

# Emerging Trends in Nanoparticle Technology: A Review of Recent Innovations

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*Abstract— Nanoparticles are minuscule particles measuring 1-100 nanometers (nm) in size. Recently, scientists from all around the world have become piqued by the numerous applications of nanoparticles in a variety of fields, including catalysis, gas detection, energy production from renewable sources, electronics, medicine, diagnostics, targeted drug delivery, cosmetics, the construction industry, and the food industry. The decisive factors that determine the properties of nanoparticles (NPs) are their sizes and shapes. To achieve the aforementioned applications, nanoparticles must be of the suitable in terms of size, structure, monodispersity, and*

*morphology. In nanotechnology, new processes have been created that are environmentally friendly and can be utilized to reliably produce nanomaterials and nanoparticles. The goal of this research is to illustrate top-down methods and bottom-up methods for the production of nanoparticles, as well as various characterization techniques, characteristics of nanoparticles, and various uses of nanoparticles. Additionally, we will discuss the reasons behind the ineffectiveness of some nanomedicines, and some important considerations in the development of nanomedicines in brief.*

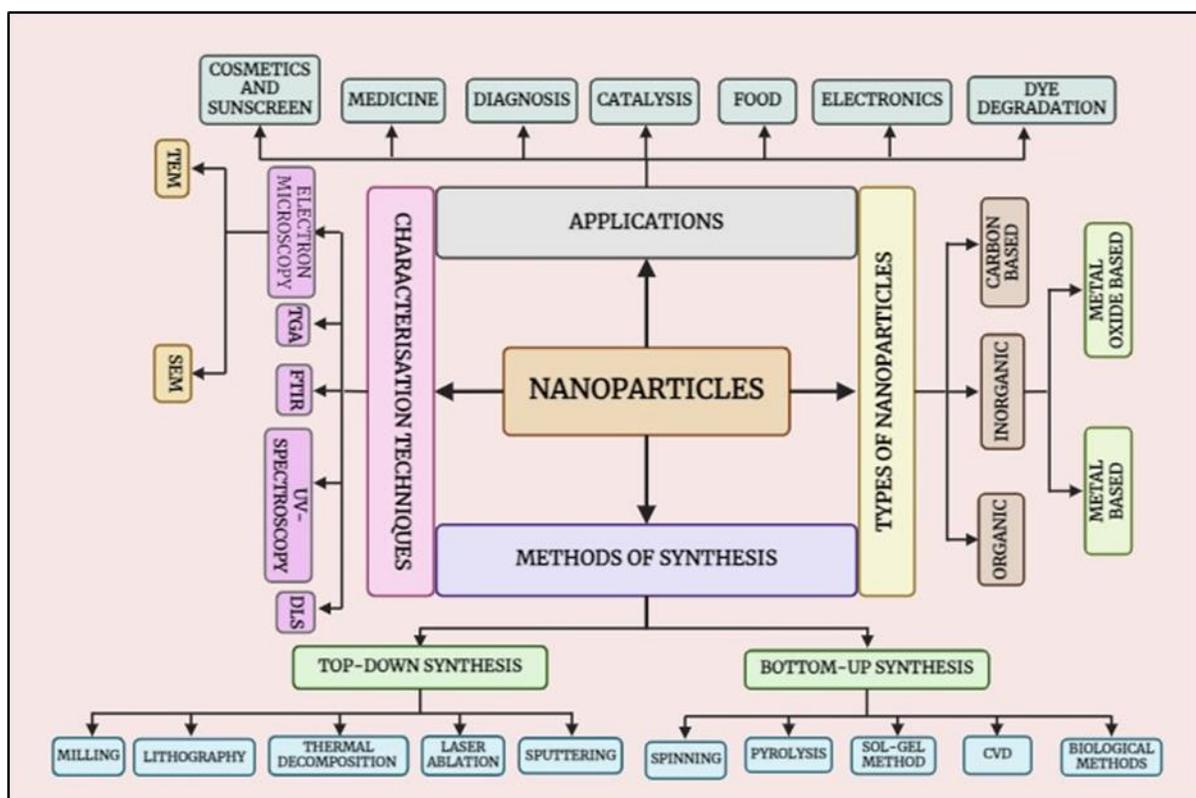


FIG 1: GRAPHICAL ABSTRACT

*Indexed Terms- Nanoparticles, Therapeutic efficacy, Targeted drug delivery, Nanomedicine*

