor solubility, and agglomeration problems. Thus, graphene oxide and structurally similar compounds can be produced from carbon sources using a straightforward top-down process. They are good substitutes for graphene since they can be easily synthesized. The diffusion of functionalized oxygen groups across the structure affects its reactivity and stability. GO also works well in nanocomposite polymers as a filler. This is due to its superior qualities and good dispersion in polymer matrices. Sp^2 carbon atoms create a tight lattice that prevents gas molecules from passing through. Consequently, it is widely used as a corrosion-resistant material, packaging material, and shield for sensitive electronics [18].

2.3.3. Carbon Nanotubes (CNTs)

One extremely versatile type of carbon allotrope is CNTs. It consists of rolled graphene sheets, forming a long, cylindrical, tubular structure. MWCNTs can be greater than 100 nm, while SWCNTs have a maximum diameter of 3 nm. Because MWCNTs have many layers of carbon atoms, their mechanical strength is higher than that of SWCNTs. It has been discovered that CNTs have far higher Young's modulus and tensile strength than typical metals like iron and steel [19]. SWCNTs' exceptional twisting capabilities make them ideal for use as sensors. MWCNTs are used in composites research because of their exceptional endurance [20]. They are ideal in the electrical industry because of their consistent shape and precise

accuracy. CNTs also store hydrogen. They are perfect for this usage because to their remarkable absorption ability. To reduce the overall weight of mechanical composites, CNTs are commonly used as reinforcement and filler [21].

2.3.4. Carbon Nanofiber (CNFs)

Carbon nanofibers (CNFs) are hollow nanostructures made of one or two graphite layers arranged along the fiber axis in parallel, angled, cup-stacked, or bamboo-like configurations. In some cases, like in [21], graphene layers form cones, cups, or plates creating spherical nanostructures. However, CNFs are considered ideal replacements for CNTs because they are cheaper and more readily available [22]. Understanding how carbon fibers develop and what controls their shape is critically important given their extensive industrial use. Multi-walled CNTs (MWNTs) cost two to three times more to produce than CNFs, while single-walled CNTs (SWNTs) are even more expensive. Developing new fabrication methods could further reduce these costs [23]. The exclusive properties of CNFs have expanded their applications. They are now commonly used in composite materials that outperform many existing options. CNFs are particularly valued in electrical applications, as a material to achieve desired conductivity levels. The structure of CNFs depends on the synthesis process (including catalysts and feedstock) and post-treatment procedures, both of which affect their characteristics [24].

2.3.5. Activated Carbon or Charcoal

Activated carbon, sometimes referred to as charcoal, is a kind of carbon that has undergone processing to produce incredibly tiny pores and a very low volume. Its synthesis aims to offer a large surface area for chemical reactions or adsorption. As a result, activated carbon is frequently adsorbent in water purification processes to get rid of impurities. It is often the process of extracting minerals from water and purifying gases and colours. The low removal efficiency is the issue. One useful type of activated carbon utilized to achieve the necessary efficiency is nanoporous activated carbon [25]. Carbon makes up the majority of nanoporous formations. Although in smaller amounts, hydrogen and oxygen are also present. Depending on the precursor, post-synthesis processing, inorganic materials, nitrogen, sulphur, and phosphorus may also be present. Oxygen groups are the most noticeable when looking at the nanoporous surface [26].

3. SYNTHESIS OF NANOPARTICLES

Using a range of techniques, this study aims to explore the procedures involved in the development of NMs. As illustrated in Figure 1, there are two different approaches to synthesizing nanomaterials.

