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Review Paper

A Comprehensive Review on Nanoparticles

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ABSTRACT

Nanotechnology refers to the creation and use of materials whose constituents exist at the nanoscale; and by Convention, be up to 100 nm in size. Nanotechnology explores electrical, optical, and magnetic activity as well as structural behavior at the molecular and sub molecular level. It has the potential to revolutionize a series of medical and biotechnology tools and procedures such that they become portable, cheaper, safer, and easier to administer. Nanoparticles are being employed for From medical treatments, using in various branches of industry production - solar and oxide fuel. from batteries for energy storage to wide incorporation into diverse materials of everyday use, such as cosmetics or clothes. optical devices, catalytic, bactericidal, electronic, sensor technology, biological labelling and treatment of some cancers. due to their unique properties, such as antibacterial activity, high resistance to oxidation, and high thermal conductivity. Nanoparticles have attracted considerable attention in recent years. Nanoparticles can be synthesized chemically or biologically. Metallic nanoparticles, which have immense applications in industries, are of different types: namely, Gold, Silver. Alloy, magnetic etc. This study aims to present an overview of nanoparticles, with special reference to their mechanism of biosynthesis and types.

INTRODUCTION

Nanotechnology is the science that prepares nano-size particles ranging from 1 to 100 nm. It uses various synthesis methods and modifies particle structure and size. It's surprising how often we use tiny particles in fields like biology, physics, chemistry, medicine, and materials science today. When particles shrink to the nano-scale, they start to show interesting traits such as their arrangement and shape, which we don't see in larger pieces of the same material. The term 'nanoparticle' comes from the Greek word 'nano,' meaning 'tiny.' As a prefix, it refers to something extremely small, like one billionth of a meter, or 1 nanometer. Nanoparticles have characteristics of both

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dissolved substances and individual particles. Their surface area is 35-45% larger than that of a larger particle or atom. This unique surface area, which is not part of the particle itself, adds to their value and influences their internal properties, such as reactivity, which depends on their size. In summary, the distinctive traits of nanoparticles give them special abilities and explain their increasing interest in areas like energy, healthcare, and food.[1]Choosing the right method for synthesizing nanoparticles (NPs) is crucial, especially when aiming for specific applications. Over time, many techniques have been devised, utilizing both bottom-up and top-down strategies. These methods offer researchers varying levels of control over the desired features of NPs. Generally, NPs are categorized based on their material origin into inorganic and organic types. Inorganic NPs encompass carbon-based particles, metals and their oxides, semiconductors, as well as ceramics. On the other hand, organic NPs derive from polymers or biomolecules. The inherent properties and intended applications of different NP types depend on their original materials and other influencing factors. Key characteristics like size, shape, and surface area are influenced not only by the chosen synthesis method but also by experimental conditions. By adjusting these conditions, one can achieve NPs with specific shapes and sizes. Nanoparticle has been defined in different ways in the literature. According to ASTM 2456-06 Standard Terminology Relating to Nanotechnology it is defined as “a particle with lengths in two or three dimensions greater than 1 nm and smaller than 100 nm and which may or may not exhibit a size-related intensive property.[2]

HISTORY OF NANOTECHNOLGY

Long before the era of nanotechnology, people were unknowingly coming across various nanosized objects and using nano-level processes. In ancient Egypt, dyeing hair in black was common and was for a long time believed to be based on plant products such as henna. However, recent research on hair samples from ancient Egyptian burial sites showed that hair was dyed with paste from lime, lead oxide, and water. In this dyeing process, galenite (lead sulfide, PbS) nanoparticles are formed. The ancient Egyptians were able to make the dyeing paste react with sulfur (part of hair keratin) and produce small PbS nanoparticles which provided even and steady dyeing. Probably the most famous example for the ancient use of nanotechnology is the Lycurgus Cup (fourth century CE). This ancient roman cup possesses unusual optical properties; it changes its color based on the location of the light source. In natural light, the cup is green, but when it is illuminated from within (with a candle), it becomes red. The recent analysis of this cup showed that it contains 50–100 nm Au and Ag nanoparticle, which are responsible for the unusual coloring of the cup through the effects of plasmon excitation of electrons . The ancient use of nanotechnology does not stop here, in fact, there is evidence for the early use of nanotechnology processes in Mesopotamia, Ancient India, and the Maya.[3]

CLASSIFICATION OF NANOPARTICLE

The nanoparticles generally are classified into the organic, inorganic, and carbon-based.

Organic nanoparticles :

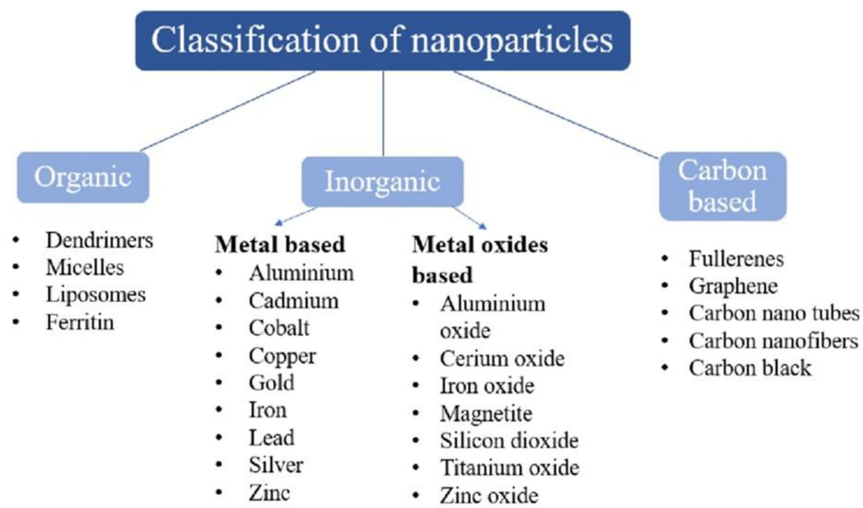
Dendrimers, micelles, liposomes, and ferritin, etc. are commonly known as the organic nanoparticles or polymers. These nanoparticles are bio-degradable, non-toxic, and some particles such as micelles and liposomes has a hollow core also known as nanocapsules and are sensitive to thermal and electromagnetic radiation such as heat and light. These unique characteristics make them an ideal choice for drug delivery. The drug carrying capacity, its stability and delivery systems, either entrapped drug or adsorbed drug system determines their field of applications and their efficiency apart from their normal characteristics such as the size, composition, surface morphology, etc. The organic nanoparticles are most widely used in the biomedical field for example drug delivery system as they are efficient and also can be injected on specific parts of the body that is also known as targeted drug delivery.

Inorganic nanoparticles:

Inorganic nanoparticles are particles that are not made up of carbon. Metal and metal oxide based nanoparticles are generally categorised as inorganic nanoparticles

Metal based:

Nanoparticles that are synthesised from metals to nanometric sizes either by destructive or constructive methods are metal based nanoparticles. Almost all the metals can be synthesised into their nanoparticles. The commonly used metals for nanoparticle synthesis are aluminium (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag) and zinc (Zn). The nanoparticles have distinctive properties such sizes as low as 10 to 100nm, surface characteristics like high surface area to volume ratio, pore size, surface charge and surface charge density, crystalline and amorphous structures, shapes like spherical and cylindrical and colour, reactivity and sensitivity to environmental factors such as air, moisture, heat and sunlight etc.



2.1 Metal oxides based:

The metal oxide based nanoparticles are synthesised to modify the properties of their respective metal based nanoparticles, for example nanoparticles of iron (Fe) instantly oxidises to iron oxide (Fe_2O_3) in the presence of oxygen at room temperature that increases its reactivity compared to iron nanoparticles. Metal oxide nanoparticles are synthesised mainly due to their increased reactivity and efficiency. The commonly synthesised are Aluminium oxide (Al_2O_3).

Carbon based:

The nanoparticles made completely of carbon are knows as carbon based. They can be classified into fullerenes, graphene, carbon nano tubes (CNT), carbon nanofibers and carbon black and sometimes activated carbon in nano size . Carbon based nanoparticles: a – fullerenes, b – graphene, c – carbon nanotubes, d – carbon nanofibers and e – carbon black .

Fullerenes:

Fullerenes (C60) is a carbon molecule that is spherical in shape and made up of carbon atoms held together by sp2 hybridization. About 28 to 1500 carbon atoms forms the spherical structure with diameters up to 8.2 nm for a single layer and 4 to 36 nm for multi-layered fullerenes.

Graphene: Graphene is an allotrope of carbon. Graphene is a hexagonal network of honeycomb lattice made up of carbon atoms in a two dimensional planar surface. Generally the thickness of the graphene sheet is around 1 nm.

