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Review Article

Sustainable Approaches towards Nanomaterial Synthesis: Strategies, Properties, and Process Integration

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Abstract

Nanomaterials (NMs) are a unique class of materials with at least one dimension between 1 and 100 nm, exhibiting exceptional properties distinct from their bulk forms. Their high surface area and tuneable physical, chemical, and magnetic behaviours make them valuable across diverse applications. Phase transitions, such as the emergence of magnetism at the nanoscale, highlight their distinctiveness. This review outlines the historical development of NMs and clarifies key terminology. It covers major synthesis techniques, including top-down and bottom-up approaches, and highlights the unique features that define nanoscale matter. A comprehensive overview of various NMs, such as fullerenes, graphene, carbon nanotubes, MXenes, and core–shell Nanoparticles (NPs) is presented. The chapter concludes with current challenges and future directions in the field of NMs.

Keywords: Nanoscience; Nanomaterials; Nanotubes; Nano sheets; Nanotechnology

Highlight points:

- Overview of sustainable top-down and bottom-up nanomaterial synthesis methods.
- Unique size-dependent properties of nanomaterials are discussed.
- Covers key nanomaterials: fullerenes, graphene, CNTs, MXenes, core–shell NPs.
- Clarifies essential nanoscience terms and historical development.
- Outlines current challenges and future prospects in nanomaterial research.

Introduction

The advent of nanotechnology can be traced back to the visionary lecture by Richard Feynman in 1959, titled "There's Plenty of Room at the Bottom," where he proposed the idea of manipulating matter at the atomic level [1]. However, nanotechnology began to flourish as a formal scientific discipline in the early 1980s with the development of tools like the scanning tunnelling microscope (STM) and atomic force microscope (AFM), enabling visualization and manipulation at the nanoscale. Nanotechnology has developed rapidly over the past few decades due to advances in materials science, biotechnology, and engineering. In energy, medicine, electronics, and environmental remediation, it has led to revolutionary applications. Research indicates that nanotechnology's impact on science and industry will be transformative over the next few decades, as evidenced by recent literature reports [2].

The development of nanotechnology has become an important scientific achievement in the twenty-first century. The field covers a variety of disciplines and deals with synthesis, handling, and application of materials smaller than 100nm in size. As a result, nanoparticles (NPs) can be used in a number of applications, such as biotechnology, biomedical, food, agriculture, and the environment. There are several fields that fit into this category, including wastewater treatment [3], functional food extracts and environmental monitoring [4], and antimicrobials [5]. The fact that nanoparticles are biocompatible, anti-inflammatory, antibacterial, have efficient drug delivery, bioactivity, tumour targeting, enhanced bioavailability, and improved bio absorption means that they are becoming increasingly useful in biotechnology and applied microbiology. Ultrafine particles or NPs describe a particle of matter with a diameter of one to one hundred nanometres (nm). Since they are so small and have such a large surface area, NPs often display unique size-dependent characteristics [6]. When a particle approaches or falls below the de Broglie wavelength or the light wavelength, its characteristic length scale disappears, disrupting the crystalline particle's periodic boundary conditions [7]. As a result, a lot of NPs' unique uses result from their physical properties differing greatly from those of bulk materials [8]. Since the beginning of this century, nanomaterials have become increasingly crucial to human progress. For instance, the only way to lower global warming and climate change is to employ green technology, which relies solely on NMs. The effectiveness of NP-based technology is greater than that of bulk materials [9, 10]. Furthermore, NMs are being used to develop diagnostic, treatment, and prevention techniques for a number of disease epidemics sweeping the globe. For instance, in 2019, NPs were used to identify and treat COVID-19, an illness that was killing a lot of people worldwide. Furthermore, the identification and treatment of the monkeypox pandemic that is currently sweeping worldwide were made possible by the use of NMs [11-13]. It is anticipated that nanotechnology, nanoscience, and NMs will be crucial to global development in the future. Consequently, everyone must possess sufficient information and comprehension of NPs.

Dimension-Based Classification of NMs

NMs are commonly classified based on their dimensionality, which significantly influences their physical, chemical, and functional properties. This dimension-based classification divides

NMs into four categories: zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) structures. In 0D NMs, all three dimensions are confined within the nanoscale (1–100 nm). Examples include quantum dots and NPs, which exhibit quantum confinement effects, resulting in unique optical and electronic properties ideal for imaging, biosensing, and optoelectronics [14].

1D NMs, such as nanorods, nanowires, and nanotubes, have one dimension outside the nanoscale range. The high aspect ratio of their surfaces and the ability to transport electrons make them an attractive material for nanoelectronics, solar cells, and drug delivery. The extraordinary mechanical strength of carbon nanotubes (CNTs) is due to their electrical conductivity as well, making them ideal for flexible electronics as well as composite structural materials [9]. In the case of nanomaterials with two dimensions, such as graphene and molybdenum disulfide (MoS_2), one dimension is only observed at the nanoscale (thickness), whereas larger dimensions are observed at the macroscale (length and width). A significant surface area is present in these materials, and they are electrically conductive and mechanically flexible. In addition to being the perfect electrocatalyst and energy storage material, they are also the perfect sensor material. A three-dimensional nanometer structure is comprised of nanoscale building blocks arranged in a bulk manner within the structure. In this category are nanocomposite materials, dendrimers, and foams with nanostructures. Nanoscale features are present in their internal structure, even though they are not fully contained within the nanoscale. As biomedical implants, environmental remediation materials, and structural materials, they are widely used. In diverse fields throughout various industries, including electronics, medicine, and environmental engineering, dimension-based classification provides guidance in selecting materials for specific applications based on shape and size.. The NMs dimension-based classification is provided in **Figure 1**

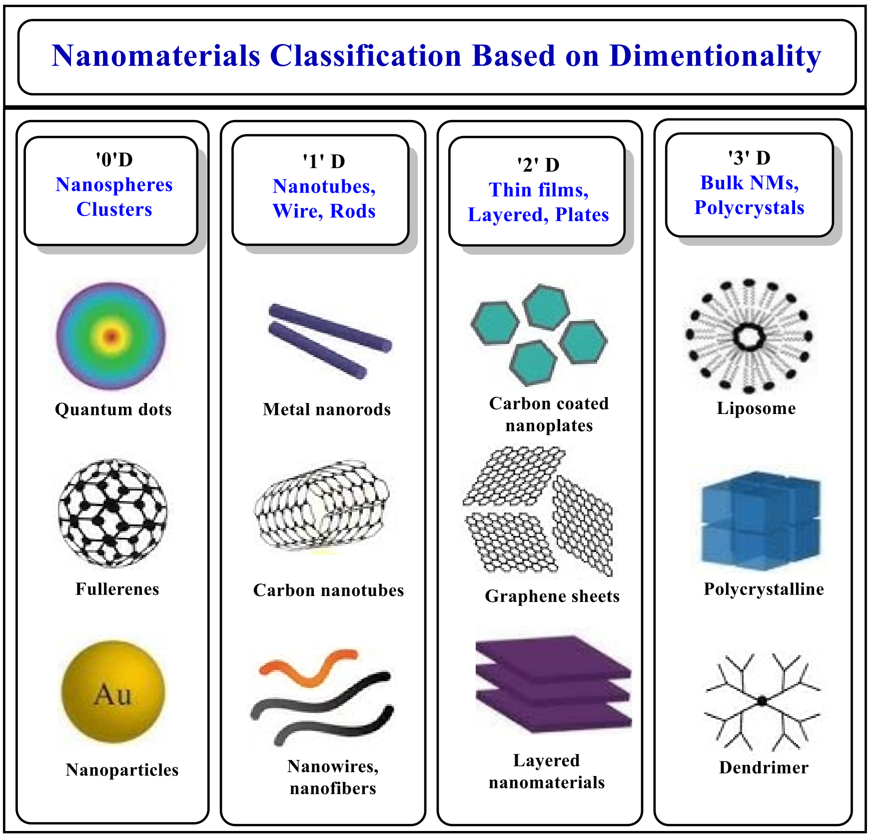

Figure 1. Dimensional classification of the Nanomaterials (NMs) [15].