## I. INTRODUCTION

Utilizing nanoparticles is the most recent and promising approach to drug delivery. A 'carrier' is used to transport the medications to various locations throughout the body. This carrier's ability to deliver the medication at a pace determined by the target tissue's requirements is crucial. The carrier should release the medication at the desired location and retain the medication until it arrives. All of this is only possible because of nanoparticles [1,2]. The medications are attached to the nanoparticle and subsequently injected into the patient. The medicine can be broken down, absorbed, or removed from the body once the nanoparticle has been released at the spot [2,3]. All of this is controlled by modifying the nanoparticle's surface characteristics and chemical makeup. There are several benefits to using nanoparticle medication delivery over traditional injection-based drug delivery. They minimize side effects, promote drug accumulation in the target tissue, shield the drug against degradation, and improve and prolong therapeutic efficacy [4]. A growing number of drug delivery systems, including lipid-based, injectable, gene-based, and site-specific systems, are gradually moving towards nanoparticle-based delivery thanks to advancements in nanotechnology. The future of medication administration depends on this advancement [5]. A notable change in medical and healthcare therapy has been made possible by the technological advancement of controlling materials at the nanoscale. Nowadays, there is an unexpected increase in the use of variety of nanoparticles in many different fields, including physics, medicine, organic or inorganic chemistry, molecular biology, and material science [6]. Nanoparticles are becoming more and more significant in biological applications because they fill the gap between molecular structures (<1 nm) and bulk materials (1 mm). Due to their exceptional qualities such as their large surface area and small size, nanoparticles can interact with biological systems very differently from larger-scale materials [7]. Furthermore, there are several nanoparticle modifications that enable the chemical and surface aspects of the particles to be customized. These particles include metal or polymer colloids, nanospheres, and nano capsules [8]. Finally, systems for nanoparticles can be engineered to break down within the body, or they can be functionalized or

tagged to target specific areas of the body using a biological system. An intriguing field for the study of nanoparticle drug delivery is created by these possible advantages over alternative molecular delivery systems that are similar in size to nanoparticles, including liposomes [9].

### 1.1 CATEGORIZATION

Nanoparticles are divided into three primary categories: organic, inorganic, and carbon-based nanoparticles.

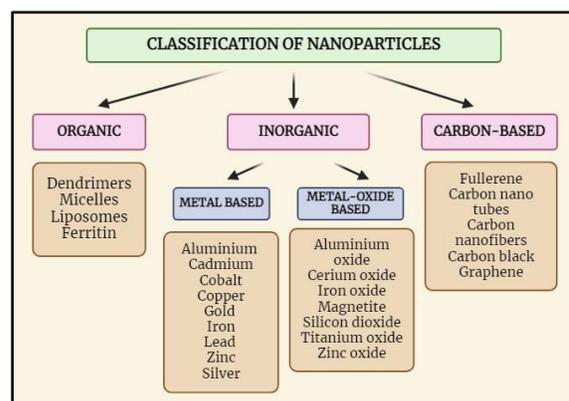


FIG 2: CATEGORIZATION OF NANOPARTICLES

#### 1.1.1. Organic nanoparticles

Organic polymers or nanoparticles are broadly referred to as micelles, dendrimers, ferritin, liposomes, etc. These nanoparticles are safe, efficient and environment friendly, such as micelles and liposomes. They have void cores and are referred to as nano capsules, and can react to both thermal and electromagnetic radiation, including heat and light [10]. They are ideal for delivering medications as a result of these unique characteristics. Organic nanoparticles are primarily employed in the biomedical industry for medication delivery systems.

#### 1.1.2. Inorganic nanoparticles

Inorganic nanoparticles are also known as non-carbon-based nanoparticles. Metal-oxide-based and metal-based nanoparticles are often referred to as inorganic nanoparticles.

#### 1.1.3. Metal-based nanoparticles

Metal-based nanoparticles refer to those that are produced from metals using either destructive or

constructive methods to nanometric sizes. Almost any metal can be manufactured into a nanoparticle [11]. Cadmium (Cd), gold (Au), aluminium (Al), cobalt (Co), zinc (Zn), copper (Cu), silver (Ag), iron (Fe), and lead (Pb) are all metals mostly employed in the manufacturing of nanoparticles.

#### 1.1.4 Metal-oxide-based nanoparticles

Metal-oxide-based nanoparticles are manufactured to improve the properties of their corresponding metal-based nanoparticles. For instance, ZnO (zinc oxide) nanoparticles have a high potential for producing ROS. That is why ZnO is especially active in cell wall breakdown, membrane permeability, and NP internalization caused by a lack of proton motive force than zinc (Zn) nanoparticles. Metal-oxide nanoparticles are mainly formed due to their increased reactivity and efficiency [12]. Titanium oxide (TiO<sub>2</sub>), aluminium oxide (Al<sub>2</sub>O<sub>3</sub>), iron oxide (Fe<sub>2</sub>O<sub>3</sub>), silicon dioxide (SiO<sub>2</sub>), magnetite (Fe<sub>3</sub>O<sub>4</sub>), copper oxide, manganese oxide and zinc oxide (ZnO) are the most frequently produced metal-oxide-based nanoparticles.

#### 1.1.5. Carbon based nanoparticles

The nanoparticles entirely formed of carbon are known as carbon-based [13]. These nanomaterials include fullerenes, graphene, carbon nanotubes (CNT), carbon nanofibers, carbon black, and activated carbon at nanoscale.

A.Fullerenes: Fullerenes (C<sub>60</sub>) are spherical carbon molecules composed of carbon atoms bonded together by sp<sup>2</sup> hybridization. The spherical structure is formed by 28-1500 carbon atoms with dimensions of up to 8.2 nm for single layers and 4-36 nm for complex fullerenes.

