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NANOPARTICLE DELIVERY SYSTEMS: A COMPREHENSIVE REVIEW

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ABSTRACT

Nanoparticles, often considered the building blocks of the nanotechnology revolution, have gained significant attention across multiple scientific disciplines. This comprehensive review aims to provide a succinct yet informative overview of nanoparticles, their synthesis methods, applications, and potential implications. Nanoparticles, typically in the size range of 1 to 100 nanometers, exhibit unique properties due to their size and high surface area-to-volume ratio. The synthesis of nanoparticles encompasses a variety of techniques, including chemical, physical, and biological methods, each offering distinct advantages for tailoring properties and functionalities. This review delves into the key synthesis approaches and highlights their relevance in the context of specific nanoparticle applications. Nanoparticles find widespread use in fields such as medicine, electronics, materials science, and environmental remediation. The versatility of nanoparticles extends to drug delivery, cancer therapy, catalysis, and advanced materials development. We discuss these applications, their current challenges, and future prospects. Furthermore, this review briefly addresses the concerns surrounding nanoparticle toxicity and environmental impact, emphasizing the importance of responsible nanoparticle development and disposal. In summary, this review provides a comprehensive overview of nanoparticles, offering insights into their synthesis, applications, and potential consequences, underscoring the pivotal role they play in shaping the future of science and technology.

KEYWORDS: Application, Metal oxides, Nanoparticle, Nanotechnology.

1. INTRODUCTION

Nanotechnology has gained huge attention over time. The fundamental component of nanotechnology is the nanoparticles. Nanoparticles are particles between 1 and 100 nanometers in size and are made up of carbon, metal, metal oxides or organic matter.[1] The nanoparticles exhibit a unique physical, chemical and biological properties at nanoscale compared to their respective particles at higher scales. This phenomena is due to a relatively larger surface area to the volume, increased reactivity or stability in a chemical process, enhanced mechanical strength, etc.[2] These properties of nanoparticles has led to its use various applications. or two-dimensional materials with at least one spatial dimension in the Nano scale range, such as graphitic carbon nitride[3] (g-C3N4) thin films or Nano sheets and phosphorenes.[4] Whether it is Nano sized grains in dense polycrystals or 3D porous nanostructures, the term three-dimensional means that the 0D, 1D, and 2D components are in compact, contact-forming surfaces.[5,6] Nanoparticles come in a wide variety of sizes, shapes, and compositions. Its sizes range from 1 to 100 nm and its shapes can be described as spherical, cylindrical, tubular, conical, hollow core, spiral, flat, etc. Surfaces can be smooth and homogeneous or uneven and wavy. Some nanoparticles have a crystalline or amorphous structure, with single- or multi-crystal solids that are dispersed or aggregated.[7]

There are a variety of synthesis methods under development or improvement to enhance characteristics and lower manufacturing costs.[8,9] Process-specific nanoparticles are created by adapting several approaches in order to improve their optical, mechanical, physical, and chemical properties.[10] Due to the advancements in technology, scientists are now better able to characterize nanoparticles and find useful applications for them.[11] Today, nanoparticles can be found everywhere from kitchenware to electronics to renewable energy to aerospace. Nanotechnology has the promise of a bright and sustainable future.

Numerous types of nanoparticles such as metal oxide, perovskite, and composite nanoparticle have been synthesized with high efficiency in their properties. Hybrid semiconductor nanoparticles and heterojunction structures are emerging nanomaterials with enhanced photocatalytic properties. The hybrid system was first demonstrated for the colloidal CdSe nanorods with the deposition of Au metal. Using advanced synthetic techniques to control the morphology, size, position, and composition of various components. These HNPs have performed in photo catalytic water splitting via hydrogen generation through clean solar-to-fuel conversion. It plays a vital role in photo catalytic CO_2 reduction. The photo catalytic property of HNPs has important environmental applications such as water purification, waste treatment, and antibacterial activities.[12]