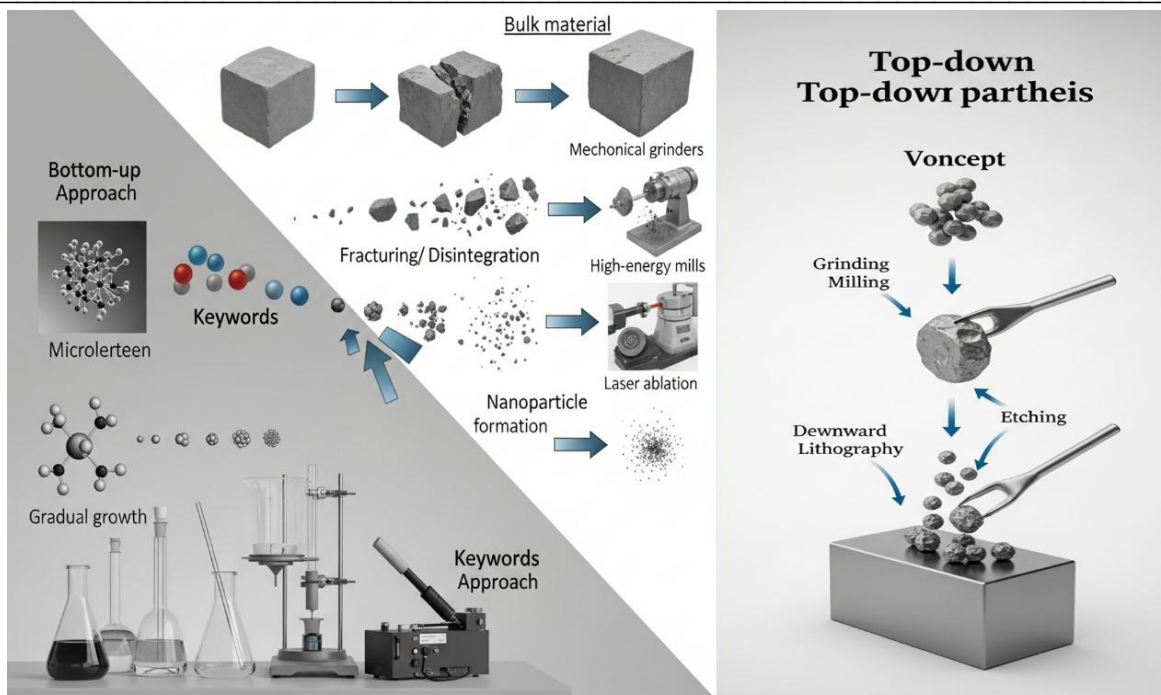


Figure 1. Overview of nanoparticle synthesis via bottom-up and top-down approaches.

3.1. Bottom-Up Method

The bottom-up approach to nanofabrication combines building pieces into functional structures by using chemical or physical operations at the nanoscale. Materials are created at the atomic, cluster, and nanoparticle levels in bottom-up synthesis. Because biological systems employ chemical forces to construct everything required for living, they serve as an inspiration for bottom-up approaches. By building atomic clusters into ever more complicated structures, scientists want to emulate nature. The most often used bottom-up methods for creating NPs are sol-gel, spinning, chemical vapor deposition (CVD), pyrolysis, and biosynthesis.

3.1.1. Sol-Gel Method

Metal oxides, glasses, and ceramics are all synthesized using the highly versatile sol-gel technology [27]. Metal alkoxides or organometallic inorganic salts are common primitives used in the sol-gel method. This process forms a colloidal suspension (sol) from the precursor through hydrolysis and polycondensation reactions. During the sol-gel process, which takes place at ambient temperature and pressure, liquid (or "sol") to a solid (or "gel") form [28-29]. Following gel preparation, the gel is dried and calcined at different temperatures to produce the metal oxide nano powder. The sol-gel technique allows for the modification of the final materials' morphology, form, and textural characteristics. The main drawbacks of the metal alkoxide-based sol-gel method are its sensitivity to moisture and the limited availability of suitable commercial precursors, particularly for mixed-metal

oxides. The sol-gel synthesis of mixed oxides from alkoxide combinations frequently encounters issues due to the various hydrolysis susceptibilities of the separate components. Moreover, during alkoxide hydrolysis, the advantage of increased homogeneity can be lost, resulting in component segregation and mixed phases in the final product [30-31].

3.1.2. Spinning Method

The apparatus utilized to perform the spinning technique of nanoparticle synthesis is a spinning disc reactor (SDR). A disc revolves within a reactor or chamber whose physical characteristics, including temperature, are modifiable. To remove oxygen from the reactor and stop chemical reactions, nitrogen or other inert gases are frequently utilized [32]. Liquid reagent streams are aimed to the centre of the disc, which is quickly rotated to produce a fluid film. The fluid layer's thickness and its extensive contact with the disc surface enable high heat and mass transfer. Consequently, the reagents in the liquid streams along the disc surface can undergo rapid and efficient macromixing due to the drag forces between the moving fluid and the disc. A manufacturing procedure that promotes nucleation while inhibiting particle clumping is necessary for NPs. Nucleation, supersaturation, and reaction rates all peak at the greatest absorption of the limiting reagent. Achieving chemical equilibrium requires macromixing, or thoroughly mixing the fluid streams toward the inside the reactor. Macromixing frequently takes place in less than a millisecond [33].

3.1.3. Chemical Vapor Deposition (CVD) Method

Chemical vapour deposition is a chemical technique it forms a solid deposited on surfaces via gas-phase precursor reactions. Powders or films are deposited by a combination of gas-phase reactions (homogeneous) and chemical processes that take place on or close to a heated surface (heterogeneous). Since the majority of CVD reactions are heat-absorbing, activation energy must be provided to the reacting arrangement. The potential for chemical hazards brought on by the explosive, toxic, and corrosive precursor gases is the primary disadvantage of the chemical vapour deposition technique. Another disadvantage of this method is the challenge of depositing multi-component compounds [34]. Based on the energy source utilized to start the process, the CVD method is separated into subcategories, such as thermally activated CVD, plasma-enhanced CVD, and photo-initiated CVD.