B.Graphene: Graphene is an allotrope of carbon. Graphene is a hexagonal framework of honeycomb structures made of carbon atoms on a two-dimensional plane. Graphene sheets are typically about 1 nm thick.

C.Carbon Nano Tubes (CNT): Carbon Nano Tubes (CNT), a graphene nano foil with a honeycomb-like structure of carbon atoms, are coiled into empty cylinders to produce nanotubes with diameters as small as 0.7 nm for a basic CNT and 100 nm for complicated CNT, and lengths ranging from a few

micrometres to several millimetres. A half fullerene molecule may have unfilled ends.

D.Carbon Nanofiber: Carbon nanofibers are produced from the same graphene nano foils as CNTs, but they are coiled into cups or cones rather than cylindrical tubes.

E.Carbon black: It is a type of amorphous carbon material having spherical shape and dimension that ranges from 20 to 70 nm. The particles interact so intensely that they form clusters of 500 nm in size.

### III. CHARACTERISTICS OF NANOPARTICLES

The unique features of a nanoparticle define its potential and application. Different measurement techniques are used to carry out the nanoparticle characterization process. Various characteristics of nanoparticles are listed below:

#### 3.1. Size

Particle size is one of the most basic and crucial measures for characterisation of nanoparticles. This component influences particle size, distribution, and whether it's micro- or nanoscale. Electron microscopy is commonly used for measuring particle size and dispersion. SEM and TEM images are applied to analyse particle and cluster sizes, whereas laser diffraction is employed to evaluate solid-phase bulk materials [14]. Using centrifugation and photon correlation spectroscopy, the particles in the liquid phase are measured whereas the particles in the gaseous phase are hard and difficult to visualize, so a scanning mobility particle sizer (SMPS) is employed, which enables rapid and more precise measurements than any other method.

#### 3.2 Surface area

Another significant factor worth considering when characterizing nanoparticles is their surface area. The surface area-to-volume ratio of nanoparticles significantly affects their efficiency and characteristics. BET analysis is a widely employed method for estimating surface area [15]. Although a simple titration is adequate for estimating the surface area of particles in the liquid phase, this method can be tedious and time-consuming. Therefore, nuclear

magnetic resonance spectroscopy (NMR) is used. To measure the surface area of nanoparticles in the gas phase, a differential mobility analyser (DMA) and a modified SMPS are used.

### 3.3. Composition

The elemental composition of the nanoparticle determines its purity and functioning. Undesirable components in nanoparticles might lower its potency and cause adverse reactions and degradation. X-ray photoelectron spectroscopy (XPS) is typically employed to assess the composition of nanoparticle [16]. Gaseous phase particles are collected using filtration or electrostatics, and then analysed using spectrometric or wet chemical procedures [17].

### 3.4. Surface morphology

Nanoparticles may be shaped and formed in many ways, allowing for optimal use of their capabilities. There are several forms, including round, flat, cylindrical, tubular, conical, and irregular. The surfaces of these forms might be crystalline, amorphous, homogeneous, or uneven. Electron microscopy imaging techniques, including SEM and TEM, are used for measuring the surface [18,19]. Gaseous phase particles are deposited on a surface for analysis, whereas liquid phase particles are captured electrostatically or through filtration for imaging with electron microscopy.

### 3.5. Surface charge

A nanoparticle's interactions with a target depend on its surface or overall charge. Zeta potentiometers are commonly used to measure surface charges and dispersion stability in solutions [14]. A differential mobility analyser (DMA) measures the charge of nanoparticles in the gaseous phase.

### 3.6 Crystallography

Crystallography is a scientific examination of atomic and molecular arrangements in crystals and other materials. Crystallography may determine the structure of nanoparticles by powder X-ray, electron, or neutron diffraction [20].

### 3.7 Concentration

The concentration of nanoparticles in the gaseous phase is monitored to determine the amount of air or gas needed for the procedure. The concentration, size,

and dispersion of nanoparticles in a given volume of air or gas determines its performance or efficiency. Concentration measurements are often conducted using a Condensation Particle Counter (CPC).

## IV. CHARACTERIZATION TECHNIQUES FOR NANOPARTICLES

Characterization techniques play a crucial role in understanding the properties and behaviour of nanoparticles. They provide valuable insights into nanoparticle size, shape, structure, composition, surface chemistry, and interactions, which are essential for optimizing their performance in various applications. Here are explanations of some commonly used characterization techniques:

### 4.1. Electron Microscopy

A. Transmission Electron Microscopy (TEM): TEM produces high-resolution images of nanoparticles, allowing visualization of their composition, size, and internal structure at the nanoscale [21].

B. Scanning Electron Microscopy (SEM): SEM produces detailed surface morphology images of nanoparticles, providing details on size, shape, and surface features of the particle [22].

### 4.1 Dynamic Light Scattering (DLS)

DLS studies the hydrodynamic size distribution of nanoparticles in solution using their Brownian motion. It provides information on nanoparticle size distribution, polydispersity, and the aggregation state in liquid environments [23].