Carbon Nano Tubes (CNT): Carbon Nano Tubes (CNT), a graphene nanofoil with a honeycomb lattice of carbon atoms is wound into hollow cylinders to form nanotubes of diameters as low as 0.7 nm for a single layered and 100 nm for multi-layered CNT and length varying from a few micrometres to several millimetres. The ends can either be hollow or closed by a half fullerene molecule.

Carbon Nanofiber:

The same graphene nanofoils are used to produce carbon nanofiber as CNT but wound into a cone or cup shape instead of a regular cylindrical tubes.

Carbon black:

An amorphous material made up of carbon, generally spherical in shape with diameters from 20 to 70 nm. The interaction between the particles are so high that they bound in aggregates and around 500 nm agglomerates are formed.[4]

METHODS OF PREPARATION

Method of preparation of PNPs play essential part in attaining the desired properties. Selection of preparation method is as important as selection of drug and polymer because it chooses the utilization and application of these NPs. They can be appropriately formed either from pre-existed polymers or by direct monomeric polymerization . Method of preparation of PNPs are as follows and illustrated. Pre-existed Polymer Dispersion Method Solvent Evaporation Method Solvent evaporation by dispersion of polymer ensues to be first and common practice for development of PNPs. In this technique, organic solvents such as chloroform, dichloromethane were used but due to toxicity and safety, ethyl acetate is preferably chosen thus, medication is dissolved and dispersed into that solvent. Polymers like PLA, PLGA, PCL etc. were also dissolved in the same solution.at that point, organic stage containing drugs and polymers put on to fluid stage. The organic stage and watery stage are blended with high velocity homogenization and brings about the development of a steady emulsion, which is changed over to nanoparticle suspension. The evaporation of dissolvable and ultracentrifugation happens followed by washing off surfactants with distilled water to get the cemented NPs. Lastly, lyophilization of product finishes the process .[5]

1. Polymerization method:

This process creates nanoparticles in an aqueous solution by polymerizing monomers. The drug is either dissolved in the polymerization medium or by adsorption onto the nanoparticles following the completion of polymerization. After that, the nanoparticle suspension is purified using ultracentrifugation to eliminate the different stabilizers and surfactants used for polymerization. The particles are then resuspended in an isotonic surfactant-free medium. There have been reports of using this method to create polybutylcyanoacrylate or poly (alkylcyanoacrylate) nanoparticles.[6]

2. Coacervation or ionic gelation method:

Biodegradable hydrophilic polymers like sodium alginate, gelatin, and chitosan are used to prepare the nanoparticles. creating an ionic gelation process to create hydrophilic chitosanoparticles. In this process, chitosan's positively charged amino group combines with negatively charged tripolyphosphate to create nanometer-sized coacervates.

[6]Solvent evaporation method: In this approach, the polymer is first dissolved in an organic solvent like dichloromethane, chloroform, or ethyl acetate, which is also the solvent for the hydrophobic drug. The solution of polymer and drug is then emulsified in an aqueous solution that contains a surfactant or emulsifying agent to create an oil-in-water (o/w) emulsion. Once a stable emulsion has been formed, the organic solvent is removed either by reducing the pressure or by continuous stirring. The size of the particles was found to depend on the type and concentrations of the stabilizer, homogenizing speed, and polymer concentration. To get a small particle size, high-speed homogenization or ultrasonication are often used.

3. Spontaneous emulsification or solvent diffusion method **:**

This technique is a modification of the solvent evaporation method. In this case, the water miscible solvent along with a small amount of the water immiscible organic solvent is utilized as the oil phase. The spontaneous diffusion of solvents causes interfacial turbulence to form between the two phases which results in small particles being produced. As the water miscible solvent's concentration increases, the size of the particle can be reduced. Solvent evaporation and solvent diffusion methods are applicable to both hydrophobic and hydrophilic drugs. However, in the case of a hydrophilic drug, a multiple w/o/w emulsion needs to be created with the drug being dissolved in the internal aqueous phase.[6]

TYPES OF NANOPARTICLE:

1. **Silver**: Silver nanoparticles were the first to be and still are the most efficient ones in the long run, owing to their excellent microbial eradication capability against the likes of bacteria, viruses and some eukaryotic micro-organisms. Supposedly, the circle of their application is the widest of all considered nanomaterials, hence the confirmation of their use as antimicrobial agents, in the textile sector, water purification, sunscreen products etc. Among the plantsthat were reported to have been successful in the green synthesis of silver nanoparticles are Azadirachta indica,Capsicum annuum and Caricapapaya.
2. **Gold**: Gold nanoparticles (AuNPs) play a role in immunochemical studies helping in the diagnosis of protein interactions. Their application in DNA fingerprinting as a lab tracer to show the presence of DNA in a sample is another instance. Moreover,they are widely used in the identification of aminoglycoside antibiotics like, streptomycin, gentamycin and neomycin. Gold nanorods have been employed for cancer stem cell detection, which can be useful for cancer diagnosis and for the classification of different groups of bacteria. Alloy: Alloy nanoparticles have distinctive structural traits compared to their bulk counterparts. As Ag ranks first among metal fillers in terms of electrical conductivity and, unlike many other metals, Ag oxides have relatively good conductivity, hence the use of Ag flakes is very common. Besides, their unique properties are such that bimetallic alloy nanoparticles benefit from both metals while showing more advantages over ordinary metallic.
3. **Magnetic**: Magnetic nanoparticles such as Fe3O4 (magnetite) and Fe2O3 (maghemite)are noted for their biocompatibility. They have already been considered promising for targeted cancer treatment (magnetic hyperthermia), stem cell sorting and manipulation, guided drug delivery, gene therapy, DNA analysis, and magnetic resonance imaging (MRI)[7]

SYNTHESIS OF NANOPARTICLE:

A. Top-Down Methods: The top-down, or destructive, approach involves breaking a material down to its atomic building blocks. Structures with a long-range order and linkages at the macroscopic level are strong candidates for top-down techniques. Using this method, large portions of material can be broken down into smaller, nano-sized pieces. While top-down methods are more accessible, they fall short when trying to produce particles with complex shapes or sizes. A major drawback of this method is the challenge it presents in producing particles with the right size and form. Common techniques for synthesizing nanoparticles include mechanical milling, nanolithography, laser ablation, sputtering, and thermal decomposition.

1. Mechanical Milling Method:Mechanical methods are the most cost-effective for mass-producing nanomaterials. Grinding materials with a ball mill is perhaps the easiest method. The term ball milling comes from the balls and the milling chamber that constitute this technique. A ball mill is essentially a stainless steel container with a large number of small iron, hardened steel, silicon carbide, or tungsten carbide balls designed to rotate within it. A powdered substance is placed into the metal jar. By adopting a ball milling process, this powder will be reduced to nanoscale dimensions. Mechanical attrition, in which the kinetic energy of the grinding medium is transferred to the material being reduced, is the mechanism by which nanomaterials are synthesized in a ball mill . Mechanical milling Catalysts 2022, 12, 1386 11 of 27 is the most widely used top-down approach for generating a wide range of nanoparticles. Using this approach, a wide range of NPs and metal alloys can be fabricated. A quantity of the powdered substance is poured into the milling vial, and the friction and interaction between the vial and the balls causes heat and pressure to generate, which may lead to a dramatic phase transition at high temperature. It is utilized to make items such as particle sizes smaller in various materials. The crystallite size, particle size reduction, mechanical dislocation, surface modification, and the likely creation of metastable phases are all profoundly influenced by ball milling powder samples. Certain reactions can be initiated that typically would not occur at room temperature. The drawback of the ball milling technique is that the microstructures obtained (nanostructures/nanoparticles) are very susceptible to the grinding atmosphere and may be accidentally contaminated by the milling media as well as the environment. Milling over a long period is required in order to prepare particles which are smaller (20 nm or smaller). Noise pollution and environmental disruption caused by the ball milling technique is another drawback.

2. Nanolithography Method : Nanolithography, which scientists are presently investigating, is utilized to fabricate structures on the nanometric scale, often with at least one dimension in the 1 to 100 nm range. To create patterns on the nanoscale, nanolithography is an extremely useful and powerful technique. Nanolithography is a multi-step procedure that can be employed to build well-defined 2D metal arrays on surfaces with a finely controlled shape, size, and spacing. Multiple nanolithographic techniques exist, such as optical, electron-beam, multiphoton, nanoimprint, and scanning probe lithography. As a rule, lithography involves printing a desired shape or structure onto a light-sensitive material and then selectively removing a part of the material in order to

obtain the desired shape and structure. The ability of nanolithography to mass produce uniformly sized and shaped nanoparticles is its biggest advantage. Complex apparatus is required, increasing the cost, and there are other costs to take into consideration