Over the past two decades, a great deal of research has been conducted on materials and NPs [9]. Numerous recent studies, however, seem to concentrate on the characteristics, methods of preparation, applications, and classification of each NM [16-20]. There is no longer any research outlining the properties, preparation, and classification of NMs that are applicable to all professions. A comprehensive examination of every NM category is necessary to remedy this problem, along with the rationale behind each classification, preparation, and preparation classification has been conducted. These materials are applicable to all classes, qualities, and sectors of application.

Classification of Nanoparticles (NPs)

NPs are generally categorized based on three primary criteria: size, shape, and chemical composition. The remarkable mechanical properties of carbon nanotubes (CNTs) are matched by their electrical conductivity, making them ideal for flexible electronics and structural composites [8, 21]. Nanomaterials with two dimensions, such as graphene and molybdenum disulfide (MoS_2), have only one dimension on the nanoscale (thickness), but two dimensions on the macroscale (length and width). As a result of their large surface area, electrical conductivity, and mechanical flexibility, the materials make excellent electrocatalysts, energy storage devices, and sensors. Bulk nanoscale building blocks arrange themselves in three dimensions to form three-dimensional structures. There are three types of nanomaterials in this category: nanocomposite materials, dendrimers, and foams with nanostructures. Although the nanoscale does not completely contain all nanoscale features, they can be identified in their internal structure. Their many applications include biomedical implants and environmental remediation materials. According to dimension-based classification, dimensions determine the material best suited to specific applications across a range of industries, including electronics, medicine, and environmental engineering [22, 23] **Figure 2**.

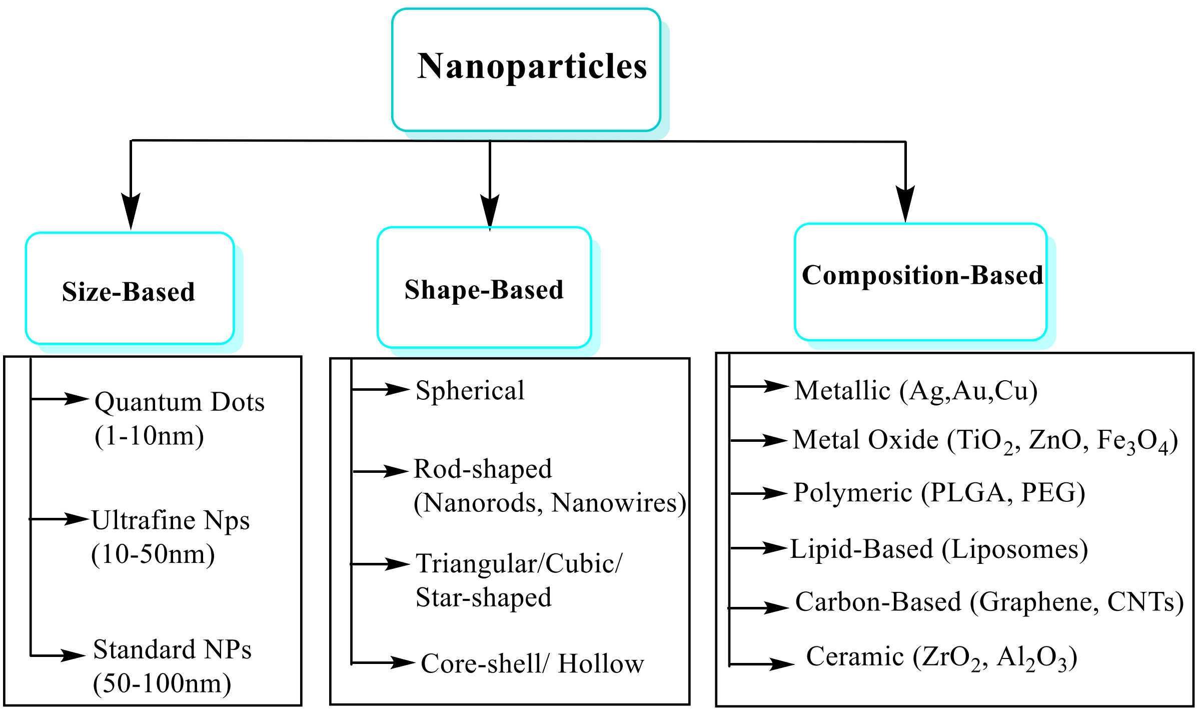

Figure 2. The classification of nanoparticles according to their physical and chemical characteristics.

A comprehensive and integrative review of NMs is provided in this article. As a result, it provides a comprehensive overview of their development, fundamental concepts, synthesis strategies, and unique physicochemical properties. In contrast to previous reviews focused on particular NMs or techniques, this work examines a wide range of NMs-including fullerenes, carbon nanotubes, graphene, MXene, core-shell structures, and emerging 2D materials-highlighting their unique nanoscale properties. There are several features of this review that make it unique, including an extensive classification of synthesis methods, a comparative discussion of recent advances, and the inclusion of underrepresented materials. It provides researchers across the fields of materials science, nanotechnology, and interdisciplinary applications with valuable insights.

Advent of Nanotechnology

A convergence of experimental developments from the 1980s, including the invention of the scanning tunnelling microscope in 1981 and the identification of fullerenes in 1985, led to the development of nanotechnology. In 1986, the book Engines of Creation presented a framework for nanotechnology's goals [24].

NPs in their early stages

During the third millennium BC, Keladi pottery dated between 600 and 300 BC was found to contain carbon nanotubes [25]. It has been discovered that cementite nanowires have been present in Damascus steel from around 900 AD; however, its origin and method of manufacture remain unknown. At the same time, it is unknown how they originated or whether the substance they were contained in was intended to accomplish this.

Discovery of Metal NPs

In the next decade, metal alloy nanoparticles, such as silver-copper (Ag-Cu) and platinum-cobalt (Pt-Co), will be increasingly developed for multifunctional applications across a wide range of scientific fields and industries. In applications like photonic devices, antimicrobial activity, and sensing, these alloyed nanostructures integrate the unique characteristics of different metals. For chemical and biological sensors, they are highly sensitive and selective due to their distinct structural and electrical properties. Alloyed metals exhibit extensive antimicrobial properties resulting from their synergistic interactions, proving effective against resistant bacteria. In the field of photonics, it has been demonstrated that the properties of light can be exploited to facilitate advanced light manipulations that can be applied to various types of imaging and optical communication systems [26, 27]. A significant amount of attention has been focused in the last decade on the enhanced performance of bimetallic nanoparticles, including silver-gold (Ag-Au) and palladium-gold (Pd-Au). Two metal nanoparticles compared to monometallic nanoparticles were more catalytically active and exhibited improved spectrum behaviour. Furthermore, the interaction between the two metals improved the device's electronic properties as well as surface reactivity and stability. These materials have various applications, including chemical catalysis, environmental remediation, and biosensors. In addition, their adjustable optical characteristics, such as surface plasmon resonance, have led to a wide range of imaging and diagnostic applications [28, 29]. As a result of developments in the field of metallic metal oxide nanoparticles, including Fe_3O_4 (magnetite), cobalt (Co), and nickel (Ni), significant advancements have been made. A broad range of biomedical applications can be achieved with nanomaterials due to their magnetic and biocompatible properties. As contrast agents, they improve the clarity and accuracy of magnetic resonance imaging (MRI) images, especially in MRI applications. Their responsiveness to external electromagnetic fields enables their application in targeted drug delivery. The therapeutic agents were then transported precisely to their targets within the body. As a further benefit, their use in electromagnetic hyperthermia provides a promising method for treating cancer by rapidly destroying tumour cells without harming healthy tissues nearby [30, 31]. A single-walled carbon nanotube with a diameter of one nanometre was produced by Iijima and Ichihashi in 1993 after carbon nanotubes were discovered in 1991. An example of NM is carbon nanotubes, also known as Bucky tubes, which contain a hexagonal lattice of carbon atoms in two dimensions. Hollow cylindrical cylinders are created by bending them in one direction and joining them together. Researchers Chen et al. speculate that carbon nanotubes bind between graphene (two-dimensional) and fullerene (zero-dimensional) [32]. In addition, nearly 120 years ago, M. C. Lea reported making citrate-stabilized silver colloids [33, 34]. Using this method, particles with an average diameter of 7 to 9 nm can be created. In line with recent discoveries on the manufacture of nano silver using silver nitrate and citrate, nanoscale size, and citrate stability [35]. Earlier research has also shown that proteins could stabilize nanosilver as early as 1902 [36]. "Collargol" is the name of a commercially produced nanosilver that has been utilized in medicine since 1897. A particular kind of silver NPs called collargol has a particle size of roughly 10 nanometres (nm). The diameter of Collargol is found to be inside the nanoscale range; this was discovered as early as 1907, diameter ranging from 2 to 20 nm. Moudry created gelatin-stabilized silver NPs in 1953, which are a distinct kind of silver NPs. A different technique than Collargol was used to create these NPs. According to a patent, "for optimal efficiency, the silver must be disseminated as particles of colloidal size less than 25 nm in crystallite size," indicates that the inventors of nano-silver formulations understood the need for nanoscale silver decades ago. Originally used to stain and adorn glassware throughout the Roman Empire, gold NPs have a lengthy history in chemistry.

Table 1: Illustrates milestones in the year-wise chronological discovery and application of metal NPs

S. No.	Year	Discovered Metal Nps	Application
1.	2020s	Metal alloy NPs (e.g., Ag-Cu, Pt-Co)	Designed for multifunctional applications: sensors, antimicrobials, and photonics.
2.	2010s	Bimetallic NPs (Ag-Au, Pd-Au, etc.)	Engineered for enhanced catalytic and optical properties.
3.	2000s	Magnetic Metal Oxide NPs (Fe_3O_4, Co, Ni)	Widely developed for MRI, drug delivery, and hyperthermia treatment.
4.	1991	Carbon NPs / Nanotubes - Iijima	Discovery of single-walled carbon nanotubes (SWCNTs) using metal catalysts.
5.	1980s	Platinum (Pt) & Palladium (Pd) NPs	Used in catalysis and hydrogenation reactions; applications in fuel cells.
6.	1971	Citrate-stabilized Ag NPs- M.C. Lea	Synthesized 7–9 nm silver NPs using citrate reduction, a widely referenced method.
7.	1953	Gelatin-stabilized Ag NPs Moudry	Introduced gelatin as a stabilizing agent; developed stable nanoformulations
8.	1907	Size of Collargol Defined	Determined to have a diameter between 2–20 nm, confirming nanoscale size.
9.	1902	Silver NPs with Protein Stabilizers	Use of protein to stabilize silver NPs , precursor to biomedical uses.
10.	1897	Silver (Ag) NPs Collargol	Commercial nanosilver is used as an antimicrobial agent in medicine.
11.	1857	Gold (Au) NPs- Michael Faraday	First scientific study of colloidal gold, observing colour variation due to particle size.

A century ago, Michael Faraday may have been the first person to notice that colloidal gold solutions were different from bulk gold. In 1857, Michael Faraday conducted research on the components and production process of colloidal suspensions of "Ruby" gold. Their unique optical and electrical properties place them among the magnetic NPs. Faraday demonstrated how gold NPs might produce solutions with different hues under particular lighting conditions [37] Table.1.

Categorization of NPs

The following classes of NPs are distinguished by their size, shape, and chemical makeup.

1. NPs based on Carbon

There are two primary kinds of carbon NPs (NPs): fullerenes and carbon nanotubes [38]. In fullerenes, the NPs of spherical hollow cages are similar to the allotropic forms of carbon. The high strength, electrical conductivity, electron affinity, and flexibility of their structure make them attractive to the economy. Each pentagonal and hexagonal shape formed by the carbon units in these materials is sp^2 hybridized. A carbon nanotube (CNT) differs from a carbon fiber in that it is long and consists of tubular structures **Figures 3 & 4**.

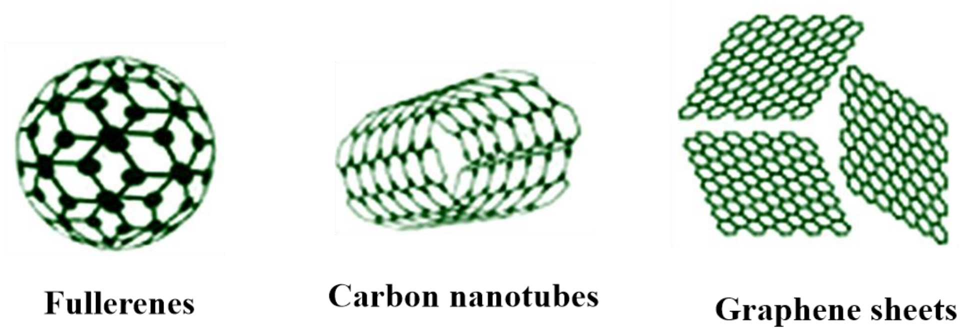

Figure 3. Carbon-based nanomaterial (NM), tube, and sheet.

These essentially have the appearance of graphite (Gr) sheets stacked on top of one another. Therefore, carbon nanotubes are categorized according to their number of concentric graphene layers: single-walled (SWCNTs), double-walled (DWCNTs), or multi-walled (MWCNTs) [39, 40].

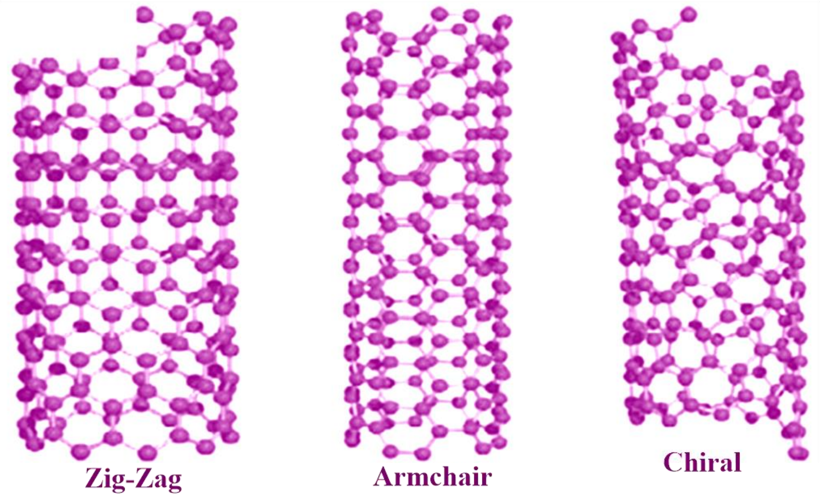

Figure 4. Three Structural Models of SWCNTs.

2. NPs based on Ceramics

The inorganic, non-metallic components that make up ceramic NPs are heat-treated and chilled to give them certain qualities. They have long-lasting qualities and are known to be heat-resistant. They may exhibit various structures, including amorphous, polycrystalline, dense, porous, or hollow forms. Ceramic NPs have applications in coating, catalysts, and batteries, among other areas [41, 42]. Pictorial presentation of NM and clay-based ceramic filters in **Figure 5.**

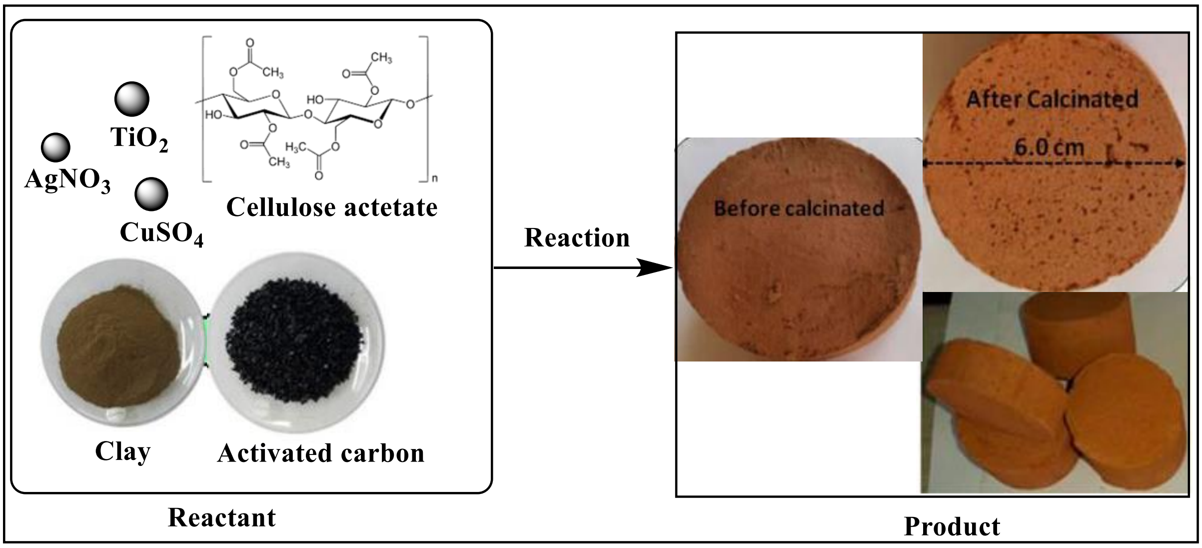

Figure 5. Preparation of NMs and clay-based ceramic filters.