### 4.2 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR is used to analyse the chemical composition and surface functional groups of nanoparticles. By measuring the absorption of infrared radiation by molecular vibrations, FTIR provides information on nanoparticle surface chemistry, ligand binding, and functionalization [24].

### 4.3 UV-Visible Spectroscopy

UV-Visible spectroscopy is used to characterize the optical properties of nanoparticles, such as absorption and plasmon resonance. It provides information on nanoparticle concentration, size, and optical bandgap,

which are relevant for applications in sensing, imaging, and photovoltaics [25].

#### 4.4. Zeta Potential Analysis

Zeta potential analysis investigates the electrokinetic properties of nanoparticles in solution, giving detailed information regarding their surface charge and stability. It is used to assess nanoparticle dispersion, aggregation, and colloidal stability in various environments [26].

#### 4.5. Thermogravimetric Analysis (TGA)

TGA is used to analyse thermal stability, composition, and mass changes of nanoparticles with temperature. It provides information on the presence of organic coatings, surface modifications, and decomposition temperatures of nanoparticles [27].

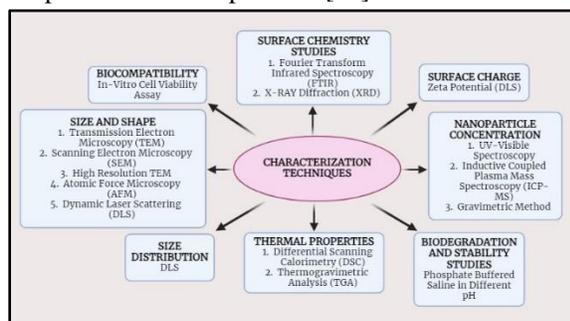


FIG 3: VARIOUS CHARACTERIZATION TECHNIQUES OF NANOPARTICLES

### V. SYNTHESIS OF NANOPARTICLES

There are two methodologies used for the synthesis of nanoparticle: top-down method and bottom-up method.

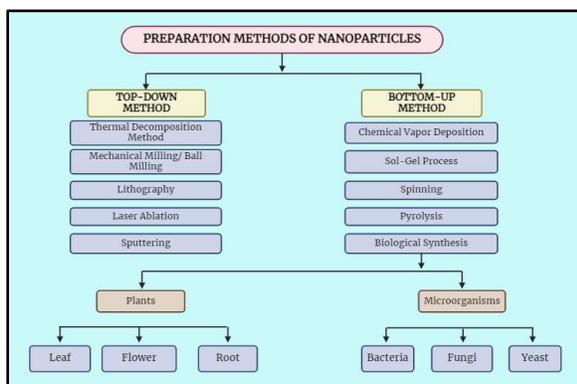


FIG 4: VARIOUS METHODS OF PREPARATION OF NANOPARTICLES

#### 5.1. Bottom-up method

Bottom-up or self-assembly or constructive technique is the building up of material from atoms to clusters to nanoparticles. The most frequent bottom-up processes used for producing nanoparticles are sol-gel, spinning, CVD, pyrolysis, and biosynthesis.

##### 5.1.1 Sol-gel method

The sol is a colloidal solution that contains solid particles suspended in a liquid phase. The gel is a solid macromolecule that are immersed in a liquid. Sol-gel method is the favoured bottom-up approach due to its simplicity and ability to synthesize most nanoparticles. Such wet-chemical approach uses a chemical solution as a raw material to create an integrated system of distinct particles. Metal oxides and chlorides usually serve as raw material for this process [28]. The raw material is then dissolved in a host liquid through sonication, stirring, or shaking, resulting in a system with both a solid and liquid phase. Nanoparticles are then retrieved through phase separation using filtration, sedimentation, and centrifugation. The moisture is removed via drying [29].

##### 5.1.2 Spinning

A spinning disc reactor (SDR) is used to form nanoparticles. A revolving disc inside a chamber/reactor allows temperature control. To prevent chemical reactions, reactors are typically filled with inert gases such as nitrogen [12]. The disc rotates at varying speeds, allowing liquids such as precursors and water to be forced in. Spinning causes atoms or molecules to attach, which are then precipitated, collected, and dried [30].