Excessive consumption of personal care products and pharmaceuticals is drastically deteriorating the environment. Novel hetero junction structures are being designed as photo catalysts with high electron-hole segregation rates, low cost, and high redox power such as $Cd_{0.5}Zn_{0.5}$ nanorods/BiOCl microspheres. In this structure, $Cd_{0.5}Zn_{0.5}S$ has excellent photocatalytic potential, strong reducing power, broad solar light response, and abundant resources. However, its photocatalytic performance is undermined due to carrier reunion, weak oxidative activity, and photo corrosion. BiOCl has photocatalytic activities with properties such as eco-friendliness, facile defect engineering, strong physical stability, and unique photo/electric properties. However, it also has the problem of having a large band gap (3.2–3.4) and recombination of photogenerated electron/hole pairs. These problems are solved by the formation of heterojunction structures. The literature has confirmed that $Cd_{0.5}Zn_{0.5}S$ /BiOCl heterojunction shows a 2.8-fold and 9.6-fold increase in photo activity compared to the individual $Cd_{0.5}Zn_{0.5}S$ and BiOCl, respectively.[13]

2. CLASSIFICATION OF NANOPARTICLES

2.1. Organic nanoparticles: Organic nanoparticles Dendrimers, micelles, liposomes and ferritin, etc. are commonly knows the organic nanoparticles or polymers. These nanoparticles are biodegradable, non-toxic, and some particles such as micelles and liposomes has a hollow core (Figure 1), also known as Nano capsules and are sensitive to thermal and electromagnetic radiation such as heat and light.[14] 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 Dendrites, micelles, liposomes and ferritin, etc. are commonly knows the organic nanoparticles or polymers. These nanoparticles are biodegradable, non-toxic, and some particles such as micelles and liposomes has a hollow core (Figure 1), also known as Nano capsules and are sensitive to thermal and electromagnetic radiation such as heat and light.[15] 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.

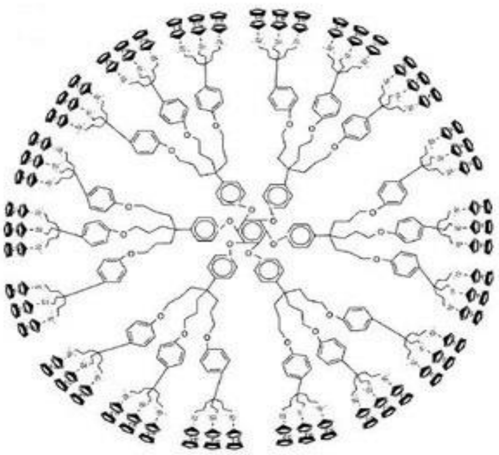

Figure: Organic nanoparticles.

2.2. Inorganic Nanoparticles: Inorganic Nanoparticles that lack carbon atoms are known as inorganic nanoparticles. Inorganic nanoparticles are typically defined as those composed of metals or metal oxides.

2.3. Metal based. Nanoparticles: Metal based. Nanoparticles that are synthesized from metals to Nano metric sizes either by destructive or constructive methods are metal based nanoparticles. Almost all the metals can be synthesized into their nanoparticles.[16] The commonly used metals for nanoparticle synthesis are aluminum (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.

2.4. Metal oxides based: Metal oxides based Nanoparticles The metal oxide based nanoparticles are synthesized to modify the properties of their respective metal based nanoparticles, for example nanoparticles of iron (Fe) instantly oxidises to iron oxide (Fe2O3) 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.[17]

2.5. Carbon-Based Nanoparticles: Carbon has played a pivotal role in the development of human civilization on Earth. When combined with other materials, it creates bonds that are unrivaled in strength. Different methods of synthesis have led to the development of a wide variety of carbon-based nanomaterial during the past few decades. As a result of their unusual shape and varied qualities, they have found application in many multiple sectors. Nanomaterial's based on carbon have several potential uses, including storing and producing energy, treating water and wastewater, and biological applications. There are a number of allotropic shapes that carbon can take. Diamond, graphite, and buckminsterfullerene are all examples of allotropes. Graphite possesses the highest thermodynamic stability among them all. Because of its high conductivity, it can be used in a variety of electronic applications, including batteries, electrodes, solar panels, etc. Graphite is made up of stacked sheets of graphene. Graphene is a new type of carbon that consists of a single layer of atoms arranged in a honeycomb arrangement on a two-dimensional sheet. It is quite useful as a building block in the creation of other forms of carbon nanoparticles[18] due to its high strength. Carbon nanotubes are another novel form of carbon (CNTs). Although CNTs, fullerenes, and graphene are all synthesized in different ways, their physical properties and chemical properties are connected. The development of derivatives and composites based on fullerenes is the most far-fetched because they are the oldest known. Despite this, CNTs and graphene have vast potential for further study and show promise as viable alternatives in a wide range of fields.

2.1.1. 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.

2.1.2. 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.

2.1.3. 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.

2.1.4. 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.

2.1.5. 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 is so high that they bound in aggregates and around 500 nm agglomerates are formed.

3. SYNTHESIS OF NANOPARTICLES

3.1. Bottom-Up Method: The bottom-up, or self-assembly, method of nanofabrication involves the utilization of chemical or physical forces acting at the nanoscale to combine building blocks into functional structures. In bottom-up synthesis, materials are synthesized from the atomic to the cluster to the nanoparticle level. Biological systems are the inspiration for bottom-up techniques since they use chemical forces to build everything necessary for existence. Scientists aim to mimic nature by creating atomic clusters that can self-assemble into increasingly complex shapes. Sol–gel, spinning, chemical vapor deposition (CVD), pyrolysis, and biosynthesis are the bottom-up processes that are utilized most frequently in the fabrication of nanoparticles.

3.1.1 Sol–Gel Method

The sol–gel technique is a highly adaptable soft chemical process that is extensively utilized in the synthesis of metal oxides, ceramics, and glasses. Ultrafine or spherical powders, thin film coatings, ceramic fibers, and microporous inorganic membranes are only some of the additional ceramics and glasses that may be available commercially.[19] Primitives for the sol–gel process typically include metal alkoxides or organometallic inorganic salts. This process involves a chain reaction of hydrolysis and polycondensation that results in a colloidal suspension or a sol from the precursor. The molecules in a system go from a homogenous liquid (or “sol”) to a solid (or “gel”) state during the sol–gel process, which occurs at room temperature and pressure.[20] After preparing the gel, the nanopowder of metal oxide is obtained by drying and calcining the gel at various temperatures. The shape, morphology, and textural qualities of the resulting materials can be adjusted with the sol–gel process. The sol–gel approach offers many.

3.1.2 Spinning. The synthesis of nanoparticles by spinning is carried out by a spinning disc reactor (SDR). It contains a rotating disc inside a chamber/reactor where the physical parameters such as temperature can be controlled. The reactor is generally filled with nitrogen or other inert gases to remove oxygen inside and avoid chemical reactions.[21] The disc is rotated at different speed where the liquid i.e. precursor and water is pumped in. The spinning causes the atoms or molecules to fuse together and is precipitated, collected and dried.[22] The various operating parameters such as the liquid flow rate, disc rotation speed, liquid/precursor ratio, location of feed, disc surface, etc. determines the characteristics nanoparticles synthesised from SDR.

3.1.3. Chemical Vapour Deposition (CVD): Chemical vapour deposition is the deposition of a thin film of gaseous reactants onto a substrate. The deposition is carried out in a reaction chamber at ambient temperature by combining gas molecules. A chemical reaction occurs when a heated substrate comes in contact with the combined gas.[23] This reaction produces a thin film of product on the substrate surface that is recovered and used. Substrate temperature is the influencing factor in CVD. The advantages of CVD are highly pure, uniform, hard and strong nanoparticles. The disadvantages of CVD are the requirement of special equipment and the gaseous by-products are highly toxic.

3.1.4. Pyrolysis: Pyrolysis is the most commonly used process in industries for largescale production of nanoparticle. It involves burning a precursor with flame. The precursor is either liquid or vapour that is fed into the furnace at high pressure through a small hole where it burn.[24] The combustion or by-product gases is then air classified to recover the nanoparticles.

3.1.5. Biosynthesis: Biosynthesis is a green and environmental friendly approach for the synthesis of nanoparticles that are nontoxic and biodegradable.[25] Biosynthesis uses bacteria, plant extracts, fungi, etc. along with the precursors to produce nanoparticle instead of convention chemicals for bioreduction and capping purposes. The biosynthesised nanoparticles has unique and enhanced properties that finds its way in biomedical applications.[26]

3.2. Top-down method: Top-down or destructive method is the reduction of a bulk material to nanometric scale particles. Mechanical milling, nanolithography, laser ablation, sputtering and thermal decomposition are some of the most widely used nanoparticle synthesis methods.

3.2.1. Mechanical milling: Among the various top-down methods, mechanical milling is the most extensively used to produce various nanoparticles. The mechanical milling is used for milling and post annealing of nanoparticles during synthesis where different elements are milled in an inert atmosphere.[27] The influencing factors in mechanical milling is plastic deformation that leads to particle shape, fracture leads to decrease in particle size and cold-welding leads to increase in particle size.

3.2.2. Nanolithography: Nanolithography is the study of fabricating nanometric scale structures with a minimum of one dimension in the size range of 1 to 100 nm. There are various nanolithography processes for instance optical, electron-beam, multiphoton, nanoimprint and scanning probe lithography.[28] Generally lithography is the process of printing a required shape or structure on a light sensitive material that selectively removes a portion of material to create the desired shape and structure. The main advantages of nanolithography are to produce from a single nanoparticle to a cluster with desired shape and size. The disadvantages are the requirement of complex equipment and the cost associated.[29]

3.2.3. Laser ablation. Laser Ablation Synthesis in Solution (LASiS) is a common method for nanoparticle production from various solvents. The irradiation of a metal submerged in a liquid solution by a laser beam condenses a plasma plume that produces nanoparticles.[30] It is a reliable top-down method that provides an alternative solution to conventional chemical reduction of metals to synthesis metal based nanoparticles. As LASiS provides a stable synthesis of nanoparticles in organic solvents and water that does not require any stabilising agent or chemicals it is a 'green' process.

3.2.4. Sputtering: Sputtering is the deposition of nanoparticles on a surface by ejecting particles from it by colliding with ions.[31] Sputtering is usually a deposition of thin layer of nanoparticles followed by annealing. The thickness of the layer, temperature and duration of annealing, substrate type, etc. determines the shape and size of the nanoparticles.[32]

3.2.5. Thermal decomposition: Thermal decomposition is an endothermic chemical decomposition produced by heat that breaks the chemical bonds in the compound.[33] The specific temperature at which an element chemically decomposes is the decomposition temperature. The nanoparticles are produced by decomposing the metal at specific temperatures undergoing a chemical reaction producing secondary products. Table 1 lists some of the nanoparticles synthesized from these methods.

4. APPLICATIONS OF NANOPARTICLES

Below are some of the significant applications of nanoparticles.

4.1. Cosmetics and Sunscreens: The conventional ultraviolet (UV) protection sunscreen lacks long-term stability during usage. The sunscreen including nanoparticles such as titanium dioxide provides numerous advantages. The UV protection property of titanium oxide and zinc oxide nanoparticles as they are transparent to visible light as well as absorb and reflect UV rays found their way to be used in some sunscreens. Some lipsticks use iron oxide nanoparticles as a pigment.[34]

4.2. Electronics: The higher necessity for large size and high brightness displays in recent days that are used in the computer monitors and television is encouraging the use of nanoparticles in the display technology. For example nanocrystalline lead telluride, cadmium sulphide, zinc selenide and sulphide, are used in the light emitting diodes (LED) of modern displays.[35] The development in portable consumer electronics such as mobile phones and laptop computers led to the enormous demand for compact, lightweight and high capacity batteries. Nanoparticles are the ideal choice for separator plates in batteries. A considerable more energy can be stored compared to traditional batteries due to their foam like (aerogel) structure. Batteries made from nanocrystalline nickel and metal hydrides, due to their large surface area require less recharging and last longer.[36] The increase in electrical conductivity of nanoparticles is used to detect gases like NO2 and NH3.[37] This is due to increase in the pores of nanoparticles due to charge transfer from nanoparticles to NO2 as the gas molecules bind them together making them better gas sensors.

4.3. Catalysis Nanoparticles: contain high surface area that offers higher catalytic activity. Due to their extremely large surface to volume ratio the nanoparticles function as efficient catalyst in the production of chemicals.[38] One of the important applications is the use of platinum nanoparticles in the automotive catalytic converters as they reduce the amount of platinum required due to very high surface area of the nanoparticles thus reducing the cost significantly and improving performance. Some chemical reactions for example, reduction of nickel oxide to metal nickel (Ni) is performed using nanoparticles.

4.4. Medicine Nanotechnology: has improved the medical field by use of nanoparticles in drug delivery. The drug can be delivered to specific cells using nanoparticles.[39] The total drug consumption and side effects are significantly lowered by placing the drug in the required area in required dosage. This method reduces the cost and side effects. The reproduction and repair of damaged tissue (Tissue engineering) can be carried out with the help nanotechnology. The traditional treatments such as artificial implants and organ transplants can be replaced by tissue engineering. One such example is the growth of bones carbon nanotube scaffolds.[40] The use of gold in medicine is not new. In Ayurveda an Indian medical system, gold is used in several practices. One common prescription is the use of gold for memory enhancement. To enhance the mental fitness of a baby gold is included in certain medical preparations.[41]

4.5. Food: The improvement in production, processing, protection and packaging of food is achieved by incorporating nanotechnology. For example a nanocomposite coating in a food packaging process can directly introduce the anti-microbial substances on the coated film surface. One of the example is the canola oil production industry includes nanodrops, an additive designed to transfer the vitamins and minerals in the food.[42]

4.6. Construction Nanotechnology: improved the construction processes by making them quicker, inexpensive and safer. For example when nanosilica (SiO2) is mixed with the normal concrete, the nanoparticles can improve its mechanical properties, and also improvements in durability. The addition of hematite (Fe2O3) nanoparticles increases the strength of the concrete. Steel is the most widely available and used material in the construction industry. The properties of steel can be improved by using nanotechnology in steel for example in bridge construction the use of nano size steel offers stronger steel cables.[43] The other important construction material is glass. Extensive research is being performed on the application of nanotechnology in construction glass. Since titanium dioxide (TiO2) nanoparticles has sterilizing and anti-fouling properties and catalyse powerful chemical reaction that breakdown volatile organic compound (VOV) and organic pollutants it is used to coat glazing.[44] The use of nanotechnology provides a better blocking of light and heat penetrating through the windows. The paints with self-healing abilities and corrosion resistance and insulation are obtained by adding nanoparticles to the paints. The hydrophobic property of these paints repels water and hence can be used to coat metal pipes to offer protection from salt water attack. The addition of nanoparticles in paints also improves its performance by making them lighter with enhanced properties[45] so when used for example on aircraft, it might reduce their overall weight and the amount of paint required, which is favorable to the environment as well the company to improve cost savings.

4.7. Renewable energy and environmental remediation: The unique physical and chemical properties of nanoparticles have made them an ideal choice to be used nowadays in environmental remediation to enhancing the performance in renewable energy sector.[46] Nanoparticles occur in nature themselves and some of them are found to cure the environment. Environmental remediation using nanoparticles or Nano remediation is successfully being used to treat or decontaminate the air, water and soil for over a decade.[47] Nano remediation is one of the effective solutions as it offers in situ treatment eliminating the necessity of pumping the ground water out for treatment and the need for excavation to reach the target destination. The nanoparticles are injected into the desired location and get carried along the groundwater flow and decontaminate the water by immobilizing the contaminants. The general mechanism involving in decontamination is the redox reactions. The nanoparticles are used to treat the surface water by disinfection, purification and desalination. Some of the contaminants are most likely to be heavy metals, pathogens and organic contaminants. It has proven to be efficient and eliminating the need for chemicals that may sometime produce secondary reaction products. Oil spill is one of the major problems worldwide as it may spread over very long distances. Cleaning them by conventional methods is difficult and time consuming that makes the situation worse as it may spread more. The nanoparticles are also used to clean-up oil spills and has also established to be effective method. The major use of nanoparticles is to treat municipal and industrial wastewater as well as the sludge produced. The replacement of nanoparticles for conventional chemicals is due to less cost, higher efficiency and lower quantity required for treatment. Nano filtration is a recent membrane filtration system for water purification widely used in food and dairy industries. Soil contamination is also an increasing concern. Contaminated soil is cleaned or treated using nanoparticles by injecting the nanoparticles into specific target locations for heavy metal contamination, toxic industrial waste, etc. The higher surface area of certain nanoparticles has been used as a Nano catalyst in gaseous reactions. The most widely used area is in industrial stacks to reduce the contaminant level to prescribed limits or to remove completely that reduces the air pollution. Extensive research is being carried out in the use of nanoparticles for renewable energy. Higher light and UV absorption with a very low reflection coatings in solar cells has improved their efficiency by considerable extent. The hydrophobic property of some nanoparticles has led to self-cleaning solar cells. High thermal conductivity and heat absorption capacity of certain nanoparticles are used to coat boilers and solar concentrators to improve their thermal efficiency.[48,49]

CONCLUSION

In conclusion, this review has provided a comprehensive overview of nanoparticles, spanning their introduction, classification, synthesis methods, and wide-ranging applications. As we look to the future, it is clear that nanoparticles will continue to drive innovation and shape the landscape of science and technology. Researchers and industries alike must stay attuned to the evolving possibilities that nanoparticles offer, ensuring their responsible use and ethical implementation as they play an increasingly pivotal role in addressing some of our world's most pressing challenges.

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