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A REVIEW OF NANOPARTICLE TECHNOLOGY: PHYSICOCHEMICAL PROPERTIES, PREPARATION TECHNIQUES, USES, AND DIFFICULTIES

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ABSTRACT

Nanoparticles (NPs) have emerged as attractive instruments in modern research due to their distinct physicochemical properties and enhanced performance compared to bulk materials. Traditional synthesis techniques often rely on chemical substance that may cause ecological damage as well as safety problems. Green synthesis processes have attracted tremendous interest as eco-friendly and sustainable alternatives for nanoparticle formation. These biological technologies harness natural resources such as plants extract, bacteria, fungi, algae, actinomycetes, and yeast, delivering advantages like biocompatibility, cost-effectiveness, and less environmental impact. Green-synthesized nanoparticles have demonstrated tremendous potential in pharmaceutical and biomedical applications, particularly in antibacterial therapy, drug transport, and diagnostic systems. This study emphasizes the classification, synthesis methods, physicochemical features, characterisation techniques, and biological uses of nanoparticles, along with present difficulties and future opportunities in bionanotechnology.

KEYWORDS: Green synthesis; Nanoparticles; Nanotechnology; Biological synthesis; Drug delivery; Antimicrobial nanotechnology; Bionanotechnology.

INTRODUCTION

Nanotechnology is the major scientific advances of the twenty-first century, emphasizing on the production, manipulation, and application of Nano scale materials (below 100 nm) materials with diameters fewer than 100 nanometers from chemistry, biology, physics, and engineering to design materials with higher physicochemical and functional qualities. Nanoparticles have gotten a lot of attention because of their many applications like environmental science, biotechnology, and particularly pharmaceutical research (Zahra *et al.*, 2020; Rassaei *et al.*, 2011). Their unique characteristics, including improved biocompatibility, antibacterial and anti-inflammatory potential, enhanced drug delivery efficiency, increased bioavailability, and targeted therapeutic action, have significantly expanded their role in modern Nano medicine and applied microbiology (Sun *et al.*, 2014; Yuan *et al.*, 2018).

A nanoparticle is commonly characterized as an ultrafine particle with a size around 1– 100 nm. At this Nano scale, materials exhibit exceptional size-dependent features that differ from bulk equivalents because of their high surface-to-volume ratio and altered physicochemical behavior. When particle diameters approach fundamental physical wavelengths, typical crystalline boundary conditions shift, leading to distinctive optical, electrical, and mechanical features (Guo *et al*., 2013). These properties enable nanoparticles to function as efficient carriers in drug delivery systems, antibacterial formulations, and diagnostic applications (Hasan, 2015).

Emergence of Nanotechnology

The rapid development of nanotechnology started throughout the 1980s following important scientific achievements such as the introduction of better microscopy techniques and the to identify of promising carbon nanostructures. These innovations enabled researchers to observe and operate resources at the submicroscopic level, setting the groundwork for modern nanoscale science and engineering (Bayda *et al*., 2019). Although nanotechnology is considered a recent discipline, historical evidence reveals that nanostructured materials existed long before formal scientific recognition. Carbon-based nanostructures have been detected in ancient pottery excavated at Keeladi, India, highlighting the early occurrence of nanoscale materials in historical artifacts (Bayda *et al*., 2019; Kokarneswaran *et al*., 2020).

Discovery of Carbon, Silver, Zinc, Copper, and Gold Nanoparticles

Carbon-based nanomaterials garnered substantial attention after the observation of carbon nanotubes and similar nanostructures, which offer excellent electrical, mechanical, and thermal capabilities. Structurally, carbon nanotubes consist of cylindrical configurations of graphene layers and form an important class of nanomaterials bridging fullerenes and graphene structures (Chen *et al*., 2021).

Silver nanoparticles have a long history of medical application. Early colloidal silver preparations were established more than a century ago, and later investigations revealed the stability of nano silver utilizing biological components. Their significant antibacterial activity has resulted in extensive inquiry for pharmacological and biological applications (Nowack *et al*., 2011; Beyene *et al*., 2017).

Gold nanoparticles also have a rich scientific history, with early studies revealing that nanoscale gold exhibits optical characteristics apart from the bulk substance.. Their high biocompatibility and surface functionalization Their capacity makes them enticing prospects for drug administration, imaging, and therapeutic applications (Bayda *et al*., 2019; Giljohann *et al*., 2020).

Categorization of Nanoparticles

NPs can be generally grouped based on their composition, shape, and physicochemical qualities into several primary categories.

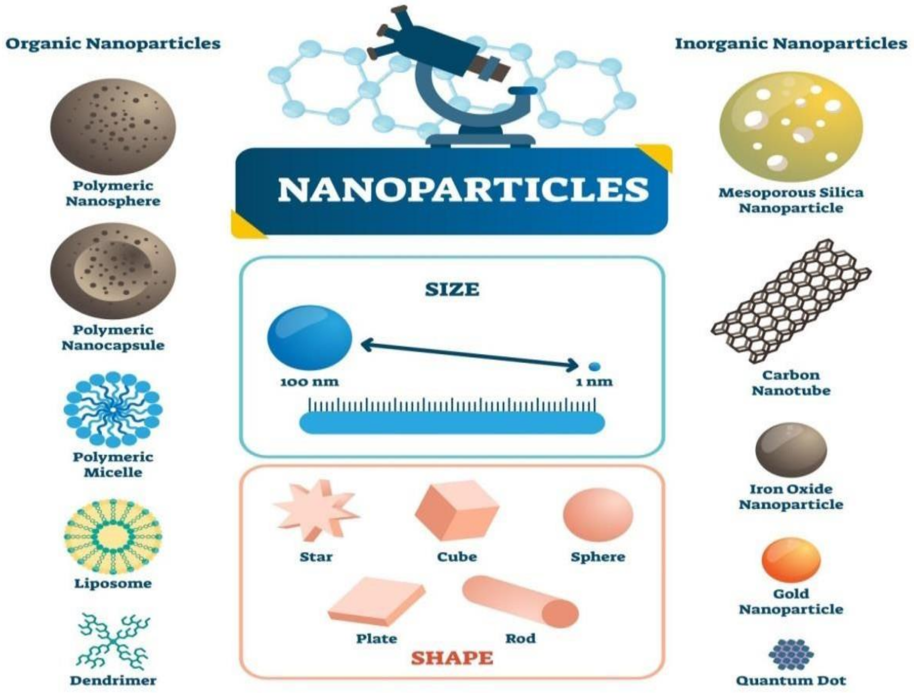

Figure 1: Categorization of nanoparticles based on composition and structure.

Carbon-Based Nanoparticles

Carbon-based nanoparticles include fullerenes and carbon nanotubes, which display remarkable electrical conductivity, structural stability, and electron-accepting capacity. These characteristics have made it possible for them to be used in sophisticated nanotechnological applications, biological sensing, and imaging (Chen *et al*., 2021; Astefanei *et al*., 2015).

Nanoparticles of metal

Metal NPs such as silver, gold, and copper display unusual optical and electrical capabilities due to localized surface plasmon resonance. Their customizable size and surface features make them appropriate for antibacterial therapy, biosensing, and drugs delivery applications (Khan *et al*., 2019).

Nanoparticles made of ceramic

Ceramic nanoparticles are non-metallic inorganic nanomaterials with exceptional mechanical strength and heat stability. Several ceramic Nano particles were studied for biological and pharmacological applications, despite their frequent use in coatings and catalysis (Sigmund *et al*., 2006).

Nanoparticles Based on Lipids

Nanoparticles based on lipids are widely utilized in pharmaceutical research due to superior biocompatibility and capacity to encapsulate lipophilic medicines. Their solid lipid core facilitates regulated drug release and increased therapeutic efficacy, making them attractive carriers in targeted medication delivery methods (Khan *et al*., 2019).

Nanoparticles of semiconductors

Nanoparticles of semiconductors exhibit unique optoelectronic capabilities and have been researched for bioimaging, cancer treatment, and diagnostic applications owing to their light- emitting and photochemical characteristics (Biju *et al*., 2008).

Nanoparticles made of polymers

Nanoparticles made of polymers are constructed of biodegradable polymeric materials capable of encapsulating therapeutic substances within nanospheres or nanocapsules. Their regulated drug release behavior and structural versatility have made them significant platforms in modern pharmaceutical formulations (Khan *et al*., 2019; Zielińska *et al*., 2020).

Types of Metal-Based Nanoparticles Silver Nanoparticles (AgNPs)

Silver nanoparticles typically vary from 1 to 100 nm and display excellent antibacterial capabilities because to their elevated surface reactivity. Various synthesis methods, including chemical reduction and green synthesis procedures, have been established to manufacture stable colloidal AgNPs for medical and pharmaceutical applications (Shenashen *et al*., 2014; Gloria *et al*., 2017).

Nanoparticles of zinc oxide (ZnONPs)

Wide band-gap semiconductors with exceptional catalytic and Zinc oxide nanoparticles contain antimicrobial effects. Numerous preparation methods such as sol–gel processing, precipitation, and hydrothermal synthesis have been documented, enabling their usage in biomedical and pharmaceutical technologies (Kumarr *et al*., 2013; Chen and Tang, 2007; Ghorbani *et al*., 2015).

Copper Nanoparticles (CuNPs)

Copper nanoparticles possess special visual properties linked with their electronic band structure and had also garnered notice for antibacterial and catalytic applications (Khan *et al*., 2019; Siwach and Sen, 2008).

AuNPs, or gold nanoparticles

The optical properties, stability, and biocompatibility of gold nanoparticles are well established. They are especially well-suited for drug administration, imaging, and targeted therapeutic applications since they may be functionalized with biomolecules (Rad *et al*., 2011; Compostella *et al*., 2017; Li *et al*., 2014).

Aluminum Nanoparticles (AlNPs)

Aluminum nanoparticles are chemically reactive nanomaterials predominantly investigated in catalytic and energy-related systems, with very limited medicinal use (Lerner *et al*., 2016).

Iron Nanoparticles (FeNPs)

Iron nanoparticles have magnetic and catalytic characteristics to be used in specific medicine delivery, imaging, and environmental remediation. Their magnetic responsiveness has led to use as contrast agents in diagnostic imaging, but toxicity issues remain crucial (Zhuang and Gentry, 2011; Jamkhande *et al*., 2019).

Synthesis Procedures for Metal Nanoparticles

NPs manufactured utilizing three major strategies: physical, chemical, and biological approaches. Physical procedures are often referred to as top-down approaches, whilst chemical and biological strategies are characterized as bottom-up approaches. Biological synthesis is sometimes called as green synthesis because of its environmentally benign and sustainable nature. Each strategy incorporates numerous techniques that differ in operational principles, processing conditions, scalability, and applicability for pharmaceutical and biological applications (Jamkhande *et al*., 2019; Baig *et al*., 2021).

Top-Down (Physical) Approach

In top-down techniques, Nanoscale structures are created from bulk materials. through physical processes involving mechanical or energetic forces. The fabrication of nanomaterials often makes use of these methods with regulated shape and structural stability.

Mechanical Milling

Mechanical milling is a high-energy technique in which bulk materials are ground into nanosized particles utilizing milling balls within rotating containers, often planetary or shaker mills (Gorrasi and Sorrentino, 2015). Continuous impact, compression, and friction during milling enable the production of nanostructured materials such as nanoalloys, reinforced metal composites, and wear-resistant coatings. Additionally, There has been a lot of interest in using ball-milled carbon nanomaterials for energy conversion. environmental remediation, and nanotechnology research (Yadav *et al*., 2012; Lyu *et al*., 2017).

Electrospinning

Electrospinning is a versatile process used to generate nanofibers, particularly from polymeric and composite materials (Ostermann *et al*., 2011). In this method, electrically charged jets are created from polymer solutions or melts, generating fibers with diameters typically in the nanoscale range (Chronakis, 2010). Advances such as coaxial electrospinning allow the combination of core–shell and multilayer nanostructures, enabling the prepare of hybrid materials made of organic, inorganic, and polymeric components. And their large surface area and adaptable architecture, these nanostructures have attracted more interest for use in pharmaceutical and biological delivery systems. (Kumar *et al*., 2013).

Ablation using a laser

In laser ablation, a solid item is exposed to a high-energy laser beam, which causes rapid heating, vaporization, and condensation into nanoparticles (Tran and Wen, 2014). Because it frequently eliminates the need for chemical reduction agents, this method is thought to be typically clean and environmentally friendly. Noble metal nanoparticles, carbon-based nanostructures, oxide materials, and ceramic nanomaterials ensure all be situated created by the process of laser ablation (Su and Chang, 2018; Baig *et al*., 2021).

Sputtering

Sputtering is a physical deposition process in which powerful ions hit a solid target, ejecting atoms or clusters that eventually condense into nanoscale structures (Behrisch, 1981). This technique is frequently used to create thin films and metallic nanostructures because it provides good control over composition and purity. Compared with certain lithographic processes, sputtering is comparatively cost-effective and capable of creating homogenous nanoparticle coatings with low contamination.

Table 1: General Characteristics of Common Metal-Based Nanoparticles.

Nanoparticle	Size Range	Shapes	Key Properties	Applications
AgNPs	~1–100 nm	Spherical/hexagonal	Strong optical activity	Antimicrobial, medical
ZnONPs	~1–100 nm	Hexagonal Semiconductor	behavior Sensors	Catalysis
CuNPs	~1–100 nm	Rods/cubes	Conductive fluorescent Catalysts	Electronics
AuNPs	~1–100 nm	Spherical/rods	High reflectivity	Drug delivery, imaging
FeNPs	~1–100 nm	Spherical	Magnetic properties	MRI, remediation
AlNPs	~1–100 nm	Nanospheres	High reactivity	Energy materials

Electron Explosion Technique

In the electron explosion method, a thin metallic wire is subjected to a high-intensity current pulse that generates fast heating, explosion, ionization, and evaporation of the metal. The created metal vapor expands into the surrounding gas or liquefied media and subsequently cools, resulting in the making of nanoscale particles through condensation (Joh *et al*., 2013). This procedure generates plasma during electrical explosion and enables nanoparticle synthesis without the requirement of chemical reducing agents, making it an effective physical strategy for creating metal nanoparticles (Joh *et al*., 2013).

Sonication

Nano fluids and nanoparticle dispersions are both made possible by the process of sonication. After preliminary mixing using magnetic stirring, ultrasonic energy is administered using ultrasonic baths, probe sonicators, or homogenizers to break particle agglomerates and produce uniform dispersion. Probe sonication is particularly successful as of his high energy delivery, facilitating the effective processing of carbon nanotubes, graphene, and metal oxides, and nano-inks (Zheng *et al*., 2010).

Pulsed Wire Discharge Method

The pulsed wire discharge technique is extensively applied for large-scale synthesis of metal nanoparticles. In this process, a fast electric current pulse heats and vaporizes a metal wire, producing metal vapor that, when cooled in an inert or ambient gas atmosphere, condenses into nanoparticles. This technique provides quick synthesis with economical energy input and good particle yield (Patil *et al*., 2021).

Arch Release Method

The arc discharge technique involves producing two graphite electrodes placed inside a gas-free enclosure form an electrical arc, commonly filled with helium. Maintaining an oxygen- free environment is vital to minimize undesired reactions and enable optimal nanostructure creation. The tremendous heat created during arc discharge vaporizes electrode material, which subsequently condenses into nanoparticles such as fullerenes, few-layer graphene, and amorphous carbon nanostructures (Shi *et al*., 2000; Kumar *et al*., 2013).

Lithography

Lithography is a nanofabrication technology that utilizes focused beams of light or electrons to build nanoscale patterns and structures (Pimpin and Srituravanich, 2012). The method can be broadly divided into masked and maskless lithography. Maskless lithography offers versatile and cost-effective patterning without the requirement for preset templates, making it suited for rapid prototyping and nanostructure manufacturing (Brady *et al*., 2019).

Bottom-Up Approach

In contrast to top-down procedures, bottom-up strategies include the assembly of nanoparticles from atoms or molecules by chemical or biological processes. These techniques enable superior control over particle size, shape, and chemical composition, making them extremely appropriate for pharmaceutical and biological applications (Baig *et al*., 2021).

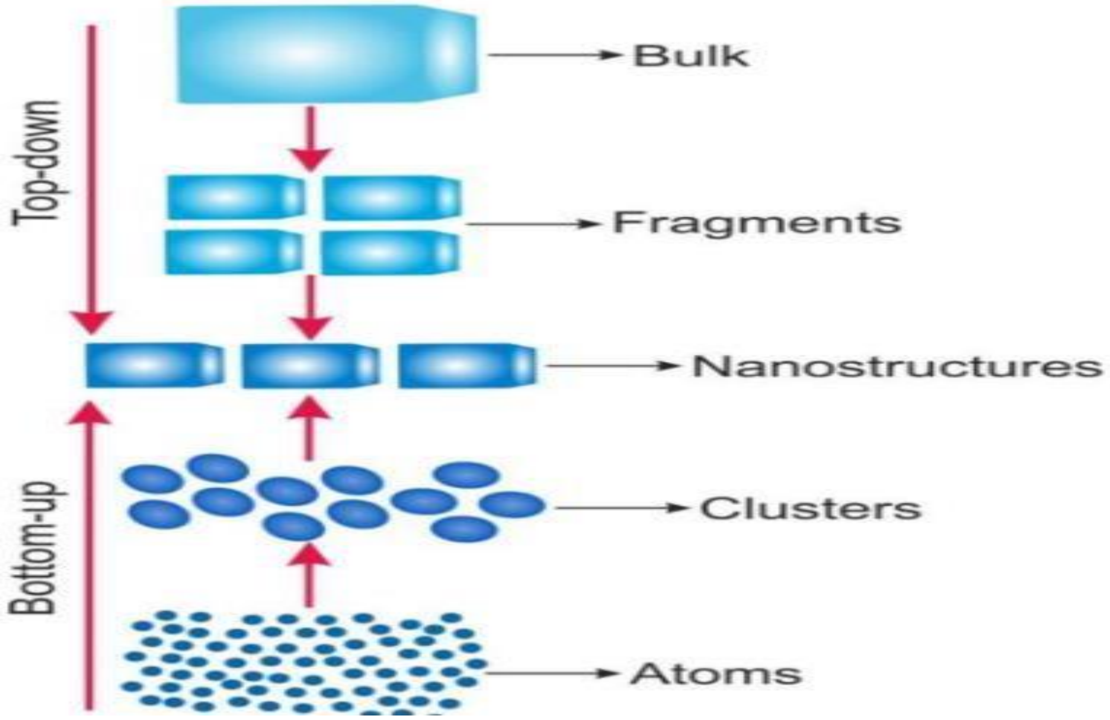

Figure 2: Top-down and bottom-up methodologies employed for nanoparticle production.

Deposition of Chemical Vapor (CVD)

Deposition of chemical vapor is a vapor-phase process in which gaseous precursors react or breakdown on a substrate surface to generate thin coatings or nanoparticles. The precursors utilized in this process must display excellent purity, adequate volatility, and chemical stability. Various CVD techniques, including plasma-enhanced CVD and metal-organic CVD, widely employed for manufacturing nanomaterials with great structural uniformity and controlled morphology (Dikusar *et al*., 2009; Machac *et al*., 2020).

Sol–Gel Method

The sol–gel method is a wet-chemical procedure in which metal precursors undergo hydrolysis and condensation events to generate a colloidal sol that subsequently converts into a gel network. Particle size and form are heavily influenced by variables like pH, temperature, and precursor concentration. Low processing temperatures, excellent consistency, and the ability to create intricate nanostructures are some benefits of this method. (Das and Srivasatava, 2016; Baig *et al*., 2021; Parashar *et al*., 2020).

Co-precipitation

Co-precipitation is a solution-based technique that produces nanoparticles by rapid nucleation brought on by interfacial tension and solvent displacement. This technique is frequently used to create water-soluble nanoparticles and is extensively used to create produce iron oxide nanoparticles for medication delivery and biomedical imaging applications (Das and Srivasatava, 2016).

Inert Gas Condensation (Molecular Condensation)

In inert gas condensation, a metal source is evaporated in an inert gas atmosphere such as argon or helium. The evaporated atoms incur energy reduction due to collisions with the surrounding gas, resulting in nucleation and production of nanoparticles typically within the 2–100 nm size range. Cooling systems such as liquid nitrogen can boost particle production efficiency and control size distribution (Pérez-Tijerina *et al*., 2008; Patil *et al*., 2021).

Hydrothermal Method

Hydrothermal synthesis is the process of creating nanoparticles in aquatic environments under controlled pressure and temperature conditions. This method makes it possible to create highly crystalline nanostructures with precise shapes and great purity, however intense reaction conditions may impair material stability (Banerjee *et al*., 2008; Patil *et al*., 2021).

Green / Biological Synthesis

Green synthesis creates nanoparticles in an environmentally safe way by using biological resources like microorganisms, plant extracts, and agricultural byproducts. (Malhotra and Alghuthaymi, 2022). This technique lowers the use of hazardous chemicals, minimizes energy usage, and allows scalable production for pharmaceutical and biological applications (Kumari *et al*., 2021).

Microbial-Assisted Biosynthesis

Microorganisms can generate nanoparticles by methods such as metal ion adsorption, enzymatic reduction, and biomolecule-mediated stabilization (Hulkoti and Taranath, 2014).

Numerous biological systems, such as yeast, bacteria, fungi, and algae, have been examined as natural nano-factories. Metal ions are collected on or within microbial cells and then reduced to generate stable nanoparticles exhibiting different biological functions (Rajeshkumar *et al*., 2014; Maharani *et al*., 2016).

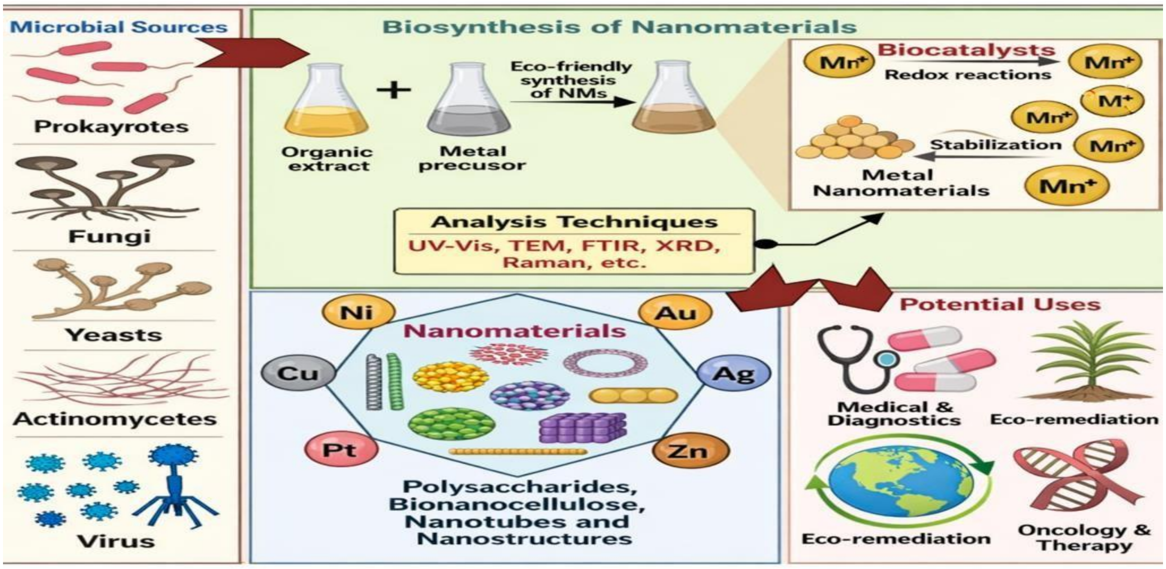

Figure 3: Mechanism of green manufacturing of metal nanoparticles using biological systems.

Extracellular Biosynthesis of Nanoparticles by Bacteria

In extracellular nanoparticle formation, enzymes produced by bacteria outside the cell play a vital role in reducing metal ions into nanoscale particles. NADH-dependent reductase enzymes are typically implicated in the bioreduction process, where electrons supplied by NADH assist the conversion of metal ions into elemental nanoparticle forms (Mathew *et al*., 2010).

During this reaction, NADH is oxidized to NAD^+ while the enzyme experiences simultaneous redox modifications (Sriram *et al*., 2012). In certain situations, nitrate reductase enzymes also contribute to quick metal ion reduction, enabling efficient nanoparticle production. Environmental parameters such as pH significantly influence nanoparticle morphology; for example, At neutral pH, According to these findings, extracellular biosynthesis produce gold nanoparticles of about 10–20 nm, while acidic circumstances encourage the creation of nanoplates and other morphologies. These results suggest that during extracellular biosynthesis, proton concentration and enzyme action simultaneously control the size and structure of nanoparticles. (Sriram *et al*., 2012).

Intracellular Biosynthesis of Nanoparticles by Bacteria

Intracellular nanoparticle formation requires ion trapping, enzymatic reduction, and stabilization within microbial cells. Polysaccharides, proteins, and cysteine residues are examples of negatively charged functional groups found in bacterial cell walls that give metal ion binding sites through electrostatic interactions.

Once internalized, enzymatic systems mediate the conversion metal ions into elemental atoms through NADH-dependent enzymes and other electron transport pathways (Zhang *et al*., 2011). The reduced atoms nucleate and develop into nanoparticles that accumulate within the cell fluid or periplasmic region.

Peptides and amino acids are examples of biomolecules that function as organic capping agents to boost stability and stop aggregation. This intracellular pathway also represents microbial detoxifying mechanisms against heavy metal stress (Mohd Yusof *et al*., 2019).

Biosynthesis of Nanoparticles by Fungi

Fungi are commonly utilized in nanoparticle biogenesis because they can create monodispersed particles with regulated size and morphology. The existence of different internal and extracellular enzymes, together with simplicity of cultivation, makes fungal systems excellent biofactories for metal nanoparticle manufacturing (Mohanpuria *et al*., 2008).

Metal ions work together with functional groups that are negatively charged on the mycelial cell wall during fungal-mediated synthesis, whereupon they undergo enzymatic reduction to produce metallic nuclei. Nanoparticles may be found on fungal surfaces as well as in cytoplasmic regions, according to microscopic research, suggesting parallel external and intracellular manufacturing pathways.

Environmental parameters like as pH and incubation temperature strongly influence nanoparticle shape and growth rate. Species such as Verticillium luteoalbum have been found to produce gold nanoparticles ranging from 20–40 nm (Mukherjee *et al*., 2001; Hulkoti and Taranath, 2014). Other fungus, such Aspergillus terreus and Penicillium brevicompactum, have showed antibacterial and cytotoxic potential through their biosynthesized nanoparticles.

Biosynthesis of Nanoparticles Using Actinomycetes

Actinomycetes are filamentous prokaryotic microorganisms often referred to as ―ray fungi‖ because of their structural similarities to fungal systems. Their nanoparticle synthesis techniques are comparable to fungal biosynthesis routes and involve enzymatic reduction and stabilization activities (Mathew *et al*., 2010). Extremophilic actinomycetes such as Extracellular spherical gold nanoparticles Thermomonospora species have been found to produce particles with an average size of about 8 nm, whereas taxa for instance Rhodococcus and Streptomyces generate nanoparticles exhibiting significant antimicrobial activity (Narayanan and Sakthivel, 2010).

Biosynthesis of Nanoparticles Using Algae

Algae include diverse biomolecules including colors, carbohydrates, proteins, minerals, and multi-unsaturated fatty chemicals that function as natural reducing and stabilizing agents during nanoparticle production. Their ability to gather heavy metal ions and transform them into stable nanoscale structures makes them valuable for eco-friendly synthesis procedures (Ramesh *et al*., 2015). Both live and non-living Algae cellulosae have been employed to create metallic nanoparticles through extracellular and intracellular processes, including gold and silver (Rajkuberan *et al*., 2017). Promising catalytic and bactericidal capabilities have been established by species such as Chlorella vulgaris, Nanochloropsis oculata, and Scenedesmus sp.

Intracellular Synthesis Using Algae

In intracellular synthesis, algal biomass is harvested, cleaned, and exposed to metal salt solutions under regulated conditions of pH and temperature. After incubation, centrifugation and sonication are conducted to separate nanoparticles generated within the cells (Paul *et al*., 2016).

Extracellular Synthesis Using Algae

Extracellular synthesis includes preparing cell-free algal extracts by drying or incubation methods. The extract functions as a capping and reducing agent when combined with solutions of metal salts, enabling nanoparticle production without the need for living cells (Saini *et al*., 2016).

Utilizing Plant Extracts for Biological Synthesis

Plant-mediated synthesis is greatest commonly investigated green ways for nanoparticle generation because plant extracts include phytochemicals capable of reducing metal ions under mild circumstances. Reaction factors such as extract concentration, pH, temperature, and metal ion concentration determine nanoparticle size and shape. Numerous plants—including Azadirachta indica, Lantana camara, Emblica officinalis, Coffea arabica, Curculigo orchioides, and Parkia roxburghii—have been reported for the olive fusion of metal nanoparticles exhibiting antibacterial, antioxidant, catalytic, and cytotoxic activities (Ajitha *et al.*, 2015; Velusamy *et al.*, 2015; Dhand *et al*., 2016; Kalaiyarasu *et al*., 2016; Pugazhendhi *et al*., 2016; Phull *et al*., 2016; Rajkuberan *et al*., 2017).

Biomimetic Synthesis

Biomimetic synthesis refers to artificial procedures that replicate natural biological mechanisms to produce nanomaterials. This method incorporates biological components such as enzymes, proteins, cells, or biomass residues to guide nanoparticle production. Functional biomimetic synthesis focuses on duplicating structural or functional elements of natural systems, whereas process biomimetic synthesis imitates biological mechanisms to generate complex hierarchical nanostructures and advanced nano-architectures (Zan and Wu, 2016).

Nanoparticle Applications

Applications of Environmental Nanoparticles

Nanoparticles have attracted a lot of interest in environmental research and commercial applications for extremely small size and distinctive physicochemical characteristics. They are Because of their huge surface area, increased reactivity, and catalytic activity, they provide excellent instruments for pollution control, environmental monitoring, and sustainable remediation technologies.

Bioremediation

Bioremediation ability to eliminate dangerous pollutants like heavy metals and organic contaminants from soil and water, Nanoparticles are intensively explored for environmental cleanup (Zhuang and Gentry, 2011). Materials such as metal oxides, carbon nanotubes, and nanoscale zeolites can penetrate contaminated areas that are hard to reach with larger particles. The treatment of chlorinated solvents in groundwater systems has made considerable use of nanoscale zero-valent iron (nZVI). Furthermore, lethal elements like pb, cadmium, arsenic, and mercury can be effectively adsorbed by superparamagnetic iron oxide nanoparticles, reducing environmental risks (Elliott *et al*., 2013).

Environmental Sensors

Nanoparticles are increasingly employed in the creation of sensitive environmental sensors capable of detecting trace amounts of contaminants (Elliott *et al*., 2013). Their nanoscale dimensions provide greater sensitivity and selectivity toward certain chemical and biological targets. For example, sensors for tracking heavy elements like mercury in water sources have incorporated gold nanoparticles (Yadav *et al*., 2010). Additionally, rapid detection of toxins and microbiological diseases in aquatic environments is made possible by nano-based sensors.

Catalytic Applications

Nanoparticles operate as efficient catalysts in several environmental processes, including biomass conversion and biofuel production. Noble metal nanoparticles, particularly platinum- based systems, lower activation energy and boost reaction efficiency. Furthermore, nanoparticle- based catalytic probes have exhibited potential in detecting heavy metal ions in environmental samples (Kora and Rastogi, 2018; Lam and Luong, 2014).

Nanoparticle Applications in Medicine

The remarkable visual, chemical, and biological characteristics of nanoparticles make them exceedingly valuable in modern medicine (Sun *et al*., 2014). Their nanoscale size enable focused interactions at the cellular and molecular levels, boosting therapeutic efficacy and decreasing systemic toxicity (Abdulle and Chow, 2019).

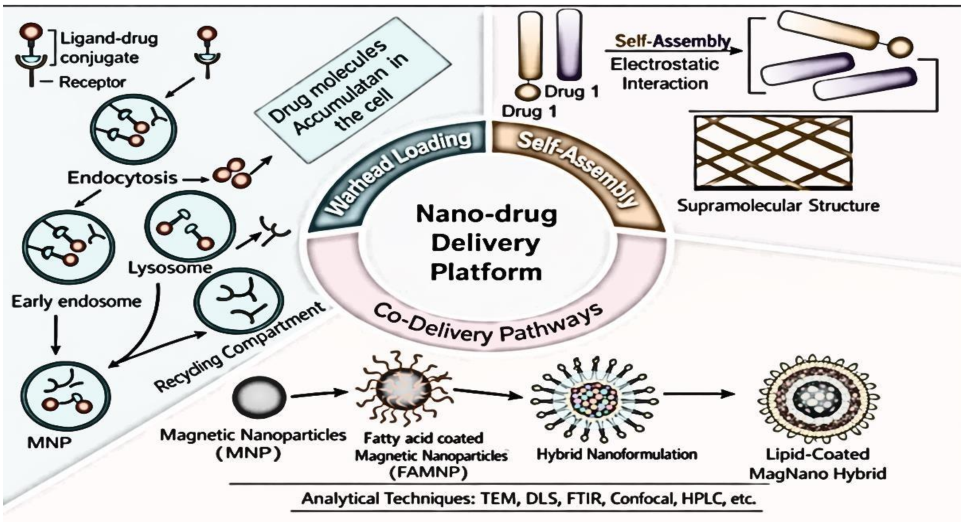

Figure 4: Targeted medication delivery utilizing nanoparticles.

Drug Delivery

Nanoparticles operate as enhanced drug delivery carriers capable of carrying therapeutic medicines to targeted tissues or cells. Gold nanoparticles are intensively investigated because to their chemical stability and optical features, enabling applications in cancer therapy, imaging, and biosensing. CDDS can be sustained-release or stimuli-responsive, reacting to pH, enzymes, temperature, or light. Silver, zinc oxide, and Cu nanoparticles have also been studied as remedy shippers owing to their antibacterial and tumor-targeting characteristics (Schröfel *et al*., 2014).

Diagnostics

In diagnostic technology, nanoparticles are used as contrast agents and imaging probes. Magnetic iron oxide nanoparticles improve the visibility of tissue in magnetic resonance imaging (MRI), while gold nanoparticles have been studied for early detection of cancer and illness biomarkers because of their strong optical responses (Siddique and Chow, 2020).

Tissue Engineering

In regenerative medicine, nanoparticles are integrated into scaffolds and biomaterials to assist tissue regeneration and repair. nanoparticles have demonstrated potential in boosting bone cell explosion, assembly them interesting ingredients for bone tissue fabrication utilizations (Kim *et al*., 2014).

Antimicrobial Applications

Certain nanoparticles, particularly silver and copper nanoparticles, have excellent antibacterial effect against a wide spectrum of microorganisms (Hoseinzadeh *et al*., 2017). These materials are included into wound dressings, implants, and medical devices to reduce infection risk and enhance patient outcomes.

Applications of Nanoparticles in the Chemical Industry

Nanotechnology has offered revolutionary ways in chemical processing by raising reaction efficiency, improving selectivity, and reducing energy usage (Bhavani *et al*., 2021).

Chemical Processing and Catalysis

Metal nanoparticles work as very efficient catalysts virtue to their huge coverage area & number of active sites. Platinum, palladium, iron, and nickel nanoparticles are commonly exploited in hydrogenation, oxidation, hydrolysis, and fuel-cell operations. Their catalytic capabilities allow chemical transformations to occur at lower temperatures with increased reaction selectivity and less by-product generation (Lara and Philippot, 2014).

Purification and Separation

Because of their high adsorption capacity and size-dependent interactions with molecules, nanoparticles are also utilized in separation technologies (Hollamby et al., 2010). While nanoparticles composed of gold and silver have been examined for eliminating of heavy metals and microbiological pollutants from water systems, iron oxide nanoparticles have been utilized to filter gasses and liquids. (Pradeep, 2009; Siddique and Chow, 2020). Aluminum-based nanoparticles have proven potential in separating oils, fuels, and other chemical compounds, demonstrating their adaptability in commercial purification procedures (Zhuang and Gentry, 2011).

Future Perspectives

In addition to their extensive implementations in catalysis, metal nanoparticles have attracted a lot of attention, nanomedicine, environmental remediation, sensing technologies, and innovative materials. Despite tremendous scientific advances, some hurdles must be solved to fully exploit their technological and medicinal promise.

Achieving precise control over the dimensions forms, and surface characteristics of nanoparticles during synthesis the main challenges. Many current manufacturing methods need high temperatures or severe chemical conditions, which may hinder scalability, repeatability, and cost-effectiveness in industrial production. Since nanoparticle physicochemical parameters greatly influence optical behavior, catalytic efficiency, and biological performance, the development of reliable, controlled, and sustainable synthesis techniques remains a key research focus.

Environmental and biological safety also constitutes an essential problem. Some metal nanoparticles may be harmful to aquatic life and ecological systems, especially if they contain silver or heavy metals. Therefore, detailed investigations on long-term environmental effect, bioaccumulation, biodegradation, and nanotoxicology are necessary. Future research is expected to focus green synthesis techniques, biodegradable nanomaterials, and ecologically benign stabilizing agents to decrease ecological concerns.

Looking ahead, metal nanoparticles are projected to have a transformational role in new technologies. In pharmaceutical and biomedical sciences, their integration into sophisticated cancer medicines, antimicrobial formulations, diagnostic imaging platforms, and tailored drug delivery systems has enormous potential. Additionally, applications in energy storage, catalytic conversion, and environmental monitoring are projected to develop with breakthroughs in material design and nanofabrication. Continued interdisciplinary collaboration, uniform regulatory frameworks, and responsible innovation will be vital for assuring the safe, ethical, and sustainable application of nanoparticle-based technologies in the future.

CONCLUSION

Nanoparticles constitute a fast expanding topic in modern science and pharmacy due to its unique physicochemical features, Nano scale dimensions, and varied applications. This review emphasizes numerous synthesis processes encompassing physical, chemical, and biological methods, as well as many types of nanoparticles and their several uses in the biomedical fields, the environment, industry, and technology. Among them, green synthesis has become a viable choice due to its low toxicity, affordability, and eco-friendliness.

Nanoparticles have demonstrated significant promise in the pharmaceutical sciences for tissue engineering, antimicrobial therapy, targeted drug delivery, and diagnostic imaging. Their potential to improve therapeutic efficacy, regulate pharmaceutical release, and boost bioavailability makes them valuable tools for future developments in healthcare. However, issues linked to toxicity, environmental safety, large-scale production, and regulatory approval remain key factors. Continued interdisciplinary research, enhanced synthesis control, and sustainable design techniques will be important for the safe and effective application of nanoparticle-based technology. Overall, nanoparticles are projected to play a transformational role in next- generation medicine and advanced material research.

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