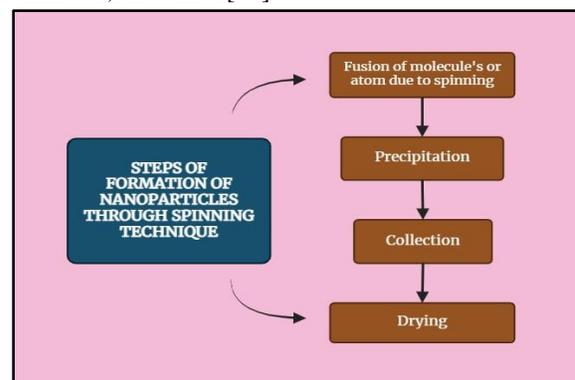


FIG 5: STEPS OF FORMATION OF NANOPARTICLES THROUGH SPINNING

### 5.1.3. Chemical Vapour Deposition (CVD)

Chemical vapour deposition is a process that involves precipitating a thin layer of gaseous reactants onto a substrate. Deposition occurs in a reaction chamber at standard temperature by mixing gas molecules. A chemical reaction occurs when a heated substrate encounters the combined gas [13]. This reaction results in a thin coating of desired nanoparticle on the substrate surface, which can be recovered and used. The critical factor in CVD is the temperature of the substrate. CVD produces pure, rigid, homogeneous, and strong nanoparticles. The chemical vapor deposition (CVD) method is classified based on the energy source utilized for initiating the process, including thermally activated CVD [31], plasma-enhanced CVD [32], and photo-initiated CVD [33]. The limitations involve requirement of specific instrumentation, and the gaseous byproducts are highly hazardous [34].

### 5.1.4. Pyrolysis

Pyrolysis is the primary method for formation of nanoparticles on a large scale. It involves igniting a precursor with flame. The precursor is either liquid or gas that is delivered into the furnace at high pressure through a small opening and burned [35]. Nanoparticles are then recovered from combustion or by-product gases using air classification. Some of the furnaces use plasma and laser instead of flame to accomplish high temperature for simple evaporation [36]. The benefits of pyrolysis include simple, cost-effective, efficient, and continuous process with a high yield.

### 5.1.5. Biosynthesis

Biosynthesis is an environmentally friendly method for producing non-toxic and biodegradable nanoparticles [37]. Biosynthesis employs plant extracts, bacteria, fungi, etc. combined with the precursors to generate nanoparticle instead of standard chemicals for bio-reduction [38].

## 5.2. Top-down method

Top-down or destructive technique involves breaking materials to nanometric-scale particles. Common methods for producing nanoparticles include nanolithography, sputtering, laser ablation, mechanical milling, and thermal decomposition/breakdown.

### 5.2.1. Mechanical milling

Mechanical milling is the most used top-down approach for synthesising nanoparticles. It is used to mill and post-anneal nanoparticles during manufacturing, with multiple elements milled in an inert environment [39]. Mechanical milling is affected by plastic deformation, fracture, and cold-welding, all of which affects particle shape and size.

### 5.2.2. Nanolithography

Nanolithography is the method of producing structures with only one dimension of 1 to 100 nm. It involves several methods, including electron-beam, nanoimprint, optical, multiphoton, and scanning probe lithography [40]. Lithography is the technique of printing a desired structure on a photo-sensitive substance by selectively removing a piece of the material. The benefit of nanolithography is the ability to transform a single nanoparticle into a cluster of nanoparticles of appropriate size and shape. The downsides include the requirement of complicated equipment and its accompanying costs [41].

### 5.2.3. Laser ablation

Laser Ablation Synthesis in Solution (LASiS) is a characteristic method for producing nanoparticles from various solvents. Irradiating a metal in a liquid solution with a laser beam creates a plasma plume, resulting in the formation of nanoparticles [42]. This top-down process is used for synthesizing metal-based nanoparticles. LASiS is a 'environmental friendly' approach since it allows steady synthesis of nanoparticles in water and organic solvents without the need of any stabilising agents.

### 5.2.4. Sputtering

Sputtering is the technique of precipitating nanoparticles on a surface by ejecting particles that impact with ions [43]. Sputtering involves deposition of a thin film of nanoparticles followed by annealing. The size and shape of nanoparticles are determined by factors such as annealing temperature and duration, layer thickness, and substrate type [44].

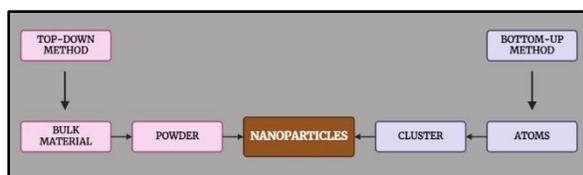


FIG 6: PROCESS OF FORMATION OF NANOPARTICLES

## VI. SIGNIFICANT CHALLENGES IN NANOPARTICLE PRODUCTION

Currently, with the growth of nanotechnology, there is a sharp increase in the amount of knowledge and study focused on nanoparticles. However, only few of them manage to advance to the point of clinical trials. The majority only get as far as the *in vitro* and *in vivo* phases. While the clinical translation of each individual nano formulation offers distinct challenges, most NPs face common barriers that can be classified into three broad groups: biological, technological, and study-design related.

The absence of administration routes, reducing biodistribution, NPs' disintegration, toxicity, and the channel by which they pass through biological barriers are some of the biological obstacles [45]. Because NPs are routinely injected intravenously (IV) into the circulation, it is difficult for them to remain and interact with the target location. As a consequence, a medicine is given at a high dosage, which may not have the desired therapeutic benefits [46]. However, several *in vitro* and *in vivo* studies have shown how 3D magnetic fields may be used to control the movement of NPs against blood flow, a challenge that magnetic nanoparticles can solve. Nevertheless, more investigation is required into the effects of magnetic fields on the human body, the interplay of multiple magnetic fields, and high NP concentrations.