3. NPs based on Lipids.

Their lipid moieties make them useful for a wide range of biological applications. Lipid NPs are spherical and usually have a diameter of 10–1,000 nm. Polymeric NPs, also known as lipid NPs, are composed of soluble lipophilic molecules in a matrix surrounding a solid lipid core. Shapes of lipid-based NMs are given in **Figure 6.**

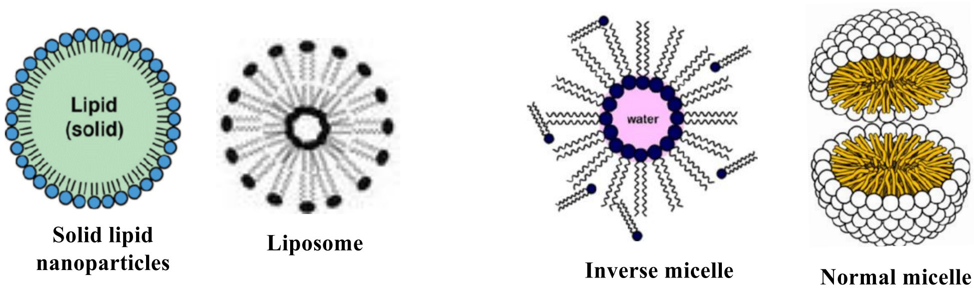

Figure 6. Numerous lipid-based NMs.

4. NPs based on Semiconductors.

Semiconductor NPs share characteristics with both non-metals and metals. Consequently, a variety of applications are made possible by the exceptional chemical and physical properties of semiconductor NPs. In electronics, semiconductor NPs enable the development of high-efficiency transistors, solar cells, and light-emitting diodes (LEDs), offering improved miniaturization and energy performance. They can produce transistors, which are faster and smaller electrical devices that are employed in cancer therapy and bioimaging **Figure 7** [43]. In environmental science, they are widely used for photocatalytic degradation of pollutants, including organic dyes and industrial waste, under sunlight or UV radiation [44, 45]. Additionally, in the biomedical field, they are applied in biosensors, targeted drug delivery, and diagnostic imaging, owing to their excellent surface functionalization and biocompatibility. In addition to their ability to absorb and emit light at certain wavelengths, quantum dots are suited for use in biolabeling and display technologies. Semiconductor NPS generally contribute significantly to the advancement of technology in a number of sectors, such as electronics, healthcare, and the environment [46-48].

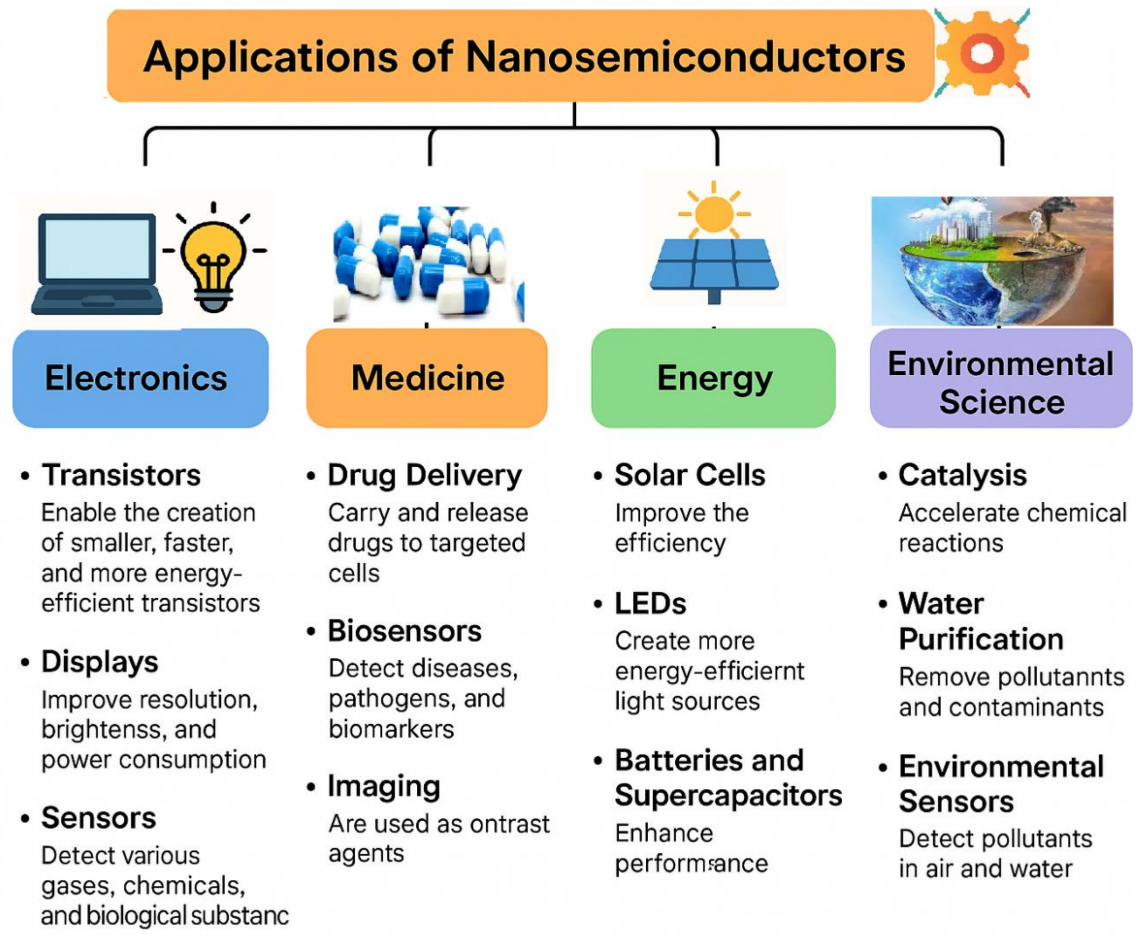

Figure 7. Application of Nano-semiconductor.

5. NPs based on Polymers

Two categories of active ingredients are utilized in polymeric nanoparticles: surface-adsorbed active ingredients, which adhere to the polymeric substrate, and trapped active ingredients, which are encapsulated within the polymeric substrate. The term polymer NPs is frequently employed in the works to refer to these NPs, which are often organic. Most of the time, they resemble NPs or nano-capsules as given in **Figure 8** [49-52].

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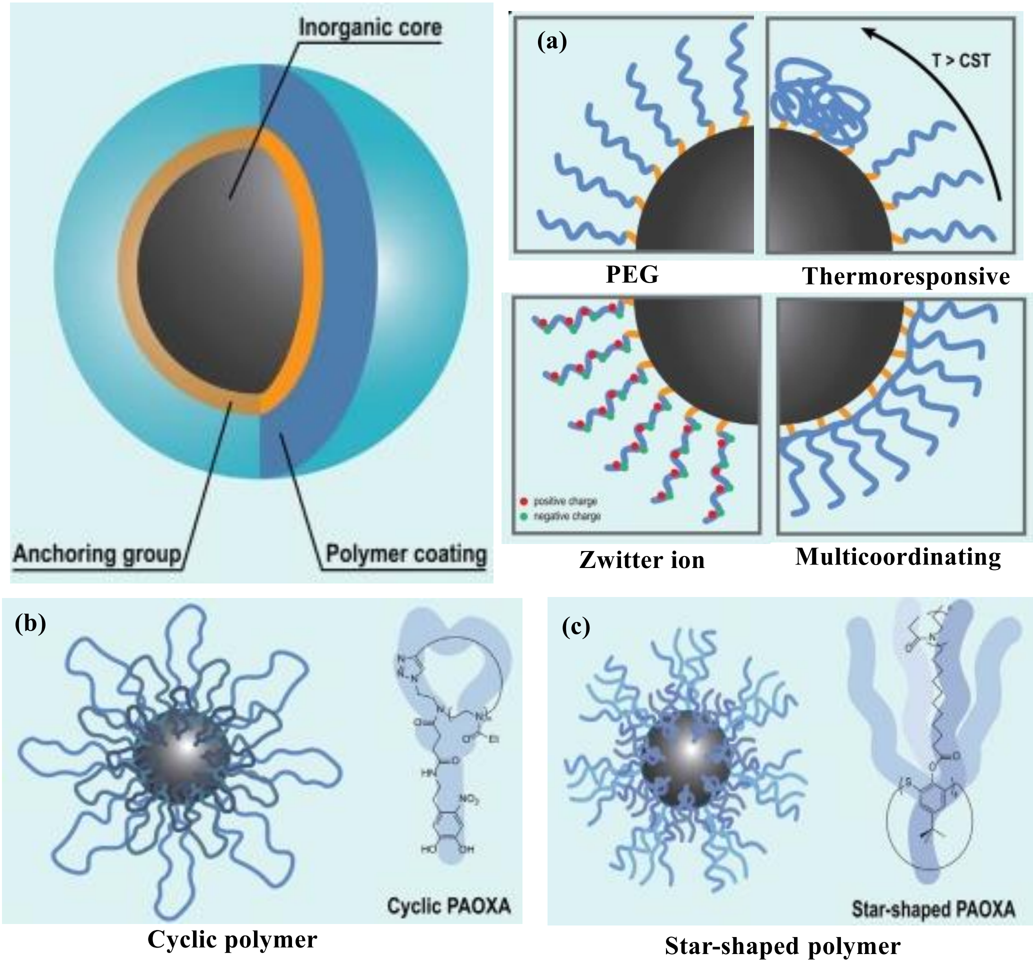

Figure 8. Numerous structure-based Polymer-coated NPs (Reproduced from [53]-CC BY-NC-ND 4.0).

6. NPs based on Metals

Metal NPs are composed only of metal precursors. In addition to their well-known LSPR sensitivity, these NPs have unique optoelectronic properties. In the visible portion of the solar electromagnetic spectrum, alkali and noble metal NPs, such as Cu, Ag, and Au, occupy a wide absorption band. The regulated synthesis of metal NPs by size, shape, and facet is essential for modern advanced materials [54].

NMs Properties

There are several properties of nanomaterials (NMs) that influence their behavior at the nanoscale, beyond surface charge and interaction, crystallography, composition, and surface area. It is well known that atoms, bulk materials, and nanoscale materials have very different characteristics than atoms and bulk materials [55]. The NPs must be meticulously regulated to ensure their proper functioning and purity. Two critical factors influence nanomaterial performance and properties: their surface area and nanoparticle volume ratio. In the field of surface area calculations, the Brunauer-Emmett-Teller (BET) method is the most widely used [56]. There is a strong correlation between nanoparticle chemical composition and purity and utility. Nanoparticle surface charge affects how particles interact with their targets. There are several ways to quantify the surface charge of a substance and the surface stability of a solution. These methods include the Zeta Potential method. Nanoparticles and targets interact because of a charge on their surface (or the overall charge on the nanoparticles).

NMs Physical Properties

Nanomaterials tend to reduce melting points as the particle size decreases. This decrease is resulting from the fact that their surface atoms are not bound to the surface of the particle [57]. Bulk materials increase their surface area when divided into nanoscale materials, but their volume remains the same. Nanoscale materials have higher surface-to-volume ratios than bulk materials. Molecules or atoms on surfaces possess significant surface energy and typically aggregate [58]. This is one of the most well-known physical properties of nanomaterials, which differ significantly from those of their bulk counterparts in a wide range of parameters. There are several factors that contribute to the increased surface-to-volume ratio of these devices, and their quantum size effects are among them. The particle size, shape, composition, and surface chemistry of the particles can be altered to tailor these properties. In Table 2, the key physical properties of NMs are summarized. There is a strong case for their possible application in a wide range of fields, such as electronics, catalysis, biomedical engineering, and environmental remediation.

Table 2: Physical properties of Nanomaterials (NMs) and their characteristic effects at the nanoscale.

S. No.	Property	Description/Effect at Nanoscale	Remarks
1.	Particle Size	1–100 nm	Determines surface-to-volume ratio
2.	Surface Area	Very high (up to 1000 m^2/g)	Enhances reactivity and adsorption
3.	Melting Point	Often lower than bulk material	Due to high surface energy
4.	Electrical Conductivity	Enhanced or tunable (e.g., CNTs, graphene)	Depending on the structure and doping
5.	Magnetic Behavior	Superparamagnetic in magnetic NPs	Observed in Fe_3O_4, Co, Ni NPs
6.	Optical Properties	Size-dependent (quantum confinement)	Color and bandgap shift in quantum dots
7.	Mechanical Strength	High strength-to-weight ratio (e.g., CNTs, graphene)	Useful in composites and coatings

NPs Magnetic Properties

The size of NPs can affect an element's magnetic behavior at the nanoscale. When bulk magnetic materials are nanostructured, the curvature results in hard or soft magnet substance with improved nanoscale properties. The critical grain sizes, the size can enhance coactivity properties of the material and super-paramagnetic behaviour. Materials that are not magnetic in bulk can change to magnetic nanoscale. For instance, in bulk, gold (Au) and platinum (Pt) are not magnetic, but at the nanoscale. As shown in **Figure 9**, magnetic NPs can be used for biomedical applications such as magnetic resonance imaging (MRI), magnetic fluid hyperthermia, and medication delivery [59-62].

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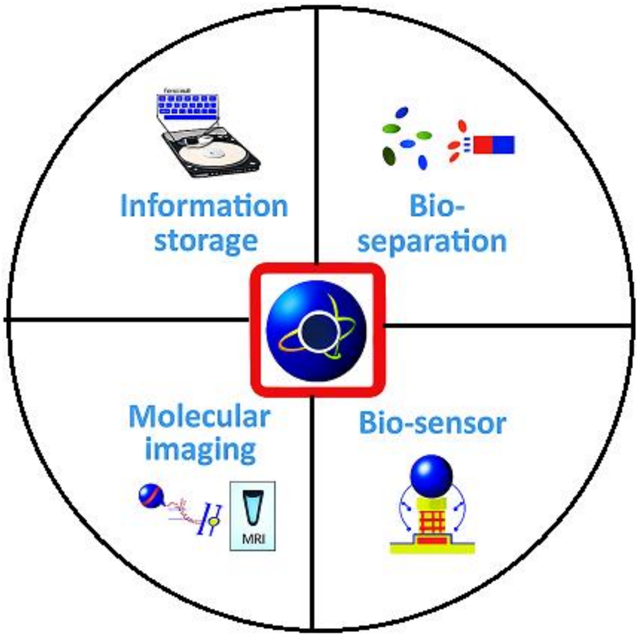

Figure 9. Application of the magnetic NPs.

NMs Optical Characteristics

In NPs, localized surface plasmon resonance (LSPR) is an optical property. The size of the NPs influences the line width. The emission light position of Au NPs migrates from the near-infrared (NIR) region to the ultraviolet (UV) region as their size decreases. NPs can lose their LSPR due to their tiny size and become photoluminescent. The nanoscale dimensions of NMs can be tuned to control visible light emission as a result of quantum confinement. It has been discovered that as the size of the NMs diminishes the peak emission shifts toward shorter wavelengths. Nanoscale color changes occur in matter; for instance, gold (Au) nanospheres can shift from yellow at 100 nm to red at 25 nm, greenish yellow at 50 nm, and orange at 200 nm. In addition, silver (Ag) can also transition from light blue at 90 nm to blue at 40 nm, which is the spherical thin film length [63, 64].

NMs Electrical Properties

The conductivity of ceramics can be increased by NMs, while metals can be made more resistant by NMs. Due to the delocalization of electron conduction in bulk materials, electrons may move freely in any direction. It is the quantum effect that is responsible for electron delocalization on nanorods, nanotubes, and nanowires at the nanoscale. Electron confinement causes conducting materials to have discrete energy states in place of energy bands, which results in both semiconductor and insulator behaviour. This result indicates that the metal is evolving into a semiconductor. Carbon nanotubes can function as conductors or semiconductors based on their nanostructure.

NMs Chemical Properties

The NPs' stability, sensitivity, and reactivity with the target of environmental factors, including heat, moisture, and light, as well as their chemical makeup, dictate the substance's potential uses. Applications are determined in part by the NPs' in flammability, anti-corrosiveness, oxidation and reduction potential. There are significant improvements or novel catalytic properties in NMs over bulk catalysts, including reactivity, selectivity, and catalytic activity [14, 60].

NMs Mechanical Properties

The mechanical characteristics of materials, including their flexibility, elasticity, tensile strength, and ductility, are crucial to their application. impact on a NMs mechanical attributes, including its toughness, elastic modulus, yield strength, and hardness in comparison to bulk materials. As grain size and grain boundary deformation decrease, nanostructured materials' strength and hardness rise. The increase in imperfection and decrease in defect probability are the only factors contributing to the rise in mechanical strength. It enhanced ceramic super plasticity, alloy toughness, and hardness [65, 66].

NMs exhibit exceptional mechanical properties, such as enhanced strength, hardness, elasticity, and wear resistance, due to their high surface area-to-volume ratio, grain refinement, and defect-free crystal structures. At the nanoscale, the mechanical behavior of materials often deviates from their bulk counterparts because dislocation movement, a key mechanism for deformation, is restricted. For instance, carbon nanotubes (CNTs) and graphene possess tensile strengths far exceeding those of steel, making them ideal reinforcements in lightweight, high-strength composites used in aerospace and automotive industries [67]. Similarly, nano-crystalline metals, such as copper and nickel, demonstrate superior hardness and resistance to fatigue, enabling their application in wear-resistant coatings and micro-electromechanical systems (MEMS). Textile industries are also benefited by NMs that are more mechanically resilient. In protective clothing and filtration systems, nanofibers produced via electrospinning are suitable because of their enhanced flexibility, tensile strength, and breathability. Nanomaterials like graphene and nanowires, which are stretchable yet strong, are also used to make flexible electronics and wearable devices. Implants and scaffolds fabricated from NMs need to be mechanically robust in order to be effective in biomedical engineering. Nanostructured titanium alloys, such as those based on titanium, provide excellent strength-to-weight ratios, corrosion resistance, and biocompatibility for orthopedic and dental implants. Hyaluronic acid nanoparticles are incorporated into polymeric scaffolds to mimic bone's physical and biological properties, helping promote osteointegration [68]. In addition, medical devices and surgical tools with nanoscale silver and zinc oxide coatings have improved mechanical durability and antimicrobial protection. MMSs possess the ability to create robust, efficient, and versatile products customized to particular requirements due to their mechanical advantages. Understanding these qualities is essential for optimizing materials for technological and biological purposes.

Structure–Property Relationship in NMs

There is a complex relationship between the size, shape, and structure of nanomaterials, as well as their distinct properties. These factors greatly influence the electromagnetic, optical, electronic, and catalytic properties of these materials. The surface-to-volume ratio of particles is strongly correlated with particle size, resulting in a predominance of surface atoms with high reactivity as particle size increases. It is possible for magnetic nanoparticles, in this case Fe_3O_4, to exhibit superparamagnetic properties below a threshold of 20 nanometers. Due to this phenomenon, magnets can respond rapidly to external electromagnetic fields without retaining any residual magnetism. There are many biomedical applications resulting from this phenomenon, including targeted drug delivery and magnetic resonance imaging (MRI) [69]. As a result of the shape and size of nanoparticles, especially noble metals such as gold and silver, there is a significant effect on their optical properties. There is a phenomenon known as localized surface plasmon resonance (LSPR), which occurs when conduction electrons oscillate in response to incident light being directed at gold nanoparticles (Au NPs). Accordingly, the size and morphology of the nanoparticles have a considerable influence on their absorption peaks. At 520 nm, the LSPR radiates red light as a result of the localized surface plasmon resonance of sphere gold nanoparticles. Alternatively, anisotropic shapes such as rods and stars exhibit a resonance shift that favors the near-infrared region, which facilitates the use of such shapes in photothermal therapy and biosensor applications [70]. In semiconducting quantum dots, quantum confinement effects directly influence the band gap. Smaller dots exhibit larger band gaps and shorter wavelengths of light, facilitating tunable fluorescence applicable in bioimaging and LEDs. The properties of nanomaterials can be affected by structural defects, crystallinity, and surface functionalization, which in turn impact their stability and performance. An effective strategy for nanotechnology design is grounded in comprehending the correlation between nanostructure and its properties. Researchers can customize nanomaterials for targeted applications in medicine, electronics, and environmental remediation by adjusting structural parameters.

NMs Synthetic Routes

NPs can be made using the three techniques outlined below: biological, chemical, and physical. NMs synthesis is a rapidly evolving field, offering various techniques to tailor particle size, morphology, composition, and functionality. Each synthesis method, whether chemical, physical, or biological, has unique advantages and limitations that significantly influence the choice of method depending on the intended application, scalability, cost, and desired material properties.

Biological Synthetic Methods

The biological method is advantageous for the environment and is generally straightforward, requiring only one step. In this sense, we can use various plant components and microbes to make the NMs, such as:

NMs from Microorganisms

Numerous organisms, such as bacteria, fungus, and algae, can create a large number of NPs from an aqueous solution of metal salts as given in **Figure 10**.

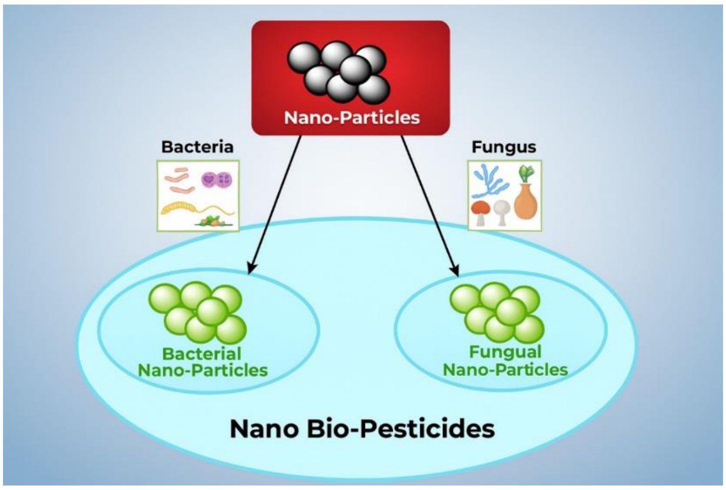

Figure 10. Nano-biopesticides formed from NMs with bacteria and fungi.

NMs from Bacteria

In order to produce NPs, living organisms engage in biomineralization using proteins. Magnetotactic bacteria utilize magnetosomes to synthesize nanosized magnetic iron oxide crystals, functioning as a compass to orient themselves towards their preferred anaerobic habitats at the ocean floor. It has been demonstrated that homogeneous particles with core diameters between 20 and 45 nm can be synthesized in vitro. Magnetosomes, however, contain potent magnetic properties that are valuable in medical applications, such as hyperthermia [71-73].

In a study by He et al., gold NPs of 10-20 nm were synthesized using bacteria that produce photosynthesis, such as *Rhodopseudomonas capsulata*, ex-vivo. The nicotinamide adenine dinucleotide hydride-dependent reductase enzyme plays a key role in reducing gold ions into NPs. They determined that the growth media's pH influences the NPs' shape and form [74]. Schluter et al. reported that extracellular palladium NPs were produced using Pseudomonas bacteria from the alpine location [75].

NMs from Fungus

Fusarium oxysporum was the fungus used to make extracellular Ag NPs. These NPs long-term stability is ascribed to NADH-enzymatic reductase activity. More protein is released by fungal cells than by bacterial cells [76]. Nowadays, *T. reesei* is widely employed in the paper, culinary, pharmaceutical, textile, and animal supply industries. Moreover, it is widely used in agricultural irrigation as depicted in **Figure 11**. Green synthesis techniques utilize plants, bacteria, fungi, or algae to produce NPs in an environmentally friendly and biocompatible manner. These methods are cost-effective and eliminate toxic solvents, making them highly suitable for biomedical and pharmaceutical applications. However, the biological variability, slow reaction rates, and challenges in controlling particle size and shape remain significant drawbacks.

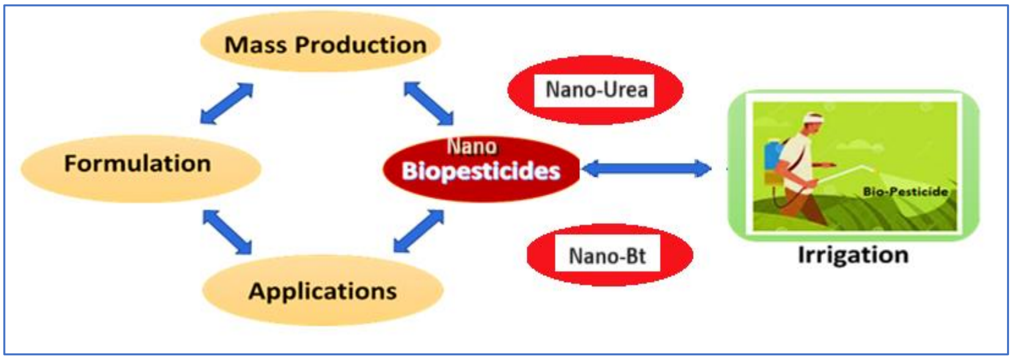

Figure 11. NMs-based bio-pesticides, urea, and *Bacillus thuringiensis* (Bt) used in agriculture.

Chemical Synthetic Methods

In the chemical approach, a variety of techniques are used, such as hydrothermal, sonochemical, coprecipitation, micro-emulsion, electrochemical, and thermal separation. To create magnetic NPs for use in medical imaging applications, a variety of chemical techniques are used, including micro-emulsions, hydrothermal processes, sol-gel synthesis, hydrolysis, flow injection synthesis, precursor thermolysis, and electrospray syntheses [77].

An ideal precursor would have a low cost, low volatility, strong evaporation stability, high chemical purity, and no risks related to chemical vapor deposition in terms of chemical vapor deposition. Moreover, following its breakdown, no contaminants ought to remain [78]. Ni and Co catalysts are used in the chemical vapor deposition procedure to produce multilayer graphene (Gr), while a Cu catalyst produces monolayer graphene. Chemical vapor deposition is a widely used technique that yields high-quality NMs in general and is also well-suited for producing two-dimensional NPs [66, 79]. Novel NMs is routinely synthesized via wet chemical methods such as the sol-gel process. Numerous high-quality metal-oxide-based NMs could be produced using this technique. Other advantages of the low-cost sol-gel technology are its ability to generate complex nanostructures and composites easily, its production of homogenous material, and its low processing temperature [80]. This process produces small, monodispersed nanoparticles, demonstrating the efficacy of the reverse micelle method for

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generating magnetic lipase-immobilized nanoparticles [81]. There has been an increase in interest in microwave-assisted hydrothermal techniques among engineers working with nanomaterials recently, as it integrates both microwaves and thermal methods in achieving successful results [82]. Hydrothermal and solvothermal processes have proven to be effective methods for synthesising a broad range of nanogeometries, including nanorods, nanosheets, nanowires, and nanospheres [83] (Figure 12).

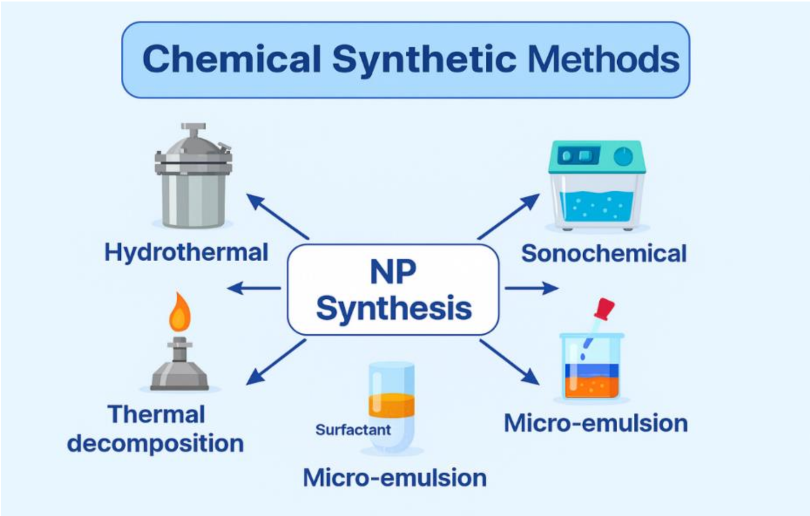

Figure 12. Scheme of Chemical Synthetic Method.

The versatility of these processes and their ability to precisely control the size and composition of nanoparticles make them important for making nanoparticles, such as sol-gel, co-precipitation, hydrothermal, and microencapsulation. The sol-gel method can be used to synthesize metal oxides and hybrid nanostructures, as well as achieve uniform particle distribution, facilitate low-temperature processing, and facilitate straightforward doping with additional elements. Because of the limitations of this method, extended processing times, precursor costs, and solvent contamination should be considered. As an alternative to hydrothermal or solvothermal methods which are associated with high-pressure reactors and present scalability constraints, this method produces high-crystallinity nanostructures at moderate temperatures and pressures. In spite of its simplicity, co-precipitation often leads to a broad distribution of sizes and low crystallinity, which makes it a suitable process for making large quantities of substantial materials at large scales. High-purity.

Physical Methods

The process involves powder ball milling, electron beam lithography, aerosols, laser-induced pyrolysis, gas-phase deposition, and pulsed laser ablation [84, 85]. Through laser ablation synthesis, nanomaterials are synthesized by the generation of nanoparticles [86]. The original material is vaporized by a laser ablation procedure, causing it to disappear. As the following steps follow, a high-intensity laser is used to produce nanoparticles as a result of the production of nanoparticles. In addition to oxide composites, metal nanoparticles, ceramics, and carbon nanoparticles, there are a number of other nanomaterials that can be prepared with this method [87].

There is a process called lithography that involves the focussing of beams of light or electrons to create architectures that are small and precise. It is a technique involving the application of prefabricated masks on a substrate to transfer the pattern of nanoparticles over a large area of the substrate using mask lithography. As an alternative to photolithography and nanoimprint lithography, soft lithography can be used for mask lithography [88]. In terms of cost-effectiveness, mechanical milling is a highly effective method for breaking down larger particles in order to produce products on the nanoscale. Additionally, mechanical milling may also be used as a method for forming nanocomposites by combining different phases through the combination of specific mechanical processes [89].

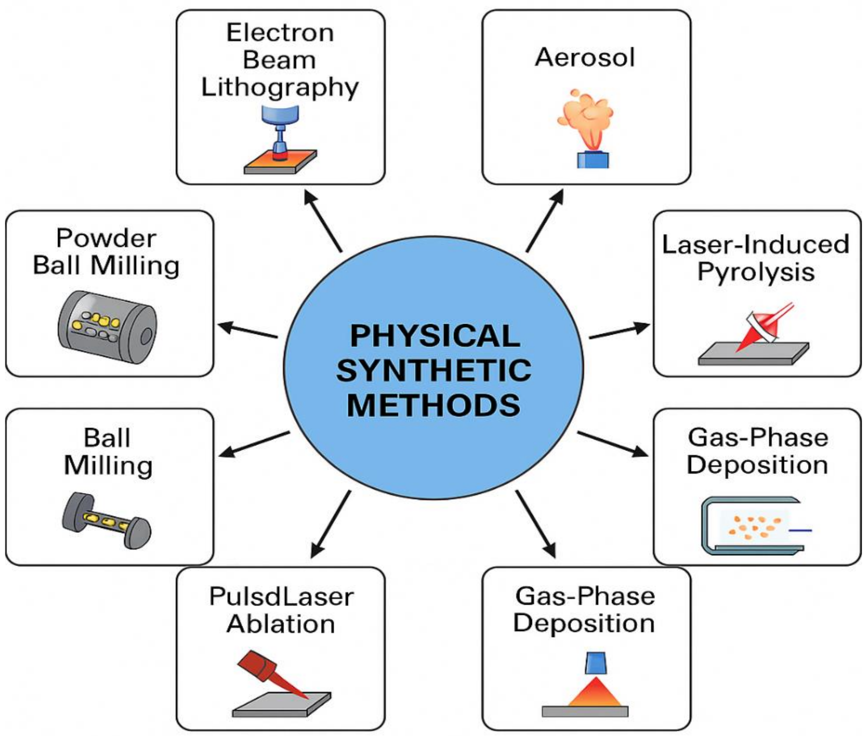

Figure 13. Scheme of Physical Synthetic Method.

The use of ball-milled carbon nanoparticles can be used for a variety of applications, including energy conversion, environmental remediation, and energy storage, among others [90]. The electrospinning process is an inexpensive and straightforward way of producing nanostructured materials. Polymers are the most common type of nanofiber-forming polymer. The method provides a means of producing hollow polymers, inorganic materials, organic compounds, core-shell structures, and hybrid materials, which include hollow polymers, inorganic materials, organic compounds, and hybrid materials. This type of deposition entails the ejection of small atom clusters from a surface by using gaseous ions as ions for bombardment, and it is part of a process called sputtering deposition [91] Figure 13. It has been shown that nanomaterials can be produced without the use of chemical reagents by a variety of techniques, including ball milling, laser ablation, sputtering, and electron beam lithography. As a method of particle size reduction, alloy synthesis, and the synthesis of nanocomposite materials, top-down ball milling is an effective method for particle size reduction. This method of particle size control appears to be both cost-effective and scalable; however, it displays limitations regarding the precision of particle size control, as well as causing structural defects in the final product. When laser ablation is combined with solid targets, highly pure nanoparticles are produced with virtually no contaminants present. In contrast, the high costs of equipment and low yields generally make it an unsuitable technology for large-scale production due to the high equipment costs. The precise control of nanoscale patterning and film deposition in applications related to electronics and photonics depends on techniques such as sputtering and lithography. Despite the high operating costs, complex configuration, and limited throughput, these systems are still limited to a number of specific applications because of their high costs and complexity.

To summarize, there are two general approaches to synthesizing NMs, top-down and bottom-up. There are several advantages and disadvantages to each methodology, along with its set of methodologies. Top-down approaches entail the reduction of bulk materials into nanoscale structures through methods including milling, lithography, or laser ablation. This approach generates a lot of NMs and is scalable, but it has little control over the generation of surface defects, particle size, and shape. The bottom-up method employs chemical techniques, including sol-gel synthesis, chemical vapor deposition (CVD), hydrothermal processing, and biological synthesis, to construct nanostructures at the atomic or molecular level. The capacity to manipulate particle size, shape, and composition through these techniques renders nanomaterials suitable for customization to particular applications. A bottom-up approach typically requires expensive precursors and conditions and can be more complex and time-consuming (Table 3). In sol-gel synthesis, uniform metal oxide nanoparticles are produced beneath mild conditions, whereas in CVD, well-defined structures are produced, making them ideal for thin films and coatings. A growing interest in biological synthesis is due to the fact that it is environmentally friendly and non-toxic, although reproducibility and scalability remain challenges [9]. In the case of bulk production applications, physical methods are preferred, while chemical and biological methods are best suited to high-precision applications in electronics, medicine, and catalysis. The selection of a synthesis technique is contingent upon the intended properties of the final nanomaterial, application specifications, cost factors, and environmental implications.

Table 3: Comparative Analysis of Nanomaterial Synthesis Methods

S. No.	Synthesis Method	Type	Advantages	Limitations
1.	Sol-Gel	Chemical	- Uniform particle distribution - Low processing temperature -Good for oxides and composites	- Long processing time - Risk of contamination from solvents - Costly precursors
2.	Co-precipitation	Chemical	- Simple and low-cost - Scalable - Mild reaction conditions	- Poor control over particle size - Low crystallinity
3.	Hydrothermal/ Solvothermal	Chemical	- High crystallinity - Good morphology control - Suitable for complex structures	- Requires high-pressure autoclaves - Limited scalability
4.	Chemical Vapour Deposition (CVD)	Chemical	- High-purity products - Thin film and 2D material synthesis - Precise control	- Expensive setup - High energy use - Toxic precursors
5.	Ball Milling	Physical	- Inexpensive - Scalable - Suitable for alloy and composite formation	- Broad particle size distribution - Structural defects
6.	Laser Ablation	Physical	- High-purity NPs - No chemical contamination - Applicable to many materials	- Low yield - High equipment cost - Limited scalability
7.	Sputtering	Physical	- Excellent film quality	- Expensive - Low deposition rate

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			- Good compositional fidelity - Reproducible	- Complex instrumentation
8.	Electron Beam Lithography	Physical	- High-resolution patterning - Suitable for electronics - Precise fabrication	- Time-consuming - High-cost - Limited to small areas
9.	Electrospinning	Physical/ Chemical	- Easy nanofiber production - Core-shell and hybrid nanostructures - Low-cost	- Limited to fibrous structures - Sensitive to ambient conditions

The most appropriate research and industrial strategy can be selected only after a thorough evaluation of each method's merits and limitations is completed. The comparative perspective allows informed decision-making in the development of NMs, and it facilitates the progress of innovations that are sustainable and innovative. Sputtering is a preferred method because it is less expensive than electron-beam lithography and has a composition that is more similar to the target material with fewer flaws.

Conclusion

This study has provided a comprehensive introduction to NMs highlighting their classification, synthesis methods, and applications in various industries. Key findings include the distinct size-dependent properties of NMs, which differentiate them from bulk materials in terms of magnetic, electrical, optical, chemical, and mechanical behaviours. These properties arise due to quantum effects, surface interactions, and high surface-to-volume ratios. The review also emphasized the importance of both top-down and bottom-up synthesis techniques, including physical, chemical, and biological methods, each of which offers unique advantages for producing nanostructures tailored to specific applications. A comprehensive classification based on size, shape, and composition is essential to understand nanoparticle behavior and tailor their application in nanotechnology. Integrating recent advances helps in designing next-generation NPs for safer and more efficient use across sectors.

Despite significant advancements in nanomaterial synthesis and characterization, challenges remain in scaling up production, ensuring environmental sustainability, and controlling the toxicity of certain NMs. The need for standardized methods for assessing the environmental and health impacts of NMs is crucial for their widespread adoption. Future research directions should focus on the development of more efficient, cost-effective, and eco-friendly synthesis routes, as well as exploring novel NMs for advanced applications in fields such as energy storage, environmental remediation, and medicine. Continued interdisciplinary collaboration will be essential to overcome current barriers and fully harness the potential of NMs for future innovations.

List of abbreviations:

NMs – Nanomaterials
NPs – Nanoparticles
STM – Scanning Tunnelling Microscope
AFM – Atomic Force Microscope
CNTs – Carbon Nanotubes
MoS_2 – Molybdenum Disulfide
SWCNTs – Single-Walled Carbon Nanotubes
DWCNTs – Double-Walled Carbon Nanotubes
MWCNTs – Multi-Walled Carbon Nanotubes
MRI – Magnetic Resonance Imaging
LSPR – Localized Surface Plasmon Resonance
NIR – Near-Infrared
UV – Ultraviolet
BET – Brunauer–Emmett–Teller (method)
MEMS – Micro-Electromechanical Systems

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