3. Laser Ablation Method:Nanoparticles can be synthesised by means of different solvents and laser ablation synthesis in solution (LASiS). Nanoparticles are formed by the condensation of a plasma plume generated upon laser irradiation of a metal immersed in a liquid solution . Nanoparticles (NPs) can be easily synthesised using laser ablation since it is a direct and fast method of producing a wide variety of NPs such as metal, semiconductor, polymer, and NPs of complicated many-element metal and semiconductor alloys. There is no need to use dangerous or explosive chemical precursors, the chemical reaction time is short, and neither high temperatures nor pressures are required. When NPs are synthesized in water, ultrapure colloidal solutions free of reaction by-products are produced. These characteristics of NPs facilitate their biological and biochemical use in living organisms. This top-down approach is a reliable alternative to the traditional chemical reduction of metals in order to synthesize metal-based nanoparticles. Since it allows the stable synthesis of nanoparticles in organic solvents and water without using stabilizing agents or chemicals, LASiS is regarded as a “green” research method. This method has some disadvantages. Long-term laser ablation causes a high concentration of nanoparticles to grow in the colloidal solution, which blocks the path of a laser and absorbs laser energy into the nanoparticles themselves rather than the target surface. Overall, this lowers the rate of ablation
4. Sputtering Method : Sputtering is the process whereby atoms are ejected from the surface of a substance (the target) via the bombardment of energetic particles . When atoms on a cathode/target are accelerated away from the cathode/target by the impact of bombarding ions, which is a momentum transfer process. When atoms are sputtered, they travel until they hit a substrate, where they are deposited and create the desired layer. Nanoparticles can be deposited on a surface via sputtering, which involves the ejection of particles from the surface in response to collisions with ions.When using sputtering, a thin coating of nanoparticles is deposited and then annealed. The nanoparticles’ size and form depend on factors such as the layer thickness, annealing temperature and time, substrate etc. Pure metals and semiconductor elements and alloys and compounds, including oxides, nitrides, sulphides, and carbides, can all be sputtered. The disadvantages of the sputtering method are that the sputtering gas composition (He, Ne, Ar, Kr, and Xe) has an effect on the surface morphology, composition, texture, and optical properties of the nanocrystalline metal oxide coating. Furthermore, compared to thermal evaporation, sputtering rates are modest, and the majority of the energy is transformed into heat when impacted on the target, which must be eliminated.
5. Thermal Decomposition Method :The synthesis of stable monodispersed nanoparticles via thermal breakdown is a novel approach. This synthesis method is also one of the most practical methods for producing monodispersed metal nanoparticles. More importantly, it solves the biggest problem in nanotechnology research: how to precisely regulate the size and form of nanomaterials (a challenge that has been estimated as being worthy at least) . The

synthesis time, temperature, reactant concentrations, stabilizer/capping agent (surfactant) concentrations, and surfactant type are other variables to consider when aiming for a precisely regulated nanometric size. Solvent-free thermal decomposition, as described by Palacious Hernández et al. and Kino et al., is a simple and moderate process that does not require raw materials Similarly, Tran et al. noted that unlike biological methods, thermal breakdown allowed for simultaneous production of a huge number of nanoparticles. Because heat can break chemical bonds, thermal breakdown is endothermic chemical decomposition . The decomposition temperature is the precise heat at which an element undergoes chemical breakdown. Manufacture of nanoparticles involves decomposition of metal at exactly the right temperature, which initiates a chemical reaction resulting in byproducts. There are some limitations to the thermal decomposition technique. A large number of metal compositions and combinations are just difficult to deposit. There are only a few processing variables available for controlling the film properties. The source material could be inadequate .[8]

B. Bottom-up approach: Bottom-up approaches of production of nanomaterials involve the miniaturization of materials constituents to the atomic level with the additional procedure leading to the development of nanostructures. During the further process, the physical forces operating at nanoscale combined simple units into larger stable structures. The methodology is mainly based on the principle of molecular recognition (self-assembly). Self-assembly signifies growing more and more things about one's kind from themselves. Several of these techniques are still in development or are just starting to find application in commercial production of nanoparticles.[9]

Methods in a bottom-up approach:

1. Sol-gel synthesis
2. Colloidal precipitation
3. Hydrothermal synthesis
4. Organometallic chemical route
5. Electrodeposition.

PROPERTIES OF NANOPARTYICLES

In general, the properties of nanoparticles can be grouped into two, namely: chemical and physical.

1. Physical Properties :

The optical properties of a nanoparticle comprise its color; its capability to transmit, absorb, and reflect light; and its capability to absorb and reflect ultraviolet light in solution or after being coated onto a surface are examples of the optical qualities that make up its physical makeup. In addition to this, it covers the mechanical properties of the material, for example, elasticity, ductility, tensile strength, and flexibility, which are vital factors in the use of the material. The hydrophilicity, hydrophobicity, suspension, diffusion, and settling qualities are some of the other properties that have found their way into many commonplace items. Nanoparticles' conductivity, semi conductivity, and resistivity, among other magnetic and electrical properties, have opened the way for their use in thermal conductivity applications in state-of-the-art electronics. These applications are for sustainable energy.

2. Chemical Properties:

The applications of this substance are determined by its chemical properties, which include the reactivity of the nanoparticles with the target, and their stability and sensitivity to elements such as moisture, environment, heat, and light. Nanoparticles are suitable for use in biological and environmental applications due to their antibacterial, antifungal, disinfecting, and toxic characteristics. The flammability, corrosiveness, anticorrosiveness, oxidative potential, and reduction potential of the nanoparticles all play a role in determining their individual applications.[8]

APPLICATIONS OF NANOPARTICLES :

A list of some of the applications of nanomaterials to biology or medicine is given below:

- Bio detection of pathogens
- Detection of proteins
- Probing of DNA structure
- Tissue engineering
- Tumour destruction via heating (hyperthermia)
- Separation and purification of biological molecules and cells
- MRI contrast enhancement

As mentioned above, the fact that nanoparticles exist in the same size domain as proteins makes nanomaterials suitable for bio tagging or labelling. However, size is just one of many characteristics of nanoparticles that itself is rarely sufficient if one is to use nanoparticles as biological tags. In order to interact with biological target, a biological or molecular coating or layer acting as a bioinorganic interface should be attached to the nanoparticle. Examples of biological coatings may include antibodies, biopolymers like collagen or monolayers of small molecules that make the nanoparticles biocompatible . In addition, as optical detection techniques are wide spread in biological research, nanoparticles should either fluoresce or change their optical properties. The approaches used in constructing nano-biomaterials are schematically presented below . Nano-particle usually forms the core of nano-biomaterial. It can be used as a convenient surface for molecular assembly, and may be composed of inorganic or polymeric materials. It can also be in the form of nano-vesicle surrounded by a membrane or a layer. The shape is more often spherical but cylindrical, plate-like and other shapes are possible. The size and size distribution might be important in some cases, for example if penetration through a pore structure of a cellular membrane is required. The size and size distribution are becoming extremely critical when quantum-sized effects are used to control material properties. A tight control of the average particle size and a narrow distribution of sizes allow creating very efficient fluorescent probes that emit narrow light in a very wide range of wavelengths. This helps with creating biomarkers with many and well distinguished colours. The core itself might have several layers and be multifunctional. For example, combining magnetic and luminescent layers one can both detect and manipulate the particles.[10]

CONCLUSION

Nanoparticles have emerged as one of the most transformative innovations in modern science, offering unique physicochemical properties that cannot be achieved by bulk materials. Their small size, high surface area, tunable structure, and remarkable reactivity make them suitable for a wide range of applications in medicine, biotechnology, environmental science, and industry. Over the years, various top-down and bottom-up techniques have been developed to synthesize nanoparticles with precise control over size, shape, and functionality, allowing researchers to tailor them for specific purposes.

The classification of nanoparticles—including organic, inorganic, metal-based, metal oxide, and carbon-based types—highlights the diversity of materials that can be engineered at the nanoscale. Their distinctive physical and chemical behaviors have opened new opportunities in drug delivery, diagnostics, imaging, catalysis, antimicrobial applications, and energy-related fields. At the same time, the ancient use of nanoscale materials reminds us that nanotechnology, though advanced today, has roots deep in human history.

Overall, the study of nanoparticles continues to evolve rapidly. As synthesis methods become safer, greener, and more efficient, the potential of nanoparticles to address global challenges in healthcare, energy, and environmental sustainability becomes even more promising. Continued research in nanoparticle characterization, toxicity, and application will play a crucial role in unlocking their full potential for future scientific and technological advancements.

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