Performance forecasts, equal optimization, and scale-up synthesis are some of the technological problems faced during NPs synthesis. These criteria are crucial for NPs' clinical effectiveness. Because most NPs used in *in vitro* and *in vivo* studies are generally produced in tiny batches, scaling up to large volumes is not always achievable due to equipment and other constraints. The process of developing lead clinical candidates that perform well in animal models is not structured or optimized. To overcome this, we may use

methodologies that allow us to analyse a large number of nano formulations and pick one ideal formulation through several iterations [47,48,49]. However, such effects should not be immediately included into human research. Nanoparticles' effectiveness and performance are difficult to anticipate, and replicating the *in vivo* outcomes is exceedingly challenging in human studies. It is possible to create theoretical or computational modelling that mimics physiological environments and tissue in conjunction with experimental data. For example, organs-on-chips are now being researched and might increase NP efficiency and performance forecasts.

Issues related to study design, such as study size, purpose, and when to administer NP treatments have a big influence on clinical trials. Most of the research uses "cell and animal models," which could not yield outcomes in clinical trials that are understandable. As such, it is difficult to replicate natural physiological reactions using a single model. Furthermore, given one of the important characteristics of cancer is metastasis, "models of cancer metastasis" ought to be thoroughly studied. Furthermore, if we concentrate on individualized therapy, N = 1 clinical investigation will be necessary. Numerous factors, including genetics, environment, and prior medical history, must be considered [50,51].

## VII. APPLICATIONS OF NANOPARTICLES

The important uses of nanoparticles are listed below.

A. Cosmetics and Sunscreens: Sunscreen utilizing nanoparticles, such as titanium dioxide or zinc oxide, has several advantages. Titanium oxide and zinc oxide nanoparticles, which absorb and reflect UV radiation while being transparent to visible light, have been used in sunscreen formulations. Iron oxide nanoparticles are used as pigments in certain lipsticks [52].

B. Electronics

The demand for huge and high-brightness screens in computer, monitors and televisions has led to increased adoption of nanoparticle display technologies. Nanocrystalline lead telluride, cadmium sulphide, zinc selenide, and sulphide are used in light emitting diodes (LEDs) on current displays [53]. The proliferation of portable consumer products, such as mobile phones and laptop computers, has resulted in a massive need for tiny, lightweight, high-capacity

batteries. Nanoparticles are useful as separator plates in batteries. The foam-like (aerogel) structure allows for significantly more energy storage compared to ordinary batteries. Nanocrystalline nickel and metal hydride batteries have a larger surface area and require less recharging, leading to longer battery life [54]. Nanoparticles can detect gases such as NO<sub>2</sub> and NH<sub>3</sub> due to their increased electrical conductivity [55]. The charge transfer from nanoparticles to NO<sub>2</sub> increases their pores, making them more effective gas sensors.

#### C.Catalysis

Nanoparticles have a vast surface area, resulting in higher catalytic activity. Because of their higher surface-to-volume ratio, nanoparticles constitute excellent catalysts for chemical synthesis [56]. Platinum nanoparticles can significantly reduce the amount of platinum required in automobile catalytic converters due to their large surface area, resulting in cost savings and increased performance. Some chemical processes, such as the reduction of nickel oxide to metal nickel (Ni), need nanoparticles.

#### D.Medicine

Nanotechnology has aided the medical profession in medicine administration. Nanoparticles provide tailored drug delivery to specific cells [58]. Administering the drug in the proper location and dosage significantly minimizes total consumption and adverse effects. This technique saves money and has fewer side effects. Tissue engineering is the process of replicating and repairing damaged tissue using nanotechnology. Tissue engineering can replace conventional procedures like organ transplants and artificial implants. One of the examples is bone development using carbon nanotube scaffolds [59]. The utilization of gold in medicine is not unique. Ayurveda, an Indian medical tradition, uses gold in many ways. One typical prescription is the use of gold to improve memory. Some paediatric medicines contain gold to improve a baby's mental health [60].

#### E.Food

By using nanotechnology, food production, processing, preservation, and packaging all are improved. Nanocomposite coatings in food packaging may deliver anti-microbial chemicals directly onto the film coated surface [61]. In canola oil manufacturing, nanodrops are utilized as a vitamin and mineral additives.

#### F.Diagnosis

Several nanoparticles are employed in the detection and treatment of certain cancers. Such nanoparticles can be used accurately for imaging tumours or to distribute drugs (theragnostic approach) with minimum adverse effects. Nanodevices synthesized for oncology applications include quantum dots (QDs), carbon nanotubes (CNTs), paramagnetic nanoparticles (NPs), liposomes, gold nanoparticles (GNPs), MRI contrast agents for intraoperative imaging, and cutting-edge NP-based methods for highly specific DNA and protein detection [62,63,64,65].

#### E.Dye Degradation

Wastewater treatment and potential future applications of nanomaterials demand the removal of water impurities prevalent in sources of water, such as azo, cationic, and acid dyes, as well as additional chemicals of the same kind. These chemicals affect aquatic life and lead to water pollution. NPs serve as catalysts and absorb contaminants [55]. They have a high surface area yet are relatively small in size. It has been established that both Ag and AuNPs have catalytic activity adequate to eliminate organic pigments. These nanoparticles accelerate the process while reducing the time needed to remove the dyes [66,67].

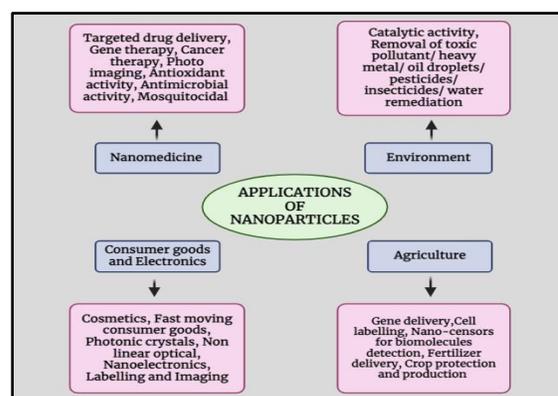


FIG 7: MAJOR APPLICATIONS OF NANOTECHNOLOGY

## VIII. FUTURE DIRECTIONS IN NANOPARTICLES RESEARCH

8.1. Advanced Synthesis Techniques: Emerging trends in nanoparticle synthesis focus on developing novel synthesis techniques that offer improved control over nanoparticle size, shape, composition, and functionality. The major synthesis techniques include

bottom-up approaches such as atomic layer deposition, molecular self-assembly, and biologically inspired synthesis methods, as well as top-down approaches such as nanolithography and laser-assisted synthesis techniques [68].

8.2. Multifunctional Nanoparticles: The development and creation of multifunctional nanoparticles with tailored characteristics for specific purposes is gaining momentum. Future research directions involve integrating multiple functionalities into nanoparticles, such as therapeutic agents, imaging probes, targeting ligands, and stimuli-responsive components, to enable synergistic effects and enhanced performance in biomedical, environmental, and energy applications [69].

8.3. Precision Medicine: Nanoparticles hold great potential for advancing precision medicine approaches by enabling personalized diagnosis and treatment strategies. Future directions in nanoparticle-based therapeutics include the development of various targeted drug delivery systems, theragnostic nanoparticles for simultaneous imaging and therapy, and precision nanomedicine platforms tailored to individual patient characteristics, disease profiles, and treatment responses [70].

8.4. Nanomaterials for Sustainable Technologies: Nanoparticles play a crucial role in advancing sustainable technologies for environmental remediation, renewable energy, and resource conservation. Future research directions include developing nanoparticle-based materials and devices for water purification, air pollution control, energy storage and conversion, and sustainable agriculture, with an emphasis on efficiency, cost-effectiveness, and environmental compatibility [71].

8.5. Nanotoxicology and Safety Assessment: As the use of nanoparticles expands across various industries, addressing nanotoxicology and safety assessment challenges becomes increasingly important. Future research directions involve advancing nanotoxicology studies to understand the mechanisms of nanoparticle toxicity, developing predictive models for assessing nanoparticle safety, and establishing guidelines for risk assessment and regulatory decision-making [72].

IX. APPROVED MARKETED FORMULATIONS OF NANOPARTICLES

NAME OF DRUG	TRADE NAME	TYPE OF NANOPARTICLE	YEAR OF APPROVAL	APPLICATIONS	REFERENCE
Iron Sucrose	Venofer	Inorganic/Metallic NPs	2000	Chronic renal failure with anaemia	[73,74]
Ferumoxytol	Feraheme	Inorganic/Metallic NPs	2009	Chronic renal failure with anaemia	[73,74]
Sodium ferric gluconate	Ferrlecit	Inorganic/Metallic NPs	1999	Chronic renal failure with anaemia	[73,74]
Lanreotide acetate	Somatuline depot	Inorganic/Metallic NPs	2007	Acromegaly	[76]
Ferric carboxymaltose	Injectafer	Inorganic/Metallic NPs	2013	Chronic renal failure with anaemia	[75]

TABLE:1 Marketed formulations containing non-polymeric nanoparticles.

NAME OF DRUG	TRADE NAME	TYPE OF NANOPARTICLE	YEAR OF APPROVAL	APPLICATIONS	REFERENCE
Megestrol acetate	Megace ES	Nanocrystals	2005	Anorexia	[73,74]
Fenofibrate	Tricor	Nanocrystals	2004	Hyperlipidaemia	[73,74]
Aprepitant	Emend	Nanocrystals	2003	Vomiting agent	[73,74]

Methylphenidate HCl	Ritalin LA	Nanocrystals	1955	Mental stimulant	[73,74]
Sirolimus	Rapamune	Nanocrystals	2000	Immunosuppressant	[73,74]
Paliperidone palmitate	Invega Sustenna	Nanocrystals	2009,2014	Schizo affective disorder	[77]
Tizanidine HCl	Zanaflex	Nanocrystals	2002	Muscle relaxant	[73,74]
Griseofulvin	Gris-Peg	Nanocrystals	1982	Fungal infection	[79]
Brinzolamide	Azopt	Nanocrystals	1998	Glaucoma	[79]
Theophylline	Elixophyllin Nostrum Labs Inc	Nanocrystals	1979	Bronchial dilation	[79]
Naproxen sodium	Naprelan	Nanocrystals	1996	Anti-inflammation	[79]
Nabilone	Cesamet	Nanocrystals	1995	Anti-emetic	[79]
Olanzapine	Zyprexa	Nanocrystals	1996	Schizophrenia	[73,74]
Dantrolene sodium	Ryanodex	Nanocrystals	2014	Malignant benign hypothermia	[78]

TABLE:2 Marketed formulations containing crystalline nanoparticles.

NAME OF DRUG	TRADE NAME	TYPE OF NANOPARTICLE	YEAR OF APPROVAL	APPLICATIONS	REFERENCE
Irinotecan	Onivyde	Liposomal irinotecan	2015	Pancreatic cancer	[81]
Cytarabine	DepoCyt	Liposomal cytarabine	1999	Lymphoma	[73,74]
Doxorubicin	Doxil	Liposomal doxorubicin	1995	Kaposi sarcoma, ovarian cancer, multiple myeloma	[73,74]
Octocog alfa	Advate	Liposome	2004	Haemophilia A	[83]
Mifamurtide	Mepact	Liposomes	2004	Myosarcoma	[84]
Daunorubicin	DaunoXome	Liposomal daunorubicin	1996	Kaposi sarcoma	[73,74]
Amphotericin B	AmBisome	Liposomal amphotericin B	1997	Fungal infection	[73,74]
Perflutren	Definity	Perflutren lipid microspheres	2001	Ultrasound contrast agent	[82]
Vincristine	Marqibo	Liposomal vincristine	2012	Acute lymphocytic blood clot	[80]
Moderna	Moderna	Liposomal nanoparticles	2020 (EUAs)	Covid-19	[85,86]
Pfizer-BioNTech	Pfizer-BioNTech	Liposomal nanoparticles	2020 (EUAs)	Covid-19	[85,86]
Cytarabine: daunorubicin	VYXEOS	Liposomes	2017	Acute myeloid leukaemia	[82]
Propofol	Diprivan	Liposomes	1989	Anaesthesia	[82]

TABLE:3 Marketed formulations containing lipid-based nanoparticles.

NAME OF DRUG	TRADE NAME	TYPE OF NANOPARTICLE	YEAR OF APPROVAL	APPLICATIONS	REFERENCE
Ibritumomab tiuxetan	Zevalin	Suspension	2002	Lymphoma	[73,74]
Verapamil HCl	Verelan PM	PLGA nanoparticles	1998	Hypertension, angina, and rhythm disorders	[79]
Denileukin diftitox	Ontak	Protein NP	1999	T-cell lymphoma	[73,74]
Docetaxel	Taxotere	Micelles	1996	Anti-neoplastic	[76]
Pegvisomant	Somavert	PEGylated HGH receptor antagonist	2003	Acromegaly	[73,74]
Pegloticase	Krystexxa	Polymer-protein conjugate	2010	Chronic gout	[73,74]
PEGylated factor VIII	Adynovate	Polymer-protein conjugate	2015	Haemophilia	[73,74]
Factor IX	Rebinyn	Glyco-pegylated coagulation factor IX	FDA 2017	Haemophilia	[88]
Triamcinolone acetamide	Zilretta	PLGA hydrogel	2017	Osteoarthritis	[88]
Trastuzumab	Kadcyla	Maytansine derivative, DM1	2013	Breast cancer	[87]
Paclitaxel	Abraxane	Protein NP	2005	Breast cancer	[82]
Pegflgrastim	Neulasta	PEGylated GCSF protein	2002	Leukopenia by chemotherapy	[73,74]

TABLE:4 Marketed formulations containing polymer-based nanoparticles.

### CONCLUSION

In conclusion, nanoparticles represent a groundbreaking field of science with vast potential for transformative applications across various industries. Their unique properties have led to significant advancements in medicine, electronics, energy, environmental science, cosmetics, food, textiles, automotive, and aerospace sectors, and among others. However, alongside these opportunities come various challenges.

One major challenge is the potential environmental and health impacts of nanoparticles, which require careful assessment and regulation to ensure their safe use. Additionally, the scalability of nanoparticle production and the cost-effectiveness of large-scale manufacturing remain areas of concern. Furthermore, ethical considerations surrounding the use of nanoparticles in areas such as medicine and food require ongoing attention.

Despite these challenges, the opportunities presented by nanoparticles are immense. Continued research and innovation in nanotechnology promise to revolutionize industries, enhance human health and well-being, and address pressing global challenges such as climate change and resource scarcity. By navigating these challenges effectively, stakeholders can harness the full potential of nanoparticles to drive sustainable development and create a brighter future for society.

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