Thermally Activated CVD

Heat is used to initiate chemical reactions in conventional CVD methods, such as thermally activated CVD (TACVD), which employ inorganic chemical precursors. To produce reactive species and accelerate the kinetics, it is usual practice to raise the temperature in the gas phase [34]. Usually, these systems provide temperatures range of 800 to 2000 °C. The main advantages of TACVD are its quick evolution rate at low pressure and ease of application. This technique is currently widely used for surface coatings because it works well with a high-volume incessant growth progression. Thermal sources have advantages, but there are disadvantages as well. For example, too much heat could ruin the temperature-sensitive substrates, which would drastically limit the precursors that are available [35]. Additionally, a large amount of energy is loss of the ineffective gas heating precursor process. As a result, numerous other forms of energy involvement were developed to enable deposition at lower temperatures.

Plasma Enhanced CVD

One technique for reducing growth temperatures is plasma-enhanced (PECVD). PECVD as glow discharge chemical vapour deposition. Low-temperature, fast deposition is made possible by using electron energy (plasma) to initiate processes rather than heat energy. This produces chemically dynamic ions and radicals that participate in heterogeneous reactions [36]. Unlike TACVD, plasma-enhanced deposition can occur at low temperatures, even close to room temperature. This opens the door for the deposition of temperature-sensitive substrates like aluminium, organic polymers, metals, and metal

alloys. Additionally, high energy delivered to the relevant species, PECVD is supposed to be the most effective CVD technique. PECVD techniques to deposit a variety of materials, both normal and unique, and to generate both organic and inorganic chemicals and polymers. However, because of its large energy intake, it often catalyzes processes too quickly, which results in unwanted side effects and more complex outcomes [37]. An alternative method for fabricating NPs is the liquid-phase plasma (LPP) process. This nonequilibrium plasma is a novel, useful, and simple method of creating metal NPs because the reactive chemical species, such as radicals, can drive rapid reactions. LPP depends solely on the solvent and process gas and can generate metals, alloys, oxides, silicon, carbonaceous, and composite NPs, are also directly synthesized in this instance of LPP due to the formation of high-energy radicals and other reactive species [39].

3.1.4. Pyrolysis Method

Heating a substance to high temperatures without oxygen is one kind of thermochemical process that breaks down into reduced components. This process is the industry average for generating NPs in large quantities. Through a small hole, the liquid or gaseous precursor is pumped at high pressure into the furnace, where it is burned [40]. The combustion or by-product gases are first classified to extract the NPs. Some furnaces use plasma and lasers in place of flame for quick evaporation. Pyrolysis is a straightforward, effective, economical, and continuous process with a high yield. However, the NPs try to aggregate and form NP chains as soon as they exit the heated chamber, making it difficult to reach the necessary size of the NPs using this procedure. This is the main flaw in the pyrolysis method of creating NPs [41].

3.1.5. Biosynthesis Method

Biosynthesis produces environmentally and human-safe NPs. Biological systems are a quick, useful, and environmentally friendly way to synthesize NPs. Additionally, the size and toxicity of NPs modified to fit the application. The viability of producing NPs using microorganisms has been the subject of numerous investigations [42]. Microorganisms contain cells that can naturally adapt to a variety of settings, multiply quickly, and need little upkeep. The manufacture of NPs utilizing biological sources is safer than the use of chemicals and physical procedures. Because they readily grow under artificial conditions and continue to grow steadily despite the low-nutrient content of the manufactured NPs, bacteria are preferred for NP manufacturing.

Via extracellular or intracellular pathways, microorganisms can transform inorganic elements into NPs, and they can adjust to rising metal concentrations. Metal ions from the growth media are absorbed by microbes, which then enzymatically convert them to their elemental form [43].

The biological method of creating NPs is safe and environmentally friendly, but it has a drawback in that plant extractions contain a lot of other compounds. It takes a long time to get rid of all the impurities, still a chance that the finished product will contain unwanted particles.

3.2. Top-Down Methods

The destructive, or top-down, method entails dissecting a substance into its constituent atoms. Strong prospects for top-down methods are structures with long-range organization and macroscopic links. Large amounts of material can be divided into smaller, nanoscale fragments using this technique. Although top-down approaches are easier to use, they are ineffective when attempting to create particles with intricate sizes or forms. The difficulty of creating particles with the proper shape and size significant difficulty of this method.

3.2.1. Mechanical Milling Method

The most economical way to produce nanomaterials in large quantities is by mechanical means. The simplest way to grind materials is probably using a ball mill. The ball milling method gets its name from the balls and milling chamber. In essence, a ball mill is a container made of stainless steel that is filled with numerous tiny balls [44]. The metal jar is filled with a powdery material. Nanomaterials are created in a ball mill through a process called mechanical attrition, it converts the kinetic energy of the grinding media into energy that reduces the material. The most popular top-down technique for producing a wide range of NPs is mechanical milling. Numerous NPs and metal alloys were formed with this technique. When a certain amount of the powdered material is placed in a milling vial, heat and pressure are produced by the friction and interaction between the vial and the balls, which can cause a dramatic phase shift at high temperatures [45]. It is employed in materials to reduce things like particle sizes. Initiate certain reactions that would not typically occur at room temperature. The ball milling method's drawback is that the resulting microstructures (nanostructures/NPs) are extremely subtle to the crushing, which may inadvertently become polluted by the environment and milling media. To prepare smaller particles (20 nm or smaller), long-term grinding is required. Another disadvantage of the ball milling technology is the noise pollution and environmental disturbance it causes.

3.2.2. Nanolithography Method

Scientists are now researching nanolithography, which creates shapes on the nanometric scale. Nanolithography is an effective and potent method for producing patterns at the nanoscale. A multi-step process called nanolithography to create precisely specified two-dimensional metal arrays on surfaces with precisely controlled size, shape, and spacing. There are several nanolithography methods, including nanoimprint and scanning probe lithography [46]. Lithography typically involves patterning a light-sensitive material and then removing selected areas to create the desired shape or structure. Nanolithography is its capacity to create evenly sized and shaped NPs in large quantities. The cost is higher since complex equipment is required, and there are other expenses to take into account.

3.2.3. Laser Ablation Method

Laser ablation synthesis in solution (LASiS) can produce NPs using various solvents. By irradiating a metal submerged in liquid, a plasma plume is condensed to form NPs. This method is simple and rapid, capable of generating metals, semiconductors, polymers, and complex multi-element alloy NPs. The process is fast, requires no high temperatures or pressures, and avoids hazardous or explosive precursors. When NPs are created in water, ultrapure colloidal solutions devoid of reaction byproducts are created [47]. These features of NPs make it easier for living things to employ them biologically and biochemically. This top-down method is a dependable substitute for the conventional chemical reduction of metals in the synthesis of metal-based NPs. LASiS is considered a "green" research technique because it allows the steady production of NPs in organic solvents and the use of chemicals or stabilizing agents. Nevertheless, there are certain drawbacks to this approach. A large concentration of NPs grows in the colloidal solution of prolonged laser ablation, obstructing the laser's trail and absorbing laser energy into the NPs target surface. In general, this reduces the ablation rate [48].

3.2.4. Sputtering Method

The process of atoms being expelled from a substance's surface by an energetic particle bombardment is known as sputtering. Sputtering occurs when atoms on a cathode or target are driven away from the cathode or target by bombarding ions, a process known as momentum transfer. Sputtered atoms move until they come into contact with a substrate, and are deposited from the appropriate layer. Sputtering ejection of particles from the surface in reaction to collisions with ions is one method of depositing NPs on a surface [49]. Sputtering involves depositing a thin layer of NPs and annealing them.

The substrate, annealing temperature and duration, layer thickness, and other variables affect the NPs. Sputter pure metals, semiconductor elements, alloys, compounds, and carbides.

The sputtering gas affects the characteristics of the nanocrystalline metal oxide coating, which is one of the sputtering method's drawbacks. Moreover, sputtering rates are low in comparison to thermal evaporation, and most of the energy is converted to heat upon interaction with the target, which needs to be removed [50].

3.2.5. Thermal Decomposition Method

Thermal breakdown is a revolutionary method for creating stable monodispersed NPs. One of the most useful techniques for creating monodispersed metal NPs is this synthesis method. More significantly, it resolves the most significant issue in nanotechnology research, which has been deemed meritorious at the very least [51]. In a similar vein, thermal breakdown made it possible to produce huge of NPs at once, in contrast to biological approaches. Thermal breakdown is an endothermic chemical decomposition because heat can disrupt chemical bonds [52]. The exact temperature at which an element begins chemical breakdown is known as the decomposition temperature. To produce NPs, the metal must be broken down at extremely high temperatures, which sets off a chemical reaction that produces byproducts. The thermal decomposition method has many drawbacks. It is just challenging to deposit of metal compositions and combinations. The film qualities

can only be precise by a small number of processing variables.

4. NANOPARTICLE CHARACTERISTICS

4.1. Physical Properties

The optical characteristics that comprise a nanoparticle's physical composition include its colour, its ability to transmit, absorb, and reflect light, including ultraviolet light, either in solution or when coated on a surface. It also discusses the material's mechanical characteristics, including its flexibility, tensile strength, elasticity, and ductility. NPs in thermal conductivity applications in cutting-edge electronics have been made possible by their conductivity, semiconductivity, resistivity, and electrical characteristics. These are sustainable energy applications.

4.2. Chemical Properties

The chemical properties of NPs, including their reactivity, stability, and sensitivity to factors such as moisture, heat, light, and environmental conditions, determine their applications. Their antibacterial, antifungal, disinfectant, and toxic properties make them useful in biological and environmental contexts. Applications are also influenced by flammability, corrosiveness, anticorrosive behavior, and redox potential.

5. CHARACTERIZATION

The distinct characteristics of NPs govern their potential and applications. An overview of the characterization techniques is shown in Figure 2.

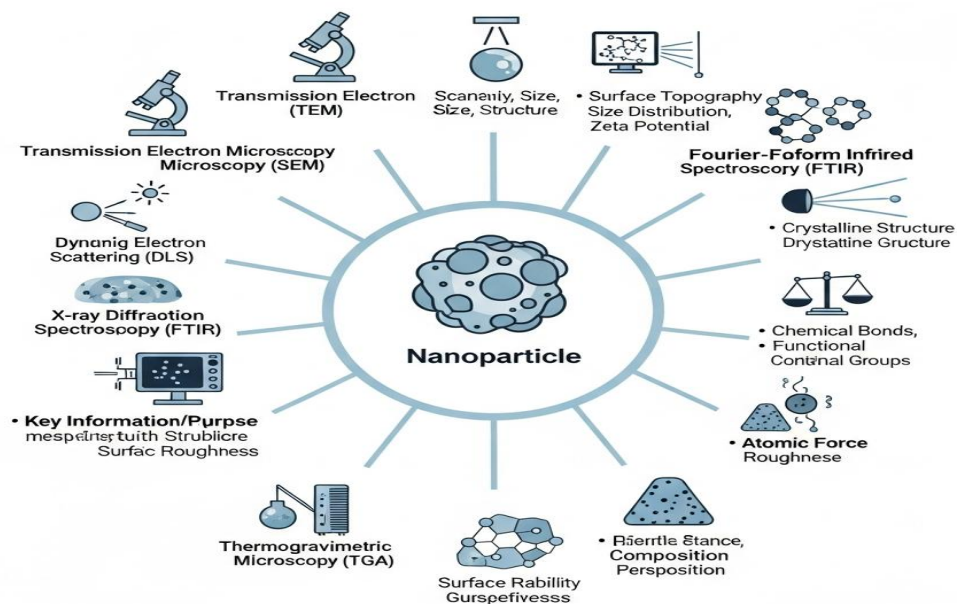


Figure 2. Overview of characterization techniques.

5.1. Size of Nanoparticles

Particle size is a key parameter in NP characterization, determining size distribution and micro- or nanoscale classification, and is typically measured by electron microscopy. Particle and cluster size examination is done using images obtained with a transmission electron microscope (TEM) or scanning electron microscope (SEM), whilst solid-phase bulk materials are evaluated using laser diffraction techniques [53]. The particles in the liquid phase are measured using centrifugation and photon correlation spectroscopy. Imaging methods are challenging and occasionally even disrespectful when working with particles in a gaseous phase.

5.2. Surface Area of Nanoparticles

Another crucial aspect to take into account when trying to describe NPs is their surface area. A nanoparticle's performance and characteristics are greatly influenced by its surface area to volume ratio. The most popular technique for estimating surface area is BET analysis [54]. The surface area of particles in the liquid phase can be determined with a simple titration, although this method is time-consuming and tedious. Nuclear magnetic resonance (NMR) spectroscopy is therefore employed. The surface area of NPs in the gaseous phase is measured using a modified scanning mobility particle sizer (SMPS) and a differential mobility analyzer (DMA).

5.3. Composition of Nanoparticles

The chemical or elemental makeup of NPs directly affects their performance and purity. In addition to causing inferior reactions and contamination throughout the process, the presence of more

secondary or undesirable constituents in the nanoparticle may result in a reduction in its efficiency. The composition is frequently measured using the XPS technique. Certain techniques involve first subjecting the particles to chemical absorption and a wet chemical analysis, which may involve ion chromatography, mass spectrometry, and atomic emission spectroscopy. Spectrometric or wet chemical analysis of the gaseous phase particles, which can be collected by filtration or electrostatically [55].

5.4. Nanoparticle Surface Morphology

NPs are an inclusive range of forms and surfaces that can be designed in different ways. These shapes can have uniform or uneven surfaces, as well as crystalline or amorphous surfaces. The surface is usually determined using electron microscope imaging techniques [56]. When imaging with electron microscopy, the gaseous phase particles are deposited on a surface for further investigation, while the liquid phase particles are either electrostatically or filtered. The surface or total charge of NPs determines their interactions with target materials [57].

5.5. Crystallography of Nanoparticles

The scientific study of how atoms and molecules are arranged in crystals and other materials is known as crystallography. Powder X-ray, electron, and neutron diffraction are used to elucidate the structural organization of NPs [58].

6. APPLICATIONS

The unique size, shape, and physicochemical properties of NPs make them applicable across numerous fields. Figure 3 illustrates their uses and major areas of nanotechnology.

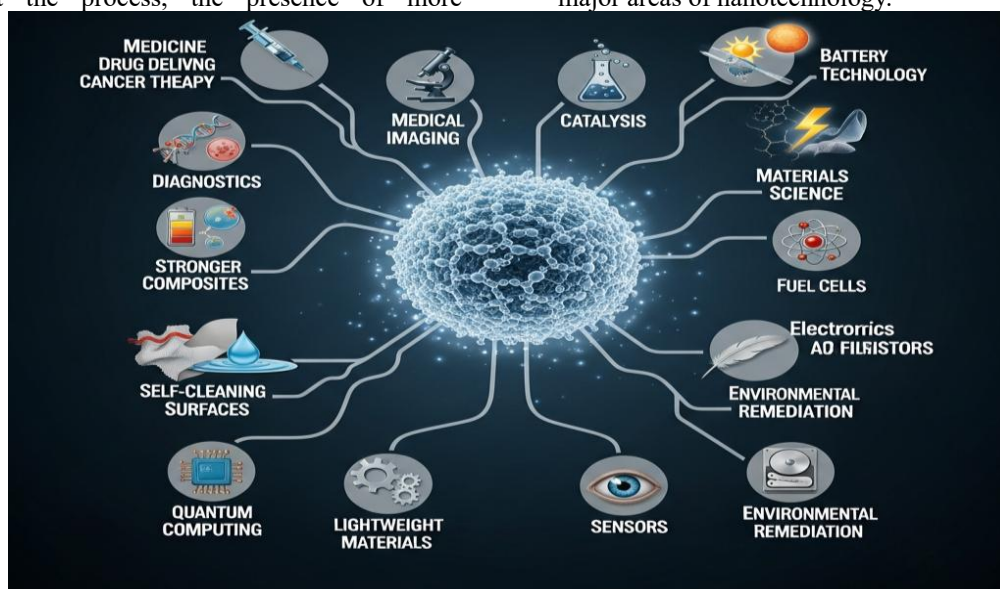


Figure 3. Nanoparticle applications in various nanotechnology fields.

6.1. Catalysis

6.1.1. Dye Degradation

Wastewater and its possible future uses depend on the elimination of water pollutants found in water bodies and other similar toxins. These pollutants affect aquatic life and contribute to water contamination. Because of their large surface area and compact size, NPs can be used as a compound or absorb pollutants. These NPs shorten the time required to eliminate the dye while simultaneously increasing the pace of reaction [59]. Efficiency is always the main technological concern for scientists using photocatalysis in environmental cleanup. The development of better materials is the main factor influencing the increased photocatalytic efficiency. The NPs' ecological cleanup is severely limited, though, because photocatalyst development has outpaced photoreactor design. For many photocatalysts in commercially viable applications, a photoreactor and reactants to come into contact are necessary. The high photocatalytic effectiveness of photoreactors has traditionally been constrained by photonic efficiency, mass transfer constraints, and nanoparticle separation [60]. Because photocatalysis can accomplish comprehensive mineralization and waste removal, it is an environmentally beneficial process. A photocatalyst able to fully decompose the pollutant, be reusable, and be economical to be commercialized. In addition to increasing catalyst efficiency, the restriction of photocatalyst efficiency must be developed [61].

6.1.2. Nitrogen Fixation

Fossil fuels are the cornerstone of the contemporary economy. However, fossil fuels are nonrenewable and release large amounts of CO₂ and other dangerous chemicals into the atmosphere. Since the Industrial Revolution, fossil fuels have exposed humanity to two major problems: environmental harm and energy scarcity. Moreover, nitrogen is necessary for the survival of all life on Earth, including plants and animals. Despite making up atmosphere, N₂ is extremely challenging to employ due to its intrinsic inertness [150]. NH₃, an ideal energy solution to address this challenge, is ammonia produced through photocatalytic or electrocatalytic conversion of atmospheric nitrogen, which emits less CO₂ than fossil-fuel-based processes [62]. The adsorption of N₂ onto the catalyst's surface is usually a prerequisite for an efficient nitrogen reduction reaction progression. Because of their large surface area, nanomaterials as catalysts are essential for the alteration or reduction of N₂ into NH₃.

6.1.3. CH₄ Conversion

Another way to produce clean energy is to convert CH₄ into lower olefins, aromatics, CO, and CO₂. Technologies for efficiently converting CH₄ into

higher-value products, due to the growing demand for these complexes and the current finding of substantial CH₄ reserves and resources. However, due to its strongest C-H bond, CH₄ least reactive alkane [63]. Because of this, C-H bonds are frequently essential at high pressures and temperatures, which raises capital costs considerably and poses operational and environmental concerns. Photocatalysis is a capable technique because it drives CH₄ oxidation using photon energy instead of heat energy.

6.2. Oil Recovery

NPs have enhanced chemical reactivity and a high surface-area-to-volume ratio petroleum sector are interested in using NPs for oil recovery. NPs have been premeditated as possible water flooding additives since the first day of manufacture. Furthermore, NPs have been studied as possible additions for water flooding in later stages. At the laboratory level, NPs were premeditated for enhanced oil recovery (EOR) applications by way of wettability modifiers, emulsion stabilizers, flooding processes, and polymer and surfactant [64] performance enhancers. Among the several types of NPs, silica NPs have drawn the greatest attention in the realm of EOR applications.

6.3. Electronics

With the current surge in demand for screens that are both larger and brighter than previously. Usually, televisions and computer monitors have these displays. The materials used to produce light-emitting diodes in modern screens include nanocrystalline lead telluride, zinc selenide, cadmium sulphide, and sulphide [65]. Due to the proliferation of portable consumer electronics like laptops and cell phones, for batteries that are lightweight and compact while still having a large capacity. When choosing materials to utilize in batteries, NPs are the best choice. Aerogel batteries can store a lot more energy than ordinary batteries outstanding to their foam-like structure. A higher surface area, batteries made of metal hydrides, and nanocrystalline nickel require less charge over time.

6.4. Gas Sensor

In average production and existence, gases that are flammable, explosive, toxic, or otherwise hazardous represent a serious threat to the health and safety of people and the environment. High-performance technology capable of detecting these harmful gases is urgently needed [66]. Gas sensors are essential for identifying gases because they can convert a preset. They are beneficial because they are inexpensive, sensitive, selective, and quick to react. Electronic interfaces can employ gas sensors for extra wire or calibration. Because of this, gas sensors are widely used in many different fields, such as food and cosmetics tracking and medical diagnostics.

The method of developing gas sensors constructed on nanomaterials has been refined during the last few decades. Various gas sensors, including solid electrolytes, semiconductors, polymers, and contact combustion. Semiconductor gas sensors are extensively used, ease of fabrication, and broad gas detection capability [67]. They are classified as resistive or non-resistive, with resistive sensors detecting gases through resistance changes in materials.

6.5. Cosmetics and Sunscreens

When applied over an extended period of time, traditional sunscreen that provides safety from ultraviolet (UV) rays is unstable. TiO₂ and ZnO NPs offer UV protection; some sunscreens use them. Both TiO₂ and ZnO NPs absorb and reflect UV light in addition to being transparent to visible light. Iron oxide NPs as a pigment in some lipsticks [68]. UV radiation is the main cause of various skin diseases, making UV protection essential. Topical sunscreens prepare method to protect against UV exposure. However, traditional sunscreens have limitations that reduce their effectiveness and acceptance. Nanotechnology has significantly contributed to creating new sunscreen formulations aimed at overcoming these issues. These innovations have improved UV protection and cosmetic appeal. This review discusses different nanosystems used in sunscreens, including polymeric NPs, liposomes, nanostructured lipid carriers, solid lipid NPs, nanoemulsions, hydrogels, nanocrystals, mesoporous silica particles, niosomes, ethosomes, transfersomes, transethosomes, and sunspheres. These nanosystems enhance sunscreen safety and effectiveness by improving dispersion, photostability, SPF, UVA protection, and water resistance. Combining multiple active ingredients creates broad-spectrum sunscreens that protect against both UVA and UVB rays. The review also covers evaluation methods such as SPF, UVA protection, and water resistance, with SPF measuring UVB defense, UVA protection indicating UVA defense, and water resistance testing durability after water or sweat exposure. Additionally, safety, regulation, and challenges of nanosystem-based sunscreens are addressed. Challenges include formulation stability, potential toxicity, and limited public awareness. Overall, nanotechnology-enabled sunscreens offer promising enhancements in UV protection. The use of various nanosystems improves both safety and effectiveness. Continued research and regulatory efforts are essential for the development and safe application of these nanosystem sunscreens.

6.6. Medicine and Drug Delivery

The first medicine based on NPs, liposomal doxorubicin, was approved for clinical use in 1995 by

the US FDA to treat cancer. Nanomedicines were first introduced to the market with this event [69]. One way that nanotechnology has helped the medical field is through NPs in medication administration. The drug can be delivered to the intended cellular site using NPs [70]. Both the total drug intake and its side effects are significantly reduced when the medication is administered at the intended site at the necessary dosage. This strategy reduces the expenses and the negative effects. Nanotechnology enables tissue engineering by supporting the replication and restoration of damaged tissues. Tissue engineering may replace more traditional medical treatments like organ transplants and artificial implants [71].

6.7. Diagnosis

NPs are widely used in cancer diagnosis and therapy. These NPs help administer drugs (a therapeutic approach) and/or accurately target tumours with little adverse effects. Nanodevices designed for oncology applications include MRI contrast agents for intraoperative imaging and state-of-the-art nanoparticle-based technologies for highly specific DNA and protein detection [72]. These developments have contributed of NP probes for cellular and molecular imaging, customized NP medications for cancer treatment. These developments of personalized therapy are a promising field of study in which a patient's cancer is identified and treated. The use of in vivo nanodevices is limited by challenges such as biocompatibility, toxicity, targeting efficiency, in vivo kinetics, immune clearance, and cost [73]. The field of nanotechnology needs new advancements. As a result, this field is characterized by its ongoing evolution in light of these limitations. Because of these efforts, nanowires, nanocantilevers, quantum dots, nanoshells, dendrimers, liposomes, nanopyramids, and nanogels have been used in cancer research for either therapeutic or diagnostic purposes [74].

6.8. Food

Over the past 20 years, food nanotechnology has grown rapidly, and nanoscale structures demonstrated special qualities that enhance the antimicrobial, nutritional, and healthful characteristics of food products. Food scientists are specifically modifying frameworks from other disciplines. By improving preservation and packaging, the application of nanotechnology benefits the food business. A nanomaterial coating is put on antimicrobial compounds to the coated film surface when utilized in food packaging [75]. One such example is nanodrops, an ingredient used in the manufacturing of canola oil. Their function is to make it easier for the food's vitamins and minerals to be absorbed.

6.9. Construction

Nanotechnology has made building processes safer, quicker, and less expensive. When nanosilica (SiO_2) is added to regular concrete, the mechanical properties and robustness both improve. Concrete gains strength when hematite (Fe_2O_3) NPs are added [76]. Steel's accessibility and adaptability make it an indispensable building material. Another essential component of building materials is glass. Due to the potential advantages of using nanotechnology, glass for construction is a prominent area of research focus. Because of their castrating and anti-fouling properties as well as their capacity to catalyze a strong chemical reaction that degrades organic pollutants and VOCs, titanium dioxide (TiO_2) NPs are employed to coat glazing [77]. Window coverings with nanotechnology are better at blocking out heat and light from the outside. Self-healing qualities, corrosion resistance, and insulation were attained by adding NPs to paints. These paints are applied to metal pipes to prevent corrosion caused by salt water due to their hydrophobic properties. Incorporating NPs into paints improves their properties and makes them lighter. For instance, when applied to huge objects like aeroplanes, the objects are generally lighter, which benefits both the atmosphere and the business's bottom line.

6.10. Renewable Energy Technologies and Environmental Remediation

Because of their exclusive characteristics, NPs are now widely used for anything from environmental remediation to performance improvement in the renewable energy sector. Other studies [78] on various geometric surfaces with varied boundary constraints and nanomaterial characteristics. Some of the NPs found in nature have been demonstrated to have therapeutic effects on the environment. For almost ten years, NPs referred to as nanoremediation, to treat or sterilize soil, water, and air. The main mechanism involved in decontamination is redox reactions. Organic pollutants, viruses, and heavy metals are probably contaminants. Chemicals must be removed effectively, occasionally produce undesirable reaction byproducts. Oil spills are a major worldwide concern. Conventional cleaning techniques are time-consuming and labor-intensive, which makes the issue worse by raising the possibility of more contamination. Another demonstrated use of this technology is the remediation of oil spills using NPs [79]. The primary use of NPs is in the cleaning of sludge and sewage from municipal and industrial sources. Because they are less expensive, more efficient, and require fewer doses for therapy, NPs are being employed in place of conventional chemicals. The use of nanofiltration, a membrane filtration method for water purification, has considerably helped the nutrition and dairy industries.

Concern over contaminated soil is growing. To eliminate or remediate contaminants like heavy metals or dangerous industrial wastes. Some NPs have been used as nanocatalysts because of their increased surface area, which is advantageous for gaseous reactions. The most popular use is in manufacturing lots, where contaminants are either completely removed or compacted to innocuous stages. There is a lot of research being done on the potential of NPs as a renewable energy source [80].

7. CONCLUSION

Nanotechnology makes everyday objects more effective and functional, which enhances our quality of life. Everyone will have a better future thanks to renewable energy sources and cleaner air and water. Leading organizations, businesses, and institutions are progressively funding research and development in nanotechnology. Many researchers are dedicating their time to the creation of novel nanotechnology applications, which is a cutting-edge scientific field. To enhance the performance and efficiency of the products or processes and lower the cost to increase their availability, this technology is being tested for a range of new applications. Nanotechnology has enormous potential for the future because of its effectiveness and minimal environmental impact.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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