Waqas AHMAD[1], Shahab KHAN[2*], Muhammad ISHAQ[3], Summia BIBI[3]
Mushtaq AHMAD[3], Faisal KHAN[3], Wail NAEEM[3], Bilal AHMAD[3], Nizam ULLAH[3]
and Noor UL ISLAM[3*]

FUNDAMENTALS, CLASSIFICATION, SYNTHESIS STRATEGIES, APPLICATIONS, AND CHALLENGES OF INORGANIC NANOPARTICLES

Abstract: Particles with at least one dimension in the nanoparticle range (1 nm to 100 nm) known as nanoparticles. These materials have an important role in chemistry, medicine, pharmacy, physics, biology, biotechnology, environment and other fields. Nanoparticles are classified in various types on the basis of material nature, dimensions and sizes. Nanoparticles can be prepared by a variety of methods, including chemical vapour deposition, co-precipitation, chemical reduction, laser ablation, sol-gel, sputtering, and biological methods. In medicine nanoparticles can be used as drug delivery system, as contrast imaging, and for targeted therapy. Apart from this, it can also be used in agriculture sector, catalysis, biosensor, solar cell etc. These applications are currently being explored, and research is ongoing. The future of nanoparticle application is promising as new nanomaterials and methods of synthesis are being developed. Research is also focusing on understanding the environmental impact of nanoparticles and improving safety protocols in their use. With the development of new and improved nanoparticles, the potential for applications in medicine, environment, and agriculture, will continue to expand.

Keywords: nanoparticles properties, nanoparticle preparation, biological potentials, agricultural role

Introduction

Nanomaterials are used in a variety of applications due to their distinctive physicochemical properties such as thermal conductivity, increased strength, improved electrical conductivity, and enhanced thermal reactivity. Examples of nanomaterials include polymeric nanoparticles, carbon nanotubes, quantum dots, and magnetic nanoparticles [1]. These materials are used in a wide range of products, ranging from medical devices to consumer electronics. They enable the development of emerging technologies**,** such as biodegradable plastics and advanced drug delivery systems. By manipulating nanomaterials at the atomic level, scientists and engineers can create materials with unique structural and

[1] Department of Chemistry, Nazarbayev University, Astana, Kazakhstan 53, Kabanbay Batyr Ave., Astana 010000, Republic of Kazakhstan, email: w.ahmad@nu.edu.kz, ORCID: 0009-0000-6274-7669.
[2] Department of Chemistry, University of Malakand, Dir Lower, KPK, Pakistan, ORCID: 0009-0009-1746-7487.
[3] Department of Chemistry, Government Degree Collage Lalqilla Dir Lower, Lalqilla 18350, Khyber Pakhtunkhwa, Pakistan, ORCID: MI 0009-0000-9600-3094, SB 0009-0005-9504-5475, MA 0009-0006-6948-1932, FK 0009-0005-9248-6451, WN 0009-0008-8024-7498, BA 0009-0000-6569-0864, NU 0009-0004-4052-2185, NUI 0000-0001-9755-8788
[*] Corresponding authors: shahabkhan332@yahoo.com, nooruomchem@gmail.com

properties [2]. Knowledge of the various types of nanoparticles and their synthesis, as well as their applications, will lead to the appropriate use of them in various fields.

The techniques employed for formulation are physical methods like laser ablation, evaporation condensation, chemical methods like chemical reduction, solvothermal method, polyol process, etc., and biological methods that make use of living biological systems to prepare nanoparticles. This is called biogenic synthesis which involves biological sources such as, fungi, algae, yeasts, actinomycetes, viruses, and plants. Nanomaterials can also be applied in renewable energy technologies. For example, quantum dots can be used in solar cells to absorb and convert sunlight into electrical energy. Nanomaterials can also be widely used for energy storage systems, such as lithium-ion batteries, which are commonly used in many electronic devices [3-5]. Nanomaterials are being employed in water purification technologies and in the development of high-performance materials with improved strength and durability [6]. The extensive application of nanoparticles in drug delivery systems is influenced by their capacity to enhance drug stability, provide controlled release, increased therapeutic efficacy, and reduced side effects. However, some potential health and environmental risks associated with the use of nanomaterials arise from their high chemical reactivity [7]. Studies have shown that certain nanomaterials may be toxic to humans and animals, and they may also pose adverse effects on the environment. Therefore, a comprehensive assessment of the potential risks associated with nanomaterials should be conducted before their application in various field [8]. Despite these potential risks, nanomaterials have already had a vital impact on modern society, and their future applications are extensive. The development of new technologies-based nanomaterials will continue to significantly influence scientific and technological advancements in the coming years [9].

Nanoparticles are particles with diameters ranging from 1 nm to 100 nm [10]. They have been widely applied in various fields including medical, agricultural, environmental, catalysis, industrial, and energy storage. Nanoparticles possess unique properties due to their small size, such as high surface-area-to-volume ratio, which provides them unique physical, chemical, and biological properties [11]. They can be engineered to interact with other materials and have the potential to revolutionise several industries, including energy production, drug delivery, and environmental remediation [12]. Nanoparticles can be utilised in a wide range of applications, from drug delivery systems to energy production technologies. They are also used in the production of various materials including nanoscale semiconductor materials, electronic components, and nanocomposites. They can transform multiple industries, including the medical and automotive industries, and are currently being applied in a host of research fields [13]. Nanoparticles may be used to improve the properties of the existing materials or to design completely new materials with new properties. They are enabling the production of stronger, lighter, and more durable materials than ever before. They may be deployed in the generation of materials that can store and communicate energy in a more productive manner or that are more productive at diffusing and absorbing light. Nanoparticles are also widely used in medical applications, such as medical imaging and drug delivery systems [14]. They can be used to improve target delivery of drugs, or to create material that can help detect and identify diseases. They can also be used in a variety of environmental applications such as water, water filtration and air purification system [15]. Overall, nanoparticles are revolutionising many industries, ranging from medical and industrial applications to environmental remediation.

Their unique properties combined with their small size, make them valuable material for improving existing technologies, and develop entirely new materials [16].

Nanoparticles possess exclusive properties due to their nanoscale size, such as a high surface-area to volume ratio, which provides unique physical, chemical, and biological properties [17]. They can be also used to enhance the existing materials or develop entirely new materials with novel properties. They are being used in variety of applications including medical, industrial, and environmental fields, and have the potential to revolutionise multiple industries [18]. This review provides a comprehensive overview of nanomaterials and nanoparticles, focusing on their classifications, synthesis approaches, including physical, chemical, and biological methods, and their diverse applications in biomedical, agriculture, environmental, energy storage, and industrial fields, while also highlighting potential health and environmental concerns associated with their use [19]. Considering all these factors, the chosen material is also a primary variable that determines the role, and especially the type, of NPs. Based on the material NPs are classified into three main types of inorganics, carbon-based, and organic and subdivided into different kinds such as metallic, ceramic, polymeric, and lipid-based due to their distinct characteristics, size and shapes are illustrated in Figure 1.

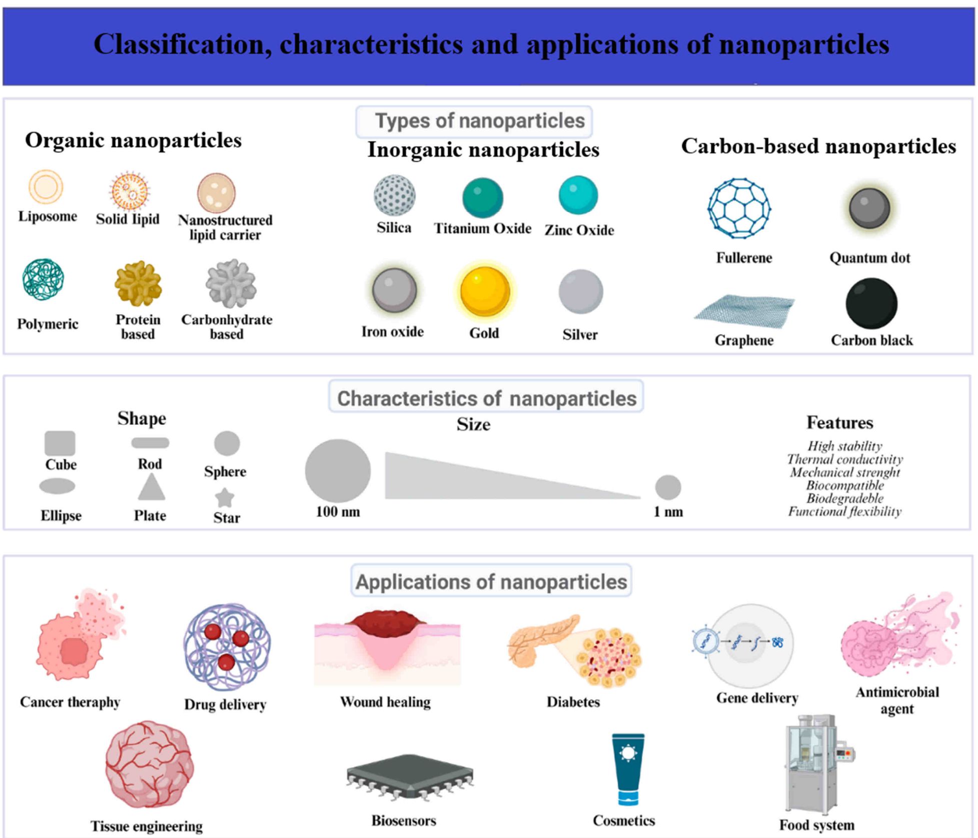

Fig. 1. Representative scheme of nanoparticles. Adopted and reproduced from [20]

Types of nanoparticles

Nanoparticles classification on the basis of material nature

On the basis of material nature, the nanoparticles are classified in various classes such as carbon-based nanoparticles, inorganic nanoparticles, organic nanoparticles etc. The details of these classes are given below, and their highlighted properties and application areas is presented in Table 1.

Carbon-based nanoparticles

Carbon-based nanoparticles are a significant class of nanomaterials composed primarily of carbon atoms arranged in different structural forms, resulting in different physicochemical properties. Major types of carbon-based nanoparticles include carbon nanotubes, graphene and graphene oxide, fullerenes and carbon dots. These nanoparticles show exceptional mechanical strength, electrical conductivity application, thermal stability and high Surface area, making them highly valuable in biomedical and technological applications. In medicine carbon-based nanoparticles are widely used for drug delivery, bioimaging, biosensing, gene delivery, photothermal therapy and tissue engineering [21]. The major types of carbon- based nanoparticles are illustrated in Figure 2.

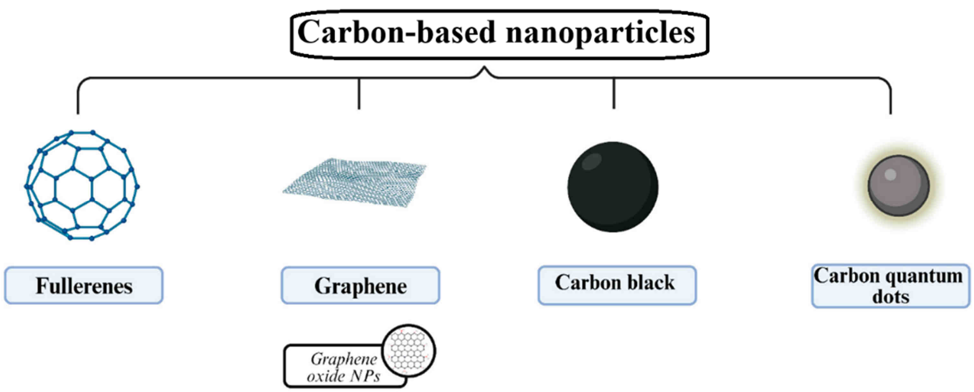

Fig. 2 Classification and subtypes of carbon-based nanoparticles. Adopted and reproduced from [20, 22, 23]

Carbon quantum dots nanoparticles

Carbon quantum dots nanoparticles are synthesised using bottom-up, or top-down approaches. Bottom-up method is more common and includes hydrothermal, or solvothermal carbonisation, microwave-assisted synthesis and thermal decomposition of organic precursors, such as glucose, citric acid, or biomass derived materials [24]. While in Top-down methods involve breaking down of bulk carbon materials through laser ablation, electrochemical oxidation, or chemical exfoliation. Carbon quantum dots are commonly used in bioimaging, and biosensing due to their tunable fluorescence and low toxicity. They are also applied in drug and gene delivery, photodynamic and photothermal cancer therapy, diagnostic imaging and antimicrobial applications [25]. GQDs, or graphene quantum dots, are small graphene fragments consisting of a single graphene sheet or a few graphene sheets with apparent graphene lattices and chemical groups on the edge or within the interlayer defect; CQDs, or carbon quantum dots, are always spherical and possess obvious crystal lattices and chemical groups on the surface; CNDs, or carbon nanodots, possess a high carbonisation degree with some chemical groups on the surface, but usually show no obvious crystal lattice structure and polymer features; CPDs, or carbonised polymer dots, have a polymer/carbon hybrid structure comprising abundant functional groups/polymer chains on the surface, and a carbon core different types of carbon dots are adapted in Figure 3.

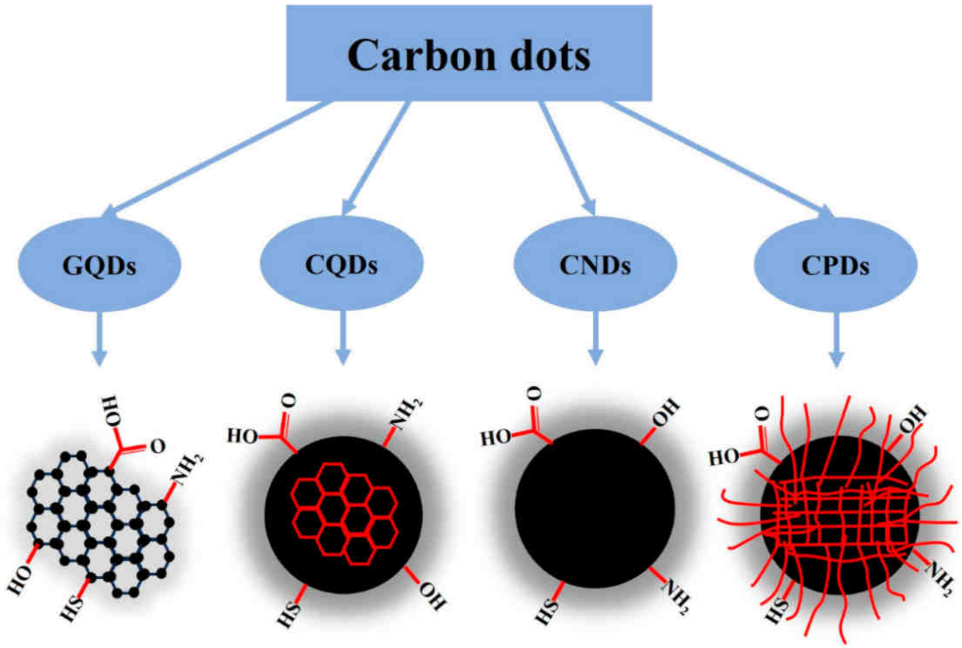

Fig. 3. Classification of carbon dots [26]

Graphene nanoparticles

Graphene nanoparticles are two-dimensional carbon-based nanomaterials composed of a single, or few layers of sp^2-hybridised carbon atoms are organised in hexagonal lattice, showing exceptional mechanical strength, thermal stability, electrical conductivity, and large surface area. Graphene nanoparticles can be also synthesised by using top down and bottom-up methods [27]. Graphene nanoparticles are used in drug and gene delivery, bio-imaging, biosensing, photothermal cancer therapy, and tissue engineering, due to their high surface area and ability to be functionalised with biomolecules. They are also applied in photocatalysis, electronics, energy storage, environmental remediation and antimicrobial coatings, making graphene versatile material for both biological and technological applications. Structural relationships among carbon-based nanomaterials derived from graphene are illustrated in Figure 4.

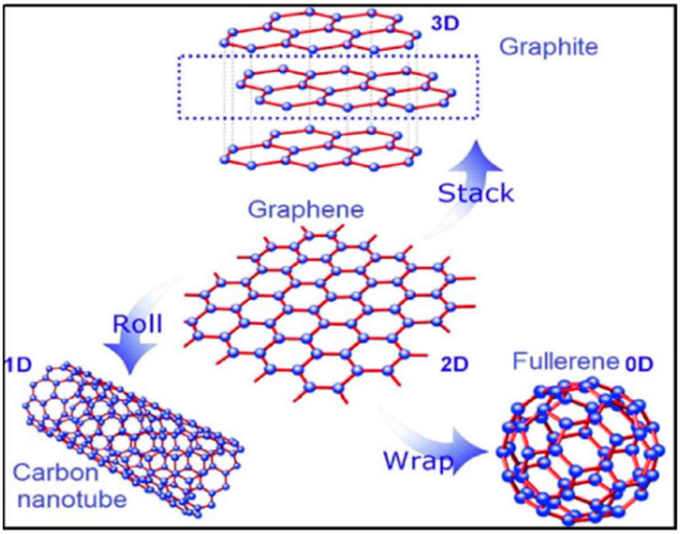

Fig. 4. Carbon-based nanomaterials. Reproduced from [28]

Fullerenes nanoparticles

As shown in Figure 5, fullerenes nanoparticles are spherical cage like nanostructures composed of entirely carbon atoms arranged in pentagonal and hexagonal ring, with C_{60} (buckminsterfullerene) being the most well-known example is illustrated in Figure 5. Fullerenes are typically synthesised using physical vaporisation methods, such as arc-discharge, laser ablation, or combustion techniques [29]. Fullerenes nanoparticles are widely used in biomedical applications, such as drug delivery, antioxidant photodynamic therapy, and neuroprotective therapies and diagnostic imaging. They are also used in organic photovoltaics, optoelectronic devices, catalysis, lubricants, and nanocomposite's, highlighting their versatility across biomedical and energy related fields.

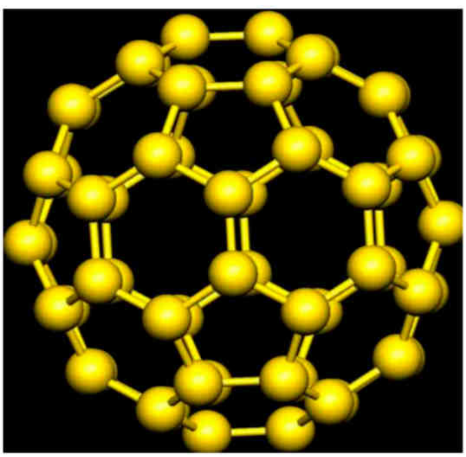

Fig. 5. The soccer-ball-like form of the carbon-60 bucky ball [30]

Carbon black nanoparticles

Carbon black nanoparticles are fine amorphous, carbon materials composed of quasi-spherical primary particles that aggregate into chainlike structures characterised by high surface area, electrical conductivity, and strong UV-absorbing light capabilities, as shown in Figure 6. Carbon black nanoparticles are primarily synthesised through incomplete combustion, or thermal decomposition of hydrocarbons [30]. They are widely used in rubber reinforcement, inks, conductive fillers, coatings, and UV-protective materials due to their mechanical strengthening and electrical properties. In biomedical and environmental they are used for biosensing, drug delivery, electrode materials and adsorption of pollutants, demonstrating their vast industrial and emerging biomedical relevance [30].

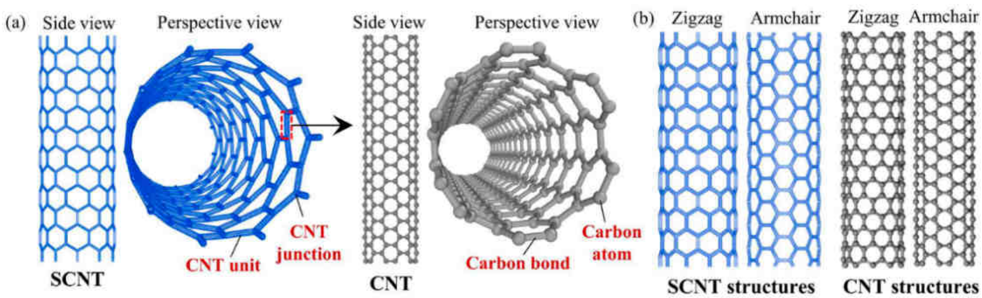

Fig. 6. Various shapes of carbon nanotubes, such as: a) structures of SCNT and CNT and b) geometrical structures of SCNT and CNT. Reproduce from [30]

Inorganic nanoparticles

Inorganic nanoparticles consist of metals, metal oxides, semiconductors, or ceramic materials, such as silver nanoparticles, gold nanoparticles, iron oxide nanoparticles, silica nanoparticles, copper nanoparticles, zinc oxide nanoparticles, fluorescent nanoparticles, titanium dioxide nanoparticles, and quantum dots. These nanoparticles are used in various applications such as catalysis, drug delivery, and sensing [31]. Inorganic nanoparticles represent a broad and significant class of nanomaterials composed of inorganic elements, such as metal, metal oxides, semiconductors and ceramic nanomaterials are shown in Figure 7. Examples of some inorganic nanoparticles are given below.

Silver nanoparticles

Silver nanoparticle (AgNPs) is known to be highly sober and easy to work with this nanoparticle and can be prepared biologically by using plants, bacteria, fungi, and algae (e.g. *Spirulinaplatenisis*, *Azadirachtaindica*), or by physical and chemical methods [32]. AgNPs exhibit strong antimicrobial, antiviral and antifungal properties due to the release of Ag^+ ions and their interaction with microbial cell membranes. They are widely used in medical devices, wound dressings, food packaging, textiles, water purification, and biosensing applications. For example, Khan et al. [33] synthesised AgNPs-1, AgNPs-2, and AgNPs-3 by varying the concentration of $AgNO_3$ (6 : 1, 10 : 1 and 14 : 1) for catalytic performance.

Gold nanoparticles

Gold nanoparticles can also be synthesised using physical, chemical, and biological methods. It is reported that gold nanoparticles can increase the shelf like of food in association with bacteriocins, and they are also utilised in the field of microscopy. Gold nanoparticles have also been investigating tuberculosis by coating them onto outer membrane vesicles of Mycobacterium to mediate immune response [34]. These nanoparticles possess unique optical properties arising from surface plasmon resonance (SPR), high chemical stability and excellent biocompatibility. The features make them appropriate for biomedical imaging, drug delivery, photothermal therapy, diagnostic and catalytic applications [35].

Copper nanoparticles

The chemical reduction method is simple and widely used approach for manufacturing copper nanoparticles (CuNPs). Copper NPs, considered attractive due to its low cost and ease of synthesis, making them a high priority material for various applications. Their antibacterial activity against pathogenic bacteria such *Klebsiella pneumoniae*, makes them significant in the field of medicine [36]. Copper nanoparticles show high electrical and thermal conductivity along with catalytic and antimicrobial activities. They are commonly employed in conductive inks, catalysts, printed electronics, antimicrobial coatings, and energy-related applications. They can be chemically synthesised by various techniques like reduction, and even biologically [37].

Zinc oxide nanoparticles

Zinc oxide (ZnONPs) are commonly synthesised by the chemical precipitation method and can also be synthesised by using biological green methods [38]. Zinc oxide nanoparticles exhibit UV-absorbing, photocatalytic, and antibacterial properties. They are extensively used in sunscreens, cosmetics, antimicrobial formulations, sensors, optoelectronic devices, and environmental remediation applications [39].

Silica nanoparticles

Silica nanoparticles have excellent stability and tunable pore size which makes them amicable for construction of composites and drug delivery system. They can be synthesised by various green methods. Nano-SiO_2-induced model have demonstrated their value in the field of research in exploring granulomas and fibrosis [40]. Silica nanoparticles are chemically inert, biocompatible and easily functionalised. They are widely used as drug carriers, reinforcing agents in composites, chromatographic media, and biosensors [41].

Iron oxide nanoparticles

Iron oxide nanoparticles (Fe_3O_4/Fe_2O_3NPs) are commonly synthesised using the co-precipitation method. However, they can also be prepared by sol-gel and hydrothermal methods [42]. These nanoparticles possess superparamagnetic behaviour, making them effective in magnetic resonance imaging, biosensing, targeted drug delivery, hyperthermia therapy, and wastewater treatment [43].

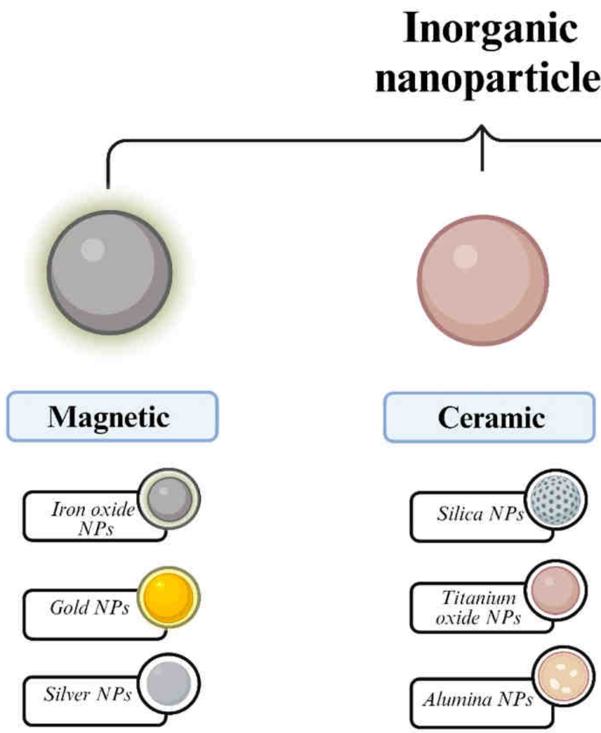

Fig. 7. Classification and subtypes of nanoparticles. Adopted and reproduced from [20, 44]

Organic nanoparticles

Organic nanoparticles are primarily composed of carbon-based materials and include polymeric nanoparticles, liposomes, dendrimers, nanogels and micelles. They are widely used in biomedical applications, particularly in drug delivery, gene delivery, and tissue engineering, due to their biocompatibility, biodegradability, and ability to encapsulate therapeutic agents. Examples of organic nanoparticles include polystyrene nanoparticles, polylactic acid nanoparticles, and chitosan nanoparticles [45]. Organic nanoparticles are basically composed of organic molecules such as, polymer, lipids, proteins and other nanomaterials are illustrated in Figure 8.

Polymeric nanoparticles

Nanoprecipitation is one of the most widely employed and favourable methods for the synthesis of polymeric nanoparticles, due to its simplicity, reproducibility and ability to produce uniformly sized under mild conditions [46]. Polymeric nanoparticles are composed of natural or anthropogenic polymers such as poly(lactic-co-glycolic) acid, chitosan or polyethylene glycol. They can exist as nanosphere or nano capsules and are widely used due to their stability and controlled drug released ability [47].

Liposomes nanoparticles

Liposomes nanoparticles are typically synthesised using self-assembly methods in which phospholipids spontaneously form bilayer vesicles in aqueous media. The most common approach is the thin film hydration method. Liposomes are spherical vesicles composed of phospholipid bilayers enclosed in aqueous core. They can encapsulate both hydrophilic and hydrophobic compounds and closely mimic biological membranes [48]. In medicine liposomes are extensively used for targeted drug delivery, particularly in cancer therapy to reduce drug toxicity, and enhance therapeutic efficacy. They are also used in gene therapy, vaccine delivery, diagnostic imaging and controlled release formulations [49].

Nanogels nanoparticles

Nanogels are commonly synthesised using polymerisation and cross-linking techniques. The most widely used method is emulsion or inverse microemulsion polymerisation [50]. Nanogels are widely used in biomedicine owing to their excellent biocompatibility, biodegradability, and stimuli responsive properties, enabling their application in controlled and targeted drug delivery, as well as gene, protein, and peptide delivery. They are also applied in cancer therapy, tissue engineering, wound healing, diagnostic imaging, biosensing, cosmetics, and personal care products for the sustained release of active ingredients [51].

Micelles nanoparticles

Micelle nanoparticles are synthesised through self-assembly when amphiphilic molecules are dispersed in water concentrations above the critical micelle concentration [52]. Micelle nanoparticles are widely used in biomedical applications, especially in drug delivery, where they enhance the stability, solubility, and bioavailability of poorly water-soluble drugs. They are also applied in targeted cancer therapy, gene delivery and diagnostic imaging. Additionally, micelles are used in cosmetics, pharmaceutical formulations, and nanomedicine research for controlled and continuous release of active materials [53].

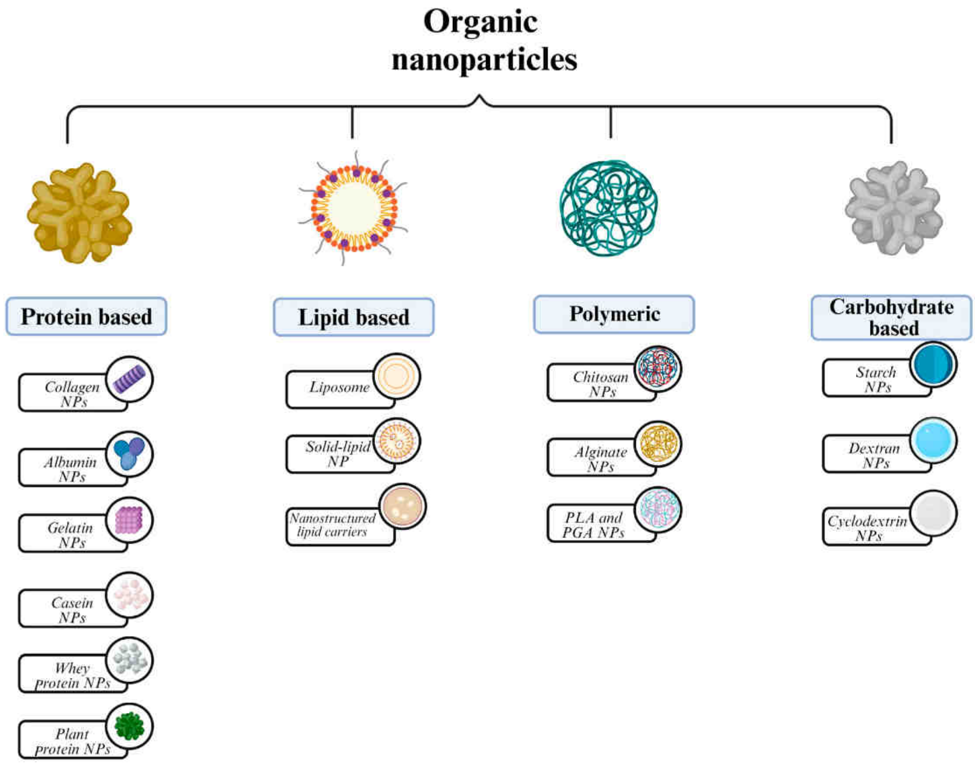

Fig. 8. Classification and subtypes of organic nanoparticles. Adopted and reproduced from [20, 54]

Classification of nanoparticles based on dimensions

The fundamental elements of nanotechnology are nanomaterials. Nanomaterials are defined as materials where at least one dimension is in the nanoscale, i.e. smaller than 100 nm. Based on their dimensionality, nanomaterials are placed into four different classes. The dimensional classification of nanomaterials is summarised in Figure 9 [55].

Zero-dimensional nanomaterials (0-D): Nanomaterials in this class all have three dimensions within the nanoscale range. Examples include fullerenes, quantum dots, and nanoparticles [56].

One-dimensional nanomaterials (1-D): Nanomaterials in this class have one dimension outside the nanoscale. Examples are nanotubes, nanorod, nanofibers, nanowires and nanohorns [57].

Two-dimensional nanomaterials (2-D): The nanomaterials in this class have two dimensions outside the nanoscale. Examples are nanosheets, nanofilms and nanolayers [58].

Three-dimensional nanomaterials (3-D) or bulk nanomaterials: In this class the materials are not confined to the nanoscale in any dimension. This class contains bulk powders, dispersion of nanoparticles, arrays of nanowires and nanotubes etc. [59].

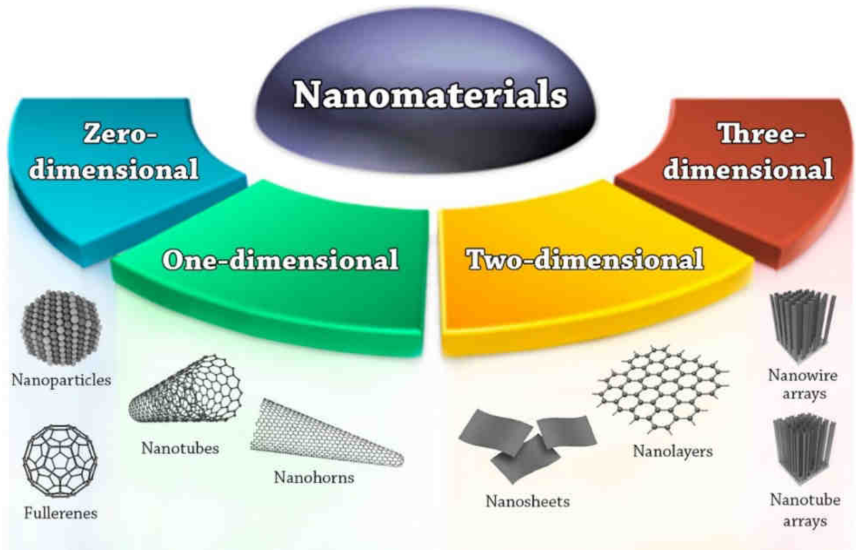

Fig. 9. Nanoparticles based on dimensionalities, reproduced from [60]

Table 1

Classification of nanoparticles according to their highlighted properties and application areas

Type of nanoparticle	Effective properties	Area of application	Representative references
Inorganic nanoparticles (Ag, Au, Fe_3O_4, SiO_2, Cu, ZnO, TiO_2, quantum dots)	• High chemical and thermal stability • Tunable optical and electronic properties • Magnetic and catalytic activity • Antimicrobial and photocatalytic behaviour	• Drug delivery • Cancer therapy • Diagnostic imaging • Catalysis • Sensors and biosensors • Antimicrobial coatings	[30]
Silver nanoparticles (AgNPs)	• Strong antimicrobial activity • High surface plasmon resonance • Chemical stability	• Antibacterial coatings • Wound healing • Medical devices • Water treatment	[30]
Gold nanoparticles (AuNPs)	• Excellent biocompatibility • Optical tunability • Easy surface functionalisation	• Drug delivery • Bioimaging • Cancer photothermal therapy • Biosensing	[30]
Iron oxide nanoparticles	• Superparamagnetic • High magnetic susceptibility • Heating efficiency	• MRI contrast agents • Magnetic hyperthermia • Targeted drug delivery	[30]
Zinc oxide nanoparticles (ZnO NPs)	• Antimicrobial activity • UV absorption • Semiconductor behaviour	• Drug delivery • Anticancer therapy • Sunscreens • Biosensors	[30]
Titanium dioxide nanoparticles (TiO_2 NPs)	• Photocatalytic activity • Chemical inertness • UV resistance	• Photocatalysis • Environmental remediation • Drug delivery • Cosmetics	[30]

Type of nanoparticle	**Effective properties**	**Area of application**	**Representative references**
Organic nanoparticles (polymeric NPs, liposomes, dendrimers, nanogels, micelles)	• High biocompatibility and biodegradability • Flexible surface modification • High drug encapsulation efficiency	• Drug and gene delivery • Tissue engineering • Cancer therapy • Vaccines	[30]
Polymeric nanoparticles (PLA, PLGA, polystyrene, chitosan)	• Controlled and sustained drug release • Biodegradability • Mechanical stability	• Drug delivery systems • Tissue engineering • Wound healing	[30]
Liposome nanoparticles	• Encapsulation of hydrophilic and hydrophobic drugs • Targeted delivery • Reduced toxicity	• Drug delivery • Gene delivery • Cosmetics	[30]
Nanogels	• Stimuli-responsive behaviour • High water content • Soft and flexible structure	• Controlled drug delivery • Cancer therapy • Drug delivery • Wound healing	[61]
Micelle nanoparticles	• Self-assembly • High solubilisation of hydrophobic drugs • Small particle size	• Tissue engineering • Cancer therapy • Diagnostic imaging	[62]
Carbon-based nanoparticles (CNTs, graphene, fullerenes, carbon dots)	• High surface area • Excellent electrical and thermal conductivity • Mechanical strength	• Drug delivery • Bioimaging • Biosensing • Tissue engineering • Energy devices	[63]
Carbon nanotubes (CNTs)	• High tensile strength • Electrical conductivity • Cellular penetration ability	• Drug and gene delivery • Biosensors • Tissue scaffolds	[64]
Graphene / Graphene oxide	• Large surface area • Excellent mechanical and optical properties • Easy functionalisation	• Drug delivery • Antibacterial and anticancer therapy • Sensors	[65]
Fullerenes	• Strong antioxidant activity • UV protection • Unique cage structure	• Drug delivery • Photodynamic therapy • Antitumor applications	[66]
Carbon quantum dots	• Strong photoluminescence • Chemical stability • Low toxicity	• Bioimaging • Biosensing • Drug delivery • Antibacterial applications	[67]

Nanoparticles can also be classified according to their size

Nanoparticles with a diameter of less than 100 nanometers [nm] are known as ultrafine particles. Nanoparticles with a diameter of between 100 nm and 1000 nm are referred to as nanosised particles. Nanoparticles with a diameter of between 1000 nm to 10,000 nm are classified as macroscale particles. Nanoparticles can also be categorised according to their shape. Some nanoparticles are spherical in shape, while others are rod-like, disk-like, or have irregular shape. Various sizes and shapes of nanoparticles are illustrated in Figure 10.

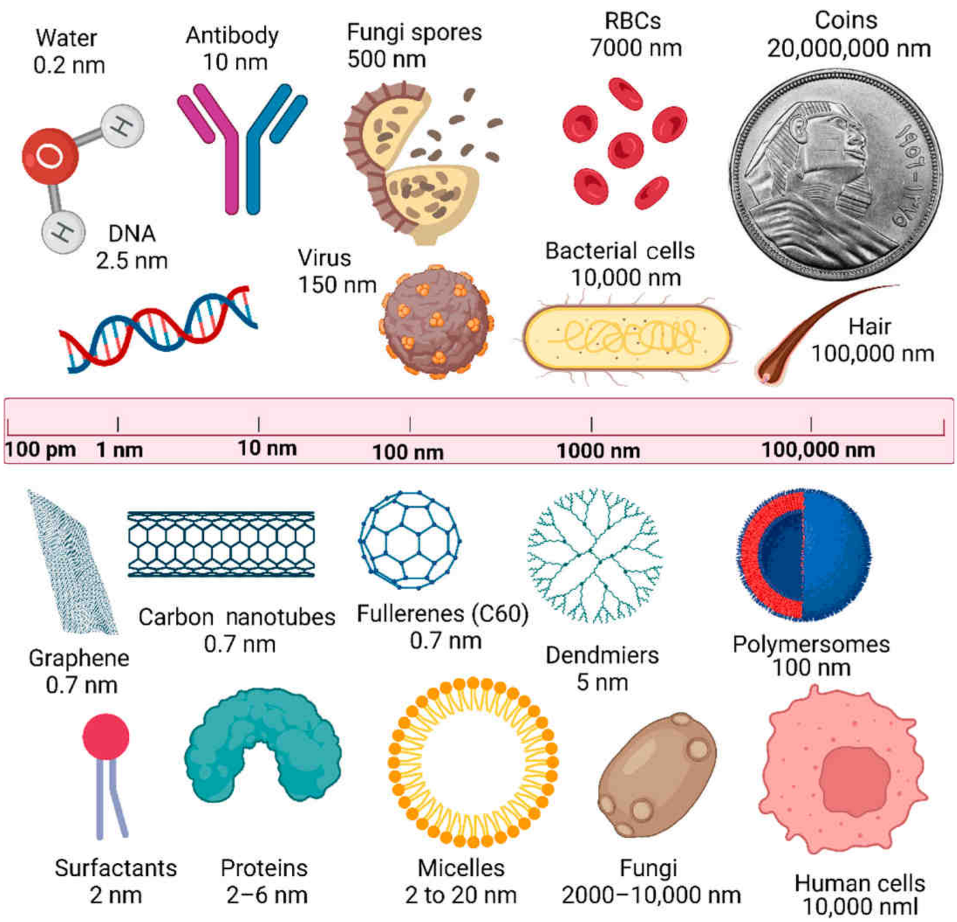

Fig. 10. Scheme showing the size scale of objects compared with the nanoscale size regime, reproduced from [68]

Methods of preparation of nanoparticles

The nanoparticles can be synthesised using a variety of methods that allow them to be controlled precisely in their size, shape, composition, and surface properties. Some of them are sustainable methods for the synthesis of chiral nanomaterials as well [69]. Such synthesis pathways can be broadly classified into chemical, physical, mechanochemical, and biological methods, with each approach having certain strengths regarding the desired material characteristics and application requirements scalability, cost-effectiveness, environmental impact, purity of the product, and the degree of structural control are some of the factors that determine the choice of a suitable preparation method. More recent developments in the fabrication of nanoparticles have focused on the establishment of effective, reproducible, and environmentally friendly methods of enabling the functional properties to be tuned. As a result, synthesis strategies have become very varied, which has significantly increased the usage of nanoparticles in catalysis, energy storage, electronics, and environmental cleanup as well as biomedicine. Moreover, synthesis parameters such as reaction conditions, precursor choice, and stabilisation schemes are vital in the production of nanoparticles with desired performance properties. The combination of the advanced fabrication methods and the principles of green chemistry has also helped in enhancing the safety and sustainability in the production of nanoparticles. All in all, scalability, functionality, and industrial applicability of nanomaterials in new spheres of technology are likely to be improved through constant innovation in the methodology of their [70]. Various methods of preparation for nanoparticles are given below.

Wet chemical methods

Wet chemical methods are widely used for the synthesis of nanoparticles. This method involves the preparation of nanoparticles from solutions, usually employing a surfactant or a stabiliser. Commonly used wet chemical methods include co-precipitation, hydrothermal synthesis, and sol-gel techniques. Among wet chemical methods schematic representation of sol-gel method is depicted in Figure 11.

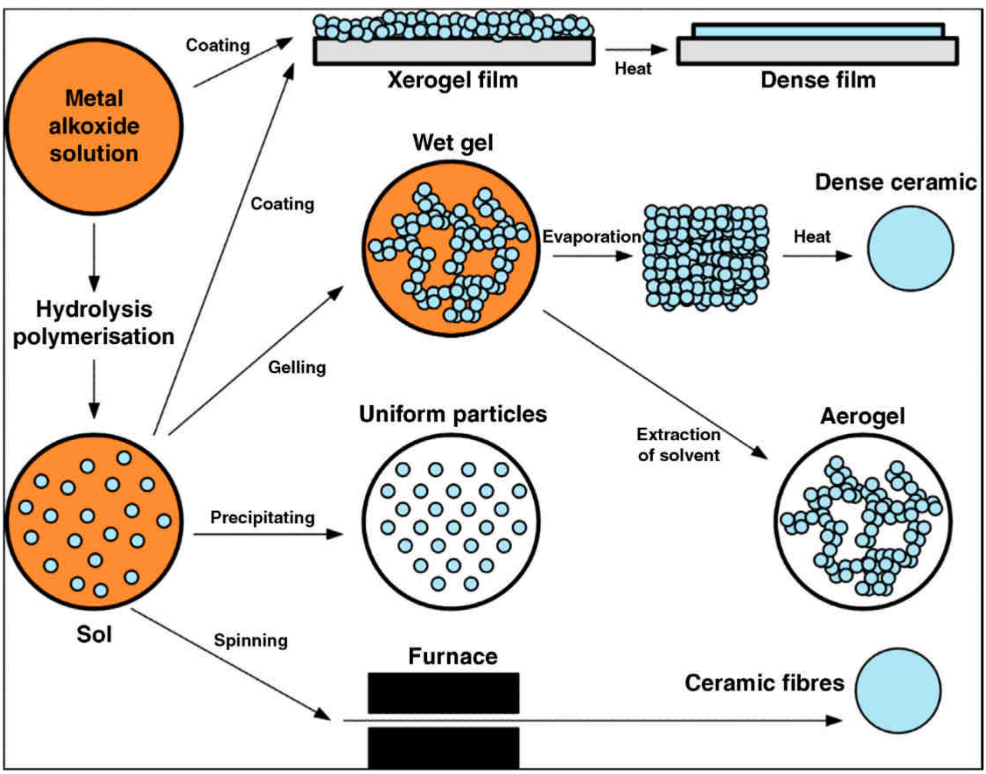

Fig. 11. Schematic representation of the different stages and routes of the sol-gel technology

Physicals methods

Physical methods of nanoparticles synthesis involve the formation of nanoparticles through physical process without chemical reactions, typically using the bulk materials as a starting source. These techniques involve the physical bombardment of a substrate with a high energy beam. This can be performed using lasers, electron beams, or ion beams. Commonly used physical methods include laser ablation, sputtering, and pulsed laser deposition.

Mechanochemical method

Dubadi et al. [71] reported that mechanochemical synthesis refers to the application of mechanical forces to cause physical and chemical changes on solid precursors and obtain nanoparticles. Such methods are usually based on high energy grinding operation that favours repetitive fracturing, cold welding and re-aggregation of particles and eventually reduce bulk materials to nanoscale sizes. The high-energy ball milling, ball-jet milling, and ball jet-stirring have been used as common mechanochemical methods and are common in the synthesis of metallic, ceramic, and composite nanoparticles. Some of the benefits of mechanochemical methods include solvent-free processing, scalability, cost-effectiveness, and the opportunity to obtain materials with specific structural defects and high reactivity Nevertheless, such difficulties as the contamination with milling media, wide particle size distribution, and amorphisation of the structure should be monitored. In spite of these drawbacks, mechanochemical synthesis has received a lot of interest as a sustainable and industrial viable method of nanoparticle synthesis, especially in the fabrication of nanoparticles in catalysis, energy storage and advanced functional materials [71].

Chemical vapour deposition

Chemical vapour deposition (CVD) is a technique that has been found very useful in high-purity and structurally well-controlled synthesis of nanomaterials, such as nanoparticles, nanotubes, and nanotubes, among others, in vapour-phase synthesis. During this, volatile chemical precursors are pumped into a hot reaction vessel where they are broken down thermally or by heterogeneous chemical reactions on a substrate surface to produce solid nanostructures with gaseous by-products being removed continuously. The CVD technique provides a fine regulation of the following parameters: temperature, pressure, rate of gas flow and precursor composition, all of which determine the nucleation, growth kinetics, crystalline and morphology of the resultant nanomaterials [72]. This method has variants such as plasma-enhanced CVD, metal-organic CVD and aerosol-assisted CVD which increase the scope of the process in making carbon-based nanostructures, semiconductor nanoparticles and functional coatings. Chemical vapour deposition has achieved wide applications in catalysis, electronics, energy storage and surface engineering because of its scalability, uniformity and the ability to produce materials with high structural integrity and purity. However, the existence of challenges such as elevated operation temperatures, complicated instrumentation, and precursor toxicity compels the continued research to produce greener and more energy-efficient CVD processes [73].

Biological methods (Green synthesis)

Biological methods involve the production of nanoparticles using biological system such as plants extract, bacteria, fungi, algae, and enzymes as natural reducing, caping, and stabilising agents. This method can be used to prepare metal nanoparticles (such as copper, silver, gold, and iron) as well as metal oxide nanoparticles (such as titanium dioxide, and zinc oxide etc.). The reducing agent can be enzymes, microorganisms, or a plant extract. For example, the glucose oxidase can be used to reduce silver ion to form silver nanoparticles. Similarly, certain bacteria have been used to reduce silver ion to form silver nanoparticles. Plant extracts such as *Justicia adathoda*, *tea*, *coffee*, *garlic* and so many others are used for the preparation of metal nanoparticles. Overall, biological methods are cost effective and eco-friendly approach for the preparation of nanoparticles. These methods can be used to prepare a wide range of nanoparticles, including metal, metal oxide nanoparticles and quantum dots [74].

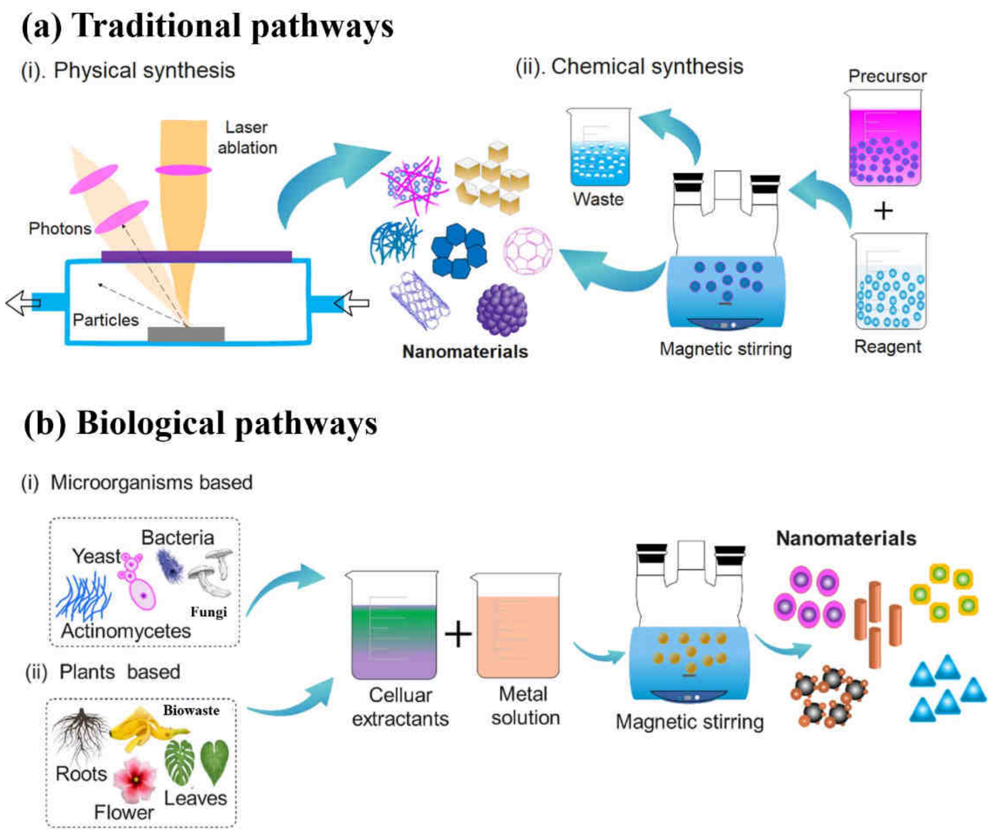

Fig. 12. Graphical illustration of general procedures for nanomaterial synthesis: a) traditional pathway and b) biological pathways, adapted and modified form [75, 76]

The biosynthesis of nanoparticles using plants is relatively new and emerging area of research. There are several methods of nanoparticles preparing nanoparticles from plants, including phytoremediation, ultra-sound assisted synthesis, and the use of plant extracts. Phytoremediation is a process that involves the use of plants to absorb and break down hazardous materials, such as heavy metals and other pollutants, into nanoparticles. Ultrasound assisted synthesis as a method that involves exposing plant extracts to high frequency sound waves, which can cause the plant material to break down into nanoparticles. Finally, the use of plant extracts involves extracting from plants, such as essential oils and polyphenols, and then using them to synthesise nanoparticles. Each of these methods has its advantages and disadvantages, and researchers are still exploring the effectiveness of each [77]. Overall, the biosynthesis of nanoparticles from plants is a promising area of research that could lead to the production of more efficient, cost-effective, and environmentally friendly materials. Schematic presentation of traditional and biological pathways for synthesis of nanomaterial synthesis is displayed in Figure 12.

Applications of nanoparticles

Medical use

Several applications, such as imaging diagnostic, targeted drug delivery, and tissue regeneration of nanomaterials have been reported in the literature [78]. Nanoparticles can be used to deliver drugs to specific cells, and tissues to reducing the dose of drug needed and minimising side effects. For example, nanoparticles coated with antibodies can be used to deliver drugs to tumour cells, allowing for more targeted treatment [79]. Nanoparticles can be also used for imaging, such as in optical imaging, and magnetic resonance imaging [80]. The uses of nanoparticles create contrast agents that can help doctors better visualise anatomy and blood vessels. Nanoparticles are being used to develop sensors that can detect cancer biomarkers in blood, or other body fluids. These sensors could be used to detect cancer earlier and more accurately [81]. Some of the common applications of nanoparticles are given below.

Tissue regeneration

The ability of nanoparticles to deliver growth factors, genes and bioactive molecules in a targeted and controlled way has now made nanoparticles highly promising tools in tissue engineering and regenerative medicine. Nanoparticle-based delivery systems help to increase cellular proliferation, differentiation and formation of extracellular matrix, which facilitate the wound healing and tissue repair processes by promoting sustained and localised release. Different types of nanomaterials have been used in regeneration of tissues like bone, cartilage, skin and neural tissues; they include polymeric nanoparticles, liposomes and inorganic nanostructures [82]. Besides delivery of growth factors, nanoparticles are also being explored in gene therapy applications, in which they are non-viral vectors that can deliver nucleic acid safely and efficiently to cells with minimal immune reactivity and toxicity. Moreover, nanoparticle-related cancer immunotherapy has been the focus of much attention since nanocarriers can control immune response by using antigens, adjuvants, or immune-modulating agents, to increase antitumor effect. Although these developments have been made, issues associated with long-term biocompatibility, immune response and clinical translation are still areas of concern and continue to be subjected to research. Recent research has identified LINC00346 as a key regulator of glioma progression and immune evasion, suggesting that nanoparticle-based delivery systems targeting this lncRNA could offer a novel strategy for glioblastoma therapy [83].

In agriculture

Nanoparticles are being used in the agriculture sector, for a variety of applications. The applications of nanoparticles in agricultural sector [84]. Nanoparticles offer transformative applications in agriculture by enhancing crop production through improved nutrient uptake, photosynthesis efficiency, and protection against pests, diseases, and environmental stressors like extreme temperatures and UV radiation. They also improve soil structure and fertility by increasing water retention and reducing the need for chemical fertilisers, thereby minimising environmental impact. In food safety, nanoparticles extend shelf life, enhance nutritional value, and reduce food-borne illnesses by eliminating pathogenic microorganisms and providing barriers against moisture and oxygen. Additionally, they contribute to animal health by boosting digestion, metabolism, and immunity, while improving feed quality. Beyond agriculture, nanoparticles aid in water purification by removing pollutants, optimise agricultural waste management to reduce pollution, and increase the efficiency of farm machinery. Their role extends to sustainable energy technologies, particularly in solar energy conversion and photocatalysis. As research advances, the diverse and innovative uses of nanoparticles are expected to expand, driving sustainability and efficiency in agriculture and beyond.

Solar cells and photocatalysis

The nanoparticles of semiconductors have received special consideration in energy-related applications because of their tunable electronic structure, high surface area and strong light-matter interaction at the nanoscale. Nanostructured semiconductors (quantum dots, metal oxide nanoparticles and perovskite nanomaterials) play a role in enhancing light absorption, charge separation and carrier transport in photovoltaic technologies and therefore improve the overall power conversion efficiency of solar cells. The bandgap tunability of semiconductor nanoparticles with size makes it possible to tune the size-dependent solar spectrum to optimise the solar spectrum utilisation, especially the quantum dot-sensitised and dye-sensitised solar cell. In addition, nanostructured materials including TiO_2, ZnO, CdS and perovskite nanoparticles have high interfacial contact area, leading to high injection of electrons and lower recombination losses. Semiconductor nanoparticles are used in the remediation of the environment and to generate energy sustainably in photocatalytic applications. When illuminated, these materials produce electron-holes that are involved in redox reactions to break down organic pollutants, clean up water and generate hydrogen using photocatalytic water splitting. In nanotechnology, high electroactivity chemical stability, and reusability of nanoparticles through the application of TiO_2 and ZnO nanostructures, g-C_3N_4, and metal sulfide nanostructures have been extensively studied. Heterostructuration, doping, and functionalisation of the surfaces even increase light absorption in the visible range and charge carrier dynamics. Although these advantages are present, photocorrosion, lack of visible light use as well as scaling are some of the challenges that are still under investigation. In general, solar and photocatalytic systems based on semiconductor nanoparticles are the promising avenues of sustainable conversion of energy and environmental safety [85].

Coating and surface engineering

Nanoparticles have been extensively applied to coating technology to improve the functionality and durability of surfaces in a multitude of industrial and technological uses. Tunable physicochemical properties, high surface area, and capacity to form uniform dispersions in matrices make nanoparticles very useful in the coating process by conferring corrosion resistance, self-cleaning behaviour, ultraviolet (UV) protection, mechanical reinforcement, and antimicrobial activity [86]. As an example, titanium dioxide (TiO_2) and zinc oxide (ZnO) are the widely used metal oxide nanoparticles in protective coatings because of their photocatalytic and UV-blocking properties that prevent the degradation of the materials and their increased service life. Likewise, nanoparticles of silver and copper are used in coating to give them antimicrobial properties and are useful on a medical device, food packaging, and infrastructure [87]. Moreover, silica and alumina nanoparticles provide enhanced scratch resistance, hardness and thermal stability on surface-engineered materials. Such nanostructured surface coating is widely used in automobile, aerospace, building, marine and biomedical industries where fine performance of the surface is a major concern. However, issues associated with the stability of dispersion of nanoparticles, adhesion of coating, environment and scale production are some of the areas of continuous research [88]. The researchers put efforts into the future of nanocomposite coating that is multifunctional, eco-friendly synthesis methods and smart surface technologies that can respond to external forces, thus taking nanotechnology to a higher level of surface engineering processes.

Electronics and sensors

Nanoparticles have found extensive use in the manufacturing of nanoscale electronic devices and sensors because of their owing electrical, optical and surface characteristics, which allow better transportation of charges, a reduction in devices dimensions and enhanced signal transduction nanoparticles based on semiconductor and metals such as quantum dots, metal oxides and metal nanostructures of various noble metals have been incorporated into transistors, memory and other electronics to obtain tunable electronic behaviour and high carrier mobility [89]. Nanoparticles in sensor will have an important role, as they are highly sensitive and selective because they raise the active surface area and the rate of the interaction with the analyte, leading to better response time and reduction of detection limits in chemical and biosensing systems [90]. Gold and silver nanoparticles are particularly useful in electrochemical and plasmonic sensors of biomolecule recognition, environmental detection, and gas detection. Moreover, flexible and wearable sensors that include carbon-based nanomