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Review Article

A Review on Polyherbal Nanoparticles with Combined Effect of Metal Nanoparticle-Properties and Applications

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ABSTRACT

The current review summarizes the processes, characteristics and uses of Nanoparticles (NPs) sourced from polyherbal formulations, such as fullerenes, metal NPs, ceramic NPs and polymeric NPs. In order to make different and useful nanoparticles from polyherbal combinations the medicinal values of several plants have to be animals. These nanoparticles have unique properties, such as improved stability, controlled-release, and targeted delivery methods, which make them considerable assets for biomedical purposes. Nanoparticles extracted from polyherbal formulations displayed anti-diabetic drug activity and were also discovered to treat alternative chronic conditions like cancer and cardiovascular disease. Furthermore, these nanoparticles exhibited low toxicity and high biocompatibility, which makes them exceptional for a range of biomedical applications. But throughout, researchers have been challenged by insufficient data and limited directions to address these aspects.

Keywords: Characterization, Drug Delivery, Metal Nps, Nanoparticles, Synthesis.

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INTRODUCTION

Nanoparticles (NPs) are particulate materials with dimensions typically below 100 nm, existing in zero-to three-dimensional forms (Laurent *et al*., 2008). Based on chemical nature, nanoparticles are classified as organic, inorganic, carbon-based, and composite materials (Sawy *et al*., 2021). Nanotechnology-based products have significantly contributed to the economies of many countries due to their wide industrial applicability.

Nanomaterials can be categorized as porous and non-porous based on their structural characteristics. Mesoporous nanomaterials, with pore sizes between 2 and 50 nm, have gained attention in biomedical applications due to their high surface area, porosity, and ability to enable controlled drug release while minimizing leakage into healthy cells (Barhoum *et al*., 2017; Sawy *et al*., 2021). These properties improve drug loading efficiency, therapeutic efficacy, and reduce adverse side effects.

Herbal drugs have been used for centuries due to its therapeutic efficacy and absence of side effects. To ensure maximum patient compliance and prevent repeated dosing, phyto-therapeutics need a scientific strategy to deliver components in a sustainable process. Novel Drug Delivery Systems (NDDS) have the possibility to reduce toxicity and enhance bioavailability. Nanotechnology is a promising approach to nano-sized drug delivery devices, which may enhance activity and bypass problems associated with plant medicines. Polyherbal preparations have attracted considerable interest over the past few years owing to their promise in a variety of applications, including the synthesis of copper nanoparticles. These formulations are a blend of various plant extracts with distinct properties that enhance the overall efficacy of the synthesis process (Zolkepli *et al*., 2022).

In the present review, we present an overview of the recent developments in nanoparticle research and their probable applications across the board. We are going to talk about the synthesis processes, characterization procedures, and effects of various parameters on nanoparticle properties and to identify the different polyherbal preparations involved in nanoparticle synthesis and their effects on efficacy and sustainability.

Types of nanoparticles

Based on nanoparticles composition and features they are classified into many categories (Figure 1). That includes, Zero-dimensional nanoparticles, like quantum dots (Khan *et al*., 2019). Nanowires and tubes are one-dimensional NPs, graphene is two-dimensions at the nanoscale. Dendrimers and liposomes partake all three dimensions in the nanoscale range. They gained

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higher stability and structural strength due to their 3-D nature, that made them suitable for engineering and materials science applications (Pablo and Katarina, 2024; Asha *et al*., 2024).

Metallic nanoparticles

Metal nanoparticles, consisting largely of gold, silver, and platinum, are one of the most common kinds. These metal nanoparticles possess unique optical and catalytic properties that render them useful in the electronics and medicine industries (Mody *et al*., 2010). Metallic nanoparticles find extensive use as they exhibit better conductivity and stability. Gold and Silver NPs are slowly replaced by Cu-NPs due to their properties like high melting point and electrical conductivity. Moreover, copper nanoparticles are fascinated for their antibacterial capabilities, making them exciting candidates for medicinal applications such as wound healing and medication delivery systems (Table 1).

Copper nanoparticles are tiny particles of copper that range in size from 1 to 100 nanometers. Earlier studies like Lee *et al*., 2013 has been reported on Cu-NPs preparation with spherical nanoparticles with sizes between 50 and 250 nm using *Magnolia kobus* leaf extract. Current research shows that copper nanoparticles reduce the copper ions, and proteins, including terpenoids and reducing sugars, assist in this reduction and provide stability to synthesized Cu-NPs.

Semiconductor nanoparticles

The dimensions of semiconductor particles ranging from 1-100 nm are referred to as semiconductor NPs (Shatters plating-semiconductor Np's). Owing to the minute size, they are able to show electronic and optical characteristics and thus used in electronics, optoelectronics, energy storage, catalysis, and biomedicine applications (Table 2). The synthesis of semiconductor NPs is dependent on its precursor chemicals, temperature, pressure, reaction duration, and availability of catalysts or surfactants (Rawalekar and Mokari, 2013). The electronic properties of semiconductor nanoparticles are probed by Density Functional Theory (DFT) and quantum mechanical calculation that gives information on energy levels, charge carrier and optical properties, aiding in the nanoscale device optimization and design (Long *et al*., 2017). These nanomaterials have found their applications in industries such as optoelectronics to improve the efficiency of solar cells and the luminescence of Light-Emitting Diodes (LEDs).

Polymeric nanoparticles

Polymer nanoparticles are tiny polymer particles ranging from 1 to 1000 nm in size (Win and Feng, 2005). They exhibit distinct characteristics because of their small size and large surface area-to-volume ratio. They are applied in the drug delivery system, imaging agents, biosensors, and in tissue engineering for drug encapsulation, targeting tissues, and controlled drug release (Table 3). Their small sizes fail to cross biological barriers and efficient loading and release of therapeutic agents ensure enhanced drug efficacy with less side effect (Mallakpour and Behranvand, 2016).

Polymeric nanospheres including liposomes, dendrimers, and micelles have received extensive attention due to their varied properties and potential applications in various industries. Liposomes are vesicles with aqueous interiors and phospholipid bilayers of variable size, content, and surface chemistry. Advantageous features of these nanoparticles include controlled drug administration, enhanced therapeutic agent stability, and targeted delivery to certain tissues or cells. Also, their biocompatibility and ability to encapsulate hydrophilic as well as hydrophobic drugs make them attractive.

Liposomes-first identified in the early 1970s (Cohen and Bangham 1972) have been used as nanoparticles for the administration of chemotherapy, and they are vesicles with aqueous cores that are encased in phospholipid bilayers that differ in size, contents, and surface chemistries. The benefits of using these nanoparticles include administered drug delivery, facilitated stability of the therapeutic agent, and targeted delivery, as well as their biocompatibility and ability to encapsulate hydrophobic and hydrophilic drugs.

Nanoparticle synthesis

Chemical Synthesis

It uses a variety of methods (Figure 2), such as chemical, physical and biological ones. Chemical methods are typical method of nanoparticles synthesis. They consist of precipitation that is mixing two or more precursor solutions to a solid product, and then further treating for the production of nanoparticles (Rane *et al*., 2018). Sol-gel synthesis consists of a liquid precursor being converted into a gel, then drying and calcination to yield nanoparticles. The sol-gel method is a wet-chemical process for obtaining high-quality metal-oxide nanostructures. Precursors are transformed into a sol, then into a gel-like network structure (Dong *et al*., 2019). Metal alkoxides are common precursors for this method.

Metal oxide hydrolysis using water or alcohol, condensation, polycondensation, and ageing are all synthesis steps. The final product is affected by parameters such as the type of precursor, the hydrolysis rate, the ageing time, the pH, and the molar ratio of H_2O to precursor. The sol-gel technology is cost-effective and provides benefits like homogeneous materials, low processing temperatures, and simple production of composites and intricate nanostructures (Azadani *et al*., 2021). Abdulkin *et al*., and Alonso *et al*., employed reducing agents and polymeric capping agents to synthesize Cu-NPs in the size range from 3 to 9 nm. They observed that the absence of water during synthesis had a limited positive effect on the stability. The scientists also varied the copper salt concentration, reduction agent, solution pH, and synthesis temperature to obtain nanoparticles of different sizes, morphologies, and activities.

Hydrothermal synthesis involves high-pressure and high-temperature conditions to facilitate the growth of nanoparticles from precursor solutions. Nanostructured materials tend to be produced by hydrothermal and solvothermal processes (Schaf *et al*., 2004). Hydrothermal reactions are carried out in an aqueous medium, while solvothermal reactions are done in a non-aqueous medium. Both strategies tend to be used in closed systems. The microwave-hydrothermal method, being an integration of hydrothermal and microwave technology, has been in the spotlight among nanomaterial engineering professionals (Shi *et al*., 2014). These technologies can be employed to form a variety of nano-geometries, such as nanowires, nanorods, nanosheets, and nanospheres. These technologies enable scientists to control the size, shape, and structure of the nanoparticles with high precision and hence adjust their properties to meet a particular requirement (Rehan *et al*., 2019).

Physical synthesis

Physical production of nanoparticles has employed ball milling and lithography techniques extensively. Ball milling is grinding and mixing materials to lower them to nanometric size, while lithography employs masks and etching processes to pattern nanometric surfaces (Kumar and Kumbhat, 2016). These physical methods deliver fine control over particle shape and size, thus making them suitable for use in applications where consistency and precision are demanded. Mechanical milling is employed in the production of aluminium alloys, spray coatings for wear resistance, and numerous nanocomposite materials.

Ball-milled carbon nanomaterials are a special type of nanomaterial that can potentially be employed in environmental remediation, energy storage, and energy conversion (Lyu *et al*., 2017). Laser ablation is another common physical process of nanoparticle formation. A target material is vaporised by a laser beam, which then condenses into nanoparticles (Abdel-Haleem *et al*., 2019). Laser ablation synthesis is a sustainable process for the production of noble metal nanoparticles without employing any stabilizers or solvents. The process yields a broad range of nanomaterials such as metals, carbon, oxide composites, and ceramics. Pulsed laser ablation in liquids is an interesting process to prepare monodisperse colloidal nanoparticle solutions without the assistance of surfactants or ligands.

Nanoparticle size and distribution parameters can be regulated by adjusting fluence, wavelength, and laser salt addition (Sportelli *et al*., 2016). Pulsed laser wavelength and fluence significantly impact sizes of as-synthesised Pd nanoparticles (Zhao *et al*., 2014). This technology lends itself to precise control of the size and composition of the generated nanoparticles, making it appropriate for drug delivery and catalytic uses.

Biological synthesis

Biological synthesis of nanoparticles involves the utilization of living organisms, including plants or bacteria, to create nanoparticles (Arya, 2010). Biological synthesis has numerous benefits compared to chemical synthesis in that it is cheaper, environmentally friendly, and can be used to synthesize nanoparticles with specific properties. Biological synthesis also provides control over size, shape, and composition of the nanoparticles synthesized (Gericke and Pinches, 2006). Green synthesis using microbes or plants is a newer approach to making nanoparticles. Copper-based nanoparticles find diverse applications in different plant extracts such as catalysis, photocatalytic and antibacterial activity, DNA binding, sensors, cytotoxicity, and antioxidants. *Jatropha curcas* L. (JC) is utilized as a traditional medicine and leaf extract for curing malaria. TiO_2 and Ag-based nanoparticles have been synthesized from *J. curcas* leaf extracts in studies, exhibiting their potential in diverse applications (Ghosh *et al*., 2020; Asha and Senthilkumar, 2020).

Polyherbal preparations are the use of more than one herb or plant extract in a single preparation. These preparations have been viewed as important in nanoparticle synthesis because of their possible advantages (Alexander *et al*., 2016). Using various herbs whose chemical structures are different, polyherbal preparations can stimulate the synthesis process by offering an expanded variety of bioactive compounds and triggering synergistic effects. This method provides the prospect of enhancing the stability, biocompatibility, and functionality of copper nanoparticles, eventually leading to new avenues of their application in different areas.

Microorganisms or plants are used as bioreactors to synthesize nanoparticles by their metabolic activity. This technology offers a sustainable and green alternative to conventional chemical processes, enabling the synthesis of nanoparticles with different characteristics (Meunier *et al*., 2010). Whereas chemical methods allow for flexibility in the synthesis of nanoparticles, biological methods involving microorganisms and plants offer a sustainable and green way that enables the production of nanoparticles with special properties.

In addition, plant use as bioreactors for nanoparticle production has the advantage of leveraging their intrinsic metabolic processes. This means that nanoparticles produced through this method have a higher chance of being biocompatible and less toxic compared to those produced chemically. In addition, the employment of plants as bioreactors enables the creation of large quantities of nanoparticles, and it is thus an affordable and scalable method to produce nanoparticles (Makarov *et al*., 2014). The bio-inspired technology is superior to chemical and physical approaches since it is cheaper, friendly to the environment, and does not involve high pressure, energy, temperature, or toxic chemicals (Mohammadinejad *et al*., 2016).

Nanoparticle Characterization

Nanoparticle characterization involves the examination and understanding their physical, chemical, and structural properties at the nano level (Table 4). This process is essential in determining the size, shape, surface area, content, and surface chemistry of the particles (Grainger and Castner, 2008). X-ray diffraction (XPS) is a surface-sensitive technique applied in depth profiling research to establish the composition and composition variation with depth. In a research paper by Lykhach *et al*. (2017), they established that out of 10 Pt atoms, a single electron is excited from the NPs to the CeO_2 support. The Debye Scherer formula provides a preliminary idea of particle size for separating single and multiphase nanoparticles (Emery *et al*., 2016; Ullah *et al*., 2017). The simplest method to achieve good contrast is by comparing computer-simulated structural models and XRD spectra observed (Ingham, 2015). Surface chemistry can also be examined through means like Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy. These studies provide valuable information to know how the behaviour of the nanoparticles is and what potential applications they will have in fields like medicine and environmental science (Movasaghi *et al*., 2008).

Microscopy methods play a key role in complementing the information obtained from spectroscopic examinations. SEM or TEM is a method of analyzing individual Nanoparticles (NPs) by irradiating component elements with electron beams. These NPs emit characteristic energy X-rays that are proportional to concentration in the element. This method is widely applied by researchers to complement SEM and other methods for validating components in manufactured materials (Iqbal *et al*., 2016). Ellipsometry, and atomic force microscopy are two widely employed methods to determine the surface characteristics of nanoparticles. They have the ability to furnish information regarding the composition, thickness, and roughness of the surface of the nanoparticles, which are significant parameters that govern their interactions with other molecules or materials (Kasper *et al*., 2019).

Another method commonly utilized to study nanoparticles is Dynamic Light Scattering (DLS). DLS is a method which investigates the light-nanoparticle interaction, giving knowledge of particle size, shape, chemistry, and optical properties. The method has various applications in materials science, biotechnology, and environmental monitoring, among others (Niemeyer, 2001). DLS is also significant in biotechnology, where more applications for drug delivery and imaging are being found using nanoparticles.

Nanoparticle applications

Nanoparticle applications have grown exponentially in recent years due to its size and unique properties especially in medicine, electronics and environmental science fields. Nanoparticle studies in the medicinal field have shown immense potential in the drug delivery systems, diagnostics, and imaging (Figure 3).

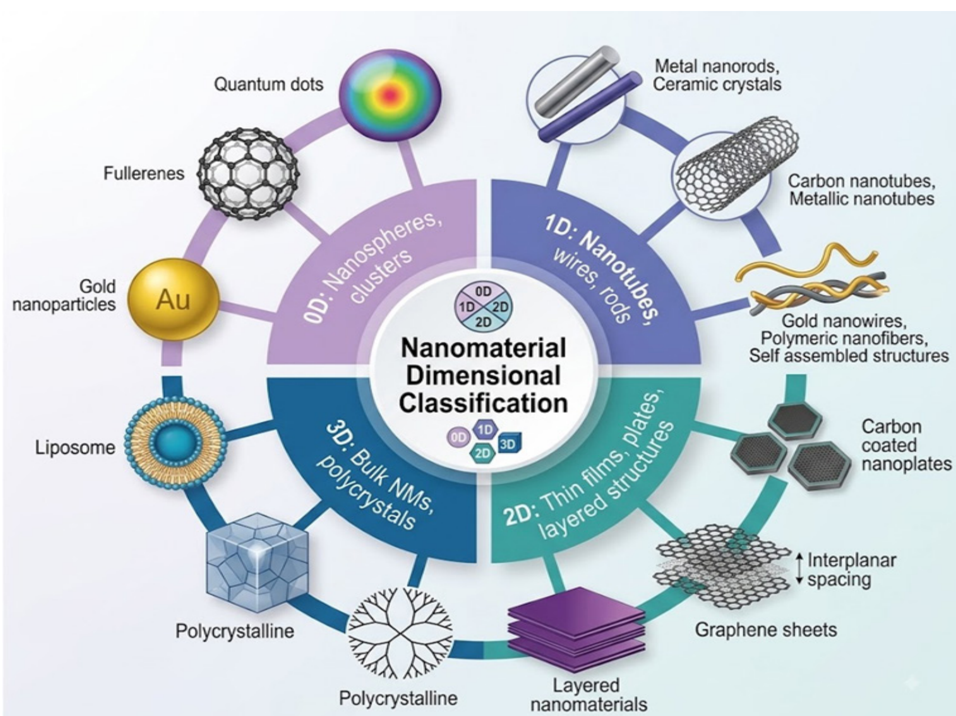

Figure 1: The relative dimensions of nanoparticles with examples of each category (Source: Tuang Yeow Poh *et al*., 2018).

Table 1: Metallic nanomaterials types and their bioactivity.

Metallic Nanoparticles	Bioactivity	References
Gold nanoparticles	Anticancer, Neuro reconstruction, Antiviral (HIV, Influenza).	Rai *et al*. 2016
Silver nanoparticles	Anticancer (Breast, Kidney and renal, Leukemia) Antibacterial (*Bacillus subtilis, Staphylococcus aureus*, Methicillin resistant coagulase) Antifungal (*Candida* sp.), Antiviral (Respiratory syncytial virus, *Leishmania tropica*, Herpes simplex virus).	Narducci, 2007; Yalcinkaya *et al*. 2016; Salama *et al*. 2021; Shahriary *et al*. 2018; Youssef *et al*. 2017
Copper nanoparticles	Antimicrobial (*Bacillus subtilis, E. coli, S. aureus, Micrococcus luteus, Pseudomonas aeruginosa, Salmonella enterica*, and *Enterobactor aerogenes*). Antifungal (*Fusarium oxysporum* and *Phytophthora capsici*). Antiviral (human influenza A (H1N1), avian influenza (H9N2). Anticancer (HeLa cells, MD A-MB-231 (human breast cancer cell lines), Caco-2 (human colon cancer cells), and HepG2 cells (Hepatic cancer cells) and Mcf-7 breast cancer cells. Wound healing activity, anti-inflammatory and anti-arthritic.	Harishchandra *et al*. 2020

Table 2: Semiconductor nanomaterials types and their bioactivity.

Semiconductor Nanoparticles	Activity	References
Gold nanorods	Anticancer	Yi *et al*. 2020
Ag-In-Zn-S quantum dots	Anticancer (human alveolar basal epithelial cells)	Zhang *et al*. 2016
Cadmium telluride quantum dots	Bioimaging human bronchial epithelial cells	Das and Gavel, 2020
Multilayer carbon nanotubes	Anti-inflammatory	Debnath and Srivastava (2021)
Single layer carbon nanotubes	Anticancer (head and neck squamous carcinoma)	Marcelo *et al*. 2015

Medicine and Healthcare

Examples of medical and health uses of nanoparticles include cancer treatment, where heat is generated by nanoparticles to kill tumour cells with minimal damage to healthy organs. Diagnostic agents in imaging early disease are also being considered using nanoparticles. Furthermore, nanoparticles have exhibited potential in regenerative medicine by promoting tissue regeneration and repair in damaged or wounded tissues (Zhang and Webster, 2009).

Due to their minute size, they can easily traverse the body and be delivered specifically to target sites. Moreover, nanoparticles can be engineered to deliver medicine in a controlled and regulated manner, which gives maximum therapeutic outcomes and prevents the adverse effects. Nanoparticle-delivery systems for medicines have been found to possess significant promise in cancer treatment. It is possible to target cancer cells selectively and safeguard healthy tissues from the toxic effects of chemotherapy drugs by encapsulating them within nanoparticles (Vahed *et al*., 2017).

The targeted strategy, not only enhances the effectiveness of treatment but also reduces the unpleasant side effects usually related to conventional cancer drugs. This technique also facilitates tissue engineering (Hasan *et al*., 2018), which can be utilized to replace conventional therapy in the form of artificial implants and organ transplants (Wang *et al*., 2021).

Gold, a widely utilized Ayurvedic material, is utilized for enhancing memory and in medical formulations for enhancing mental fitness. Gold nanoparticles have also been promising in targeting and destroying cancer cells with minimal damage to normal cells (Cai *et al*., 2008; Sztandera *et al*., 2018). *D. bulbifera* tuber extract was used to synthesize monodispersed spherical Cu-NPs with high inhibitory activity against amylase and glucosidase, which are key targets for T2DM therapy. These biogenic Cu-NPs also exhibited improved antioxidant activity, providing solid scientific evidence for their potential to be used against diabetes and describing their application in T2DM therapy and treatment (Gosh *et al*., 2015).

In addition, Cu NPs showed considerable protection of functional cardiovascular abnormalities of diabetics. These NPs can enhance nitric oxide bioavailability and alleviate oxidative stress on the vascular endothelium. Numerous previous studies have also proved that the application of copper nanoparticles is relevant in wound detection of mice (Piyush *et al.*, 2015). *S. grandiflora*-mediated CuO nanoparticles were green-synthesised. Sg-CuO nanoparticle research on anti-hyperglycemic studies inhibited the α-amylase and α-glucosidase enzymes, hence indirectly affecting blood glucose levels and controlling insulin secretion (Ramasubbu *et al.*, 2023). Hence, diabetic patient hyperglycemia could be managed.

The seed oil of the plant *Momordica charantia*, and polypeptide-k are antioxidant and anti-diabetic in nature. They are -glucosidase and -amylase inhibitors, lowering blood glucose levels. Polypeptide-k is a phyto-insulin that mimics the action of insulin (Kumar *et al.*, 2010). Liposomes, solid lipid nanoparticles, and nanostructured lipid carriers have exhibited high encapsulation efficiency or loading capacity of plant products, rendering them appropriate as large concentration of pharmaceuticals carriers (Kambale *et al.*, 2022).

Electronics and Energy

Nanoparticles find a wide range of applications in electronics, energy, biotechnology, and energy storage. Nanoparticles are found in solar cells, sensors, fuel cells, and batteries, as well as in environmental remediation, diagnostics, and imaging (Mobasser and Firoozi, 2016). Owing to their miniature size and unique characteristics, nanoparticles make excellent catalysts for chemical reactions, paving the way to eco-friendly and sustainable industrial processes. They can also play a role in revolutionizing energy storage, particularly in batteries and supercapacitors. Through the use of nanoparticles in battery materials, scientists can increase their energy storage capacity and performance (Kong *et al.*, 2020).

Nanoparticles have also been utilized in the fabrication of supercapacitors, which can transform energy storage with their high-power density and rapid charging properties. The application of nanoparticles in renewable energy is widely being researched. Greater light and UV absorption with very low reflectance coatings in solar cells has greatly improved their efficiency (Hanaei *et al.*, 2016).

Environmental remediation

Due to their distinctive physical as well as chemical properties, nanoparticles are a most suitable option for environmental remediation and making the renewable energy sector more efficient. These nanoparticles have been employed to treat and decontaminate air, water, and soil for more than a decade, treating *in situ* without requiring groundwater pumping or excavation (Ossai *et al.*, 2020). They are delivered to the target site and transported along the groundwater flow, where they detoxify water through redox reactions.

Nanoparticles are applied for disinfection, purification, and desalination of surface water by eliminating heavy metals, pathogens, and organic pollutants. Oil spills are a large-scale issue throughout the world, and they are cleaned up using nanoparticles, which lowers cost, increases efficiency, and decreases the amount of treatment needed (Dhaka and Chattopadhyay, 2021).

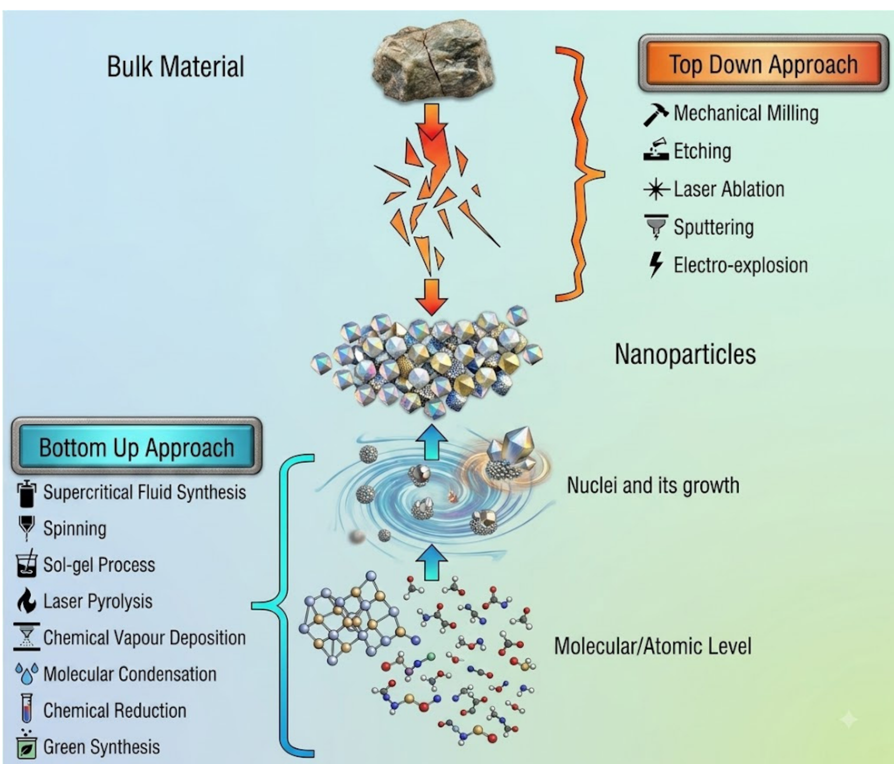

Figure 2: Top-down and Bottom-up approaches for synthesis of nanoparticles (Source: Khanna *et al.*, 2019).

Table 3: Polymeric nanomaterials types and their bioactivity.

Polymeric Nanoparticles	Activity	References
Liposomes	Anti-inflammatory effect in a rat model of adjuvant-induced arthritis *in vivo*, Anticancer effect in mice xenografted with colon cancer cells *in vivo*, Free-radical scavengers, carcinogenic activity, inhibition of proinflammatory kinases.	Bhirde *et al*. 2010; Ruzycka-Ayoush *et al*. 2021; Tong *et al*. 2013
Poly-amido-amine dendrimers	Anticancer effect in methotrexate -sensitive and resistant human acute lymphoblastoid leukemia (CCRF-CEM) and Chinese Hamster Ovary (CHO) cells.	Prabha and Raj, 2017
Poly-lactic acid	Anticancer effect in a mouse model of ovarian cancer *in vivo*.	Prabha and Raj, 2017
Chitosan	Therapeutic effect in a rat model of Alzheimer's disease *in vivo* (preclinical study).	Luo *et al*. 2011

Table 4: Characterization of Nanoparticles.

Characteristics	Solid	Liquid
Size	Electron microscope and laser diffraction for bulk samples.	Photon correlation spectroscopy and centrifugation.
Surface area	BET Isotherm	Simple titration and NMR experiments.
Composition	XPS and Chemical digestion followed by wet chemical analysis for bulk samples.	Chemical digestion for mass spectrometry, atomic emission spectroscopy and ion chromatography.
Surface morphology	Image analysis of electron micrographs.	Deposition onto a surface for electron microscopy.
Surface charge	Zeta potential	Zeta potential
Crystallography	Powder X-ray or neutron diffraction.	-

BET: Brunauer-Emmett-Teller model, NMR: Nuclear Magnetic Resonance Spectroscopy, XPS: X-ray Photoelectron Spectroscopy (Anu Mary and Saravanakumar, 2017).

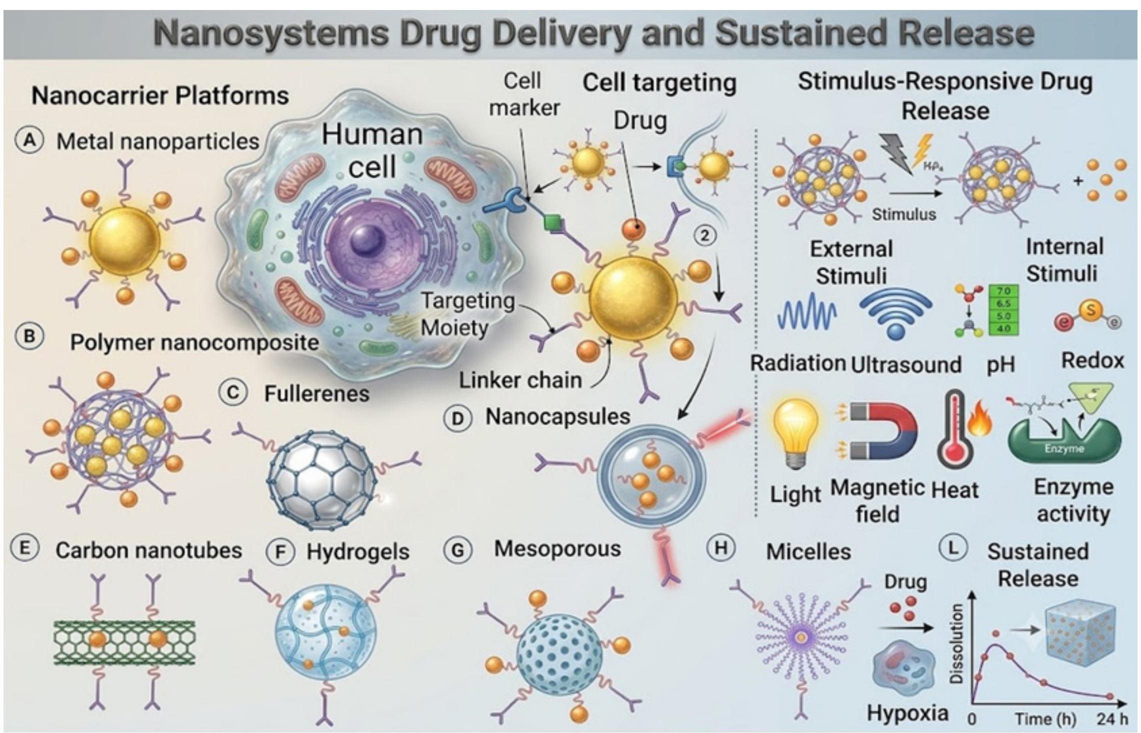

Figure 3: Nanomaterial for precise drug delivery through biological membranes (Source: Vancha Harish *et al*., 2022 Copyright © 2022 Licensee MDPI, Basel, Switzerland).

Nanofiltration is a membrane filtration device that is widely employed in the food and dairy sectors. Soil pollution is also emerging as a significant problem, and nanoparticles are being utilized to treat or clean it by injecting nanoparticles into specific sites for contamination with heavy metals and toxic industrial waste (Azimi *et al*., 2017). Nanoparticles are applied in the form of small catalysts in gaseous activity, especially in industrial stacks, to cut down contaminants to certain levels or eliminate them entirely, hence minimizing air pollution.

Challenges and Future Directions Relating to Nanoparticles

Despite their advantages, concerns remain regarding the potential environmental and health risks associated with nanoparticles. Understanding nanoparticle behaviour, toxicity, and long-term impacts is essential for developing safe and sustainable applications. Future research should focus on environmentally friendly synthesis methods, regulatory frameworks, and risk assessment strategies to ensure responsible use of nanotechnology.

CONCLUSION

Nanoparticles exhibit unique nanoscale properties that enable applications in medicine, energy, electronics, and environmental remediation. Nanoparticle-based drug delivery systems improve targeting, efficacy, and safety, particularly for chronic diseases. Green and polyherbal-mediated synthesis approaches provide sustainable alternatives, though challenges related to toxicity and regulation must be addressed for safe and responsible nanotechnology development.

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ABBREVIATIONS

NPs: Nanoparticles; **Cu-NPs:** Copper Nanoparticles; **Ag-NPs:** Silver Nanoparticles; **Au-NPs:** Gold Nanoparticles; **CuO NPs:** Copper Oxide Nanoparticles; **NDDS:** Novel Drug Delivery Systems; **DNA:** Deoxyribonucleic Acid; **T2DM:** Type 2 Diabetes Mellitus; **TNF-α:** Tumor Necrosis Factor-alpha; **IL-6:** Interleukin-6; **XPS:** X-ray Photoelectron Spectroscopy; **XRD:** X-ray Diffraction; **FTIR:** Fourier Transform Infrared Spectroscopy; **SEM:** Scanning Electron Microscopy; **TEM:** Transmission Electron Microscopy; **AFM:** Atomic Force Microscopy; **DLS:** Dynamic Light Scattering; **BET:** Brunauer-Emmett-Teller; **NMR:** Nuclear Magnetic Resonance Spectroscopy; **DFT:** Density Functional Theory; **LEDs:** Light Emitting Diodes; **Pt:** Platinum; **CeO_2:** Cerium Oxide; **eV:** Electron Volt.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

SUMMARY

Nanotechnology offers transformative potential across medicine, energy, electronics and environmental remediation. Nanoparticles exhibit unique physical, chemical, and biological properties that enable applications in drug delivery, diagnostics, tissue engineering, biosensors, renewable energy, and pollution control. Continued research and sustainable innovation are essential to harness the full benefits of nanotechnology while minimizing associated risks, ensuring a cleaner and more efficient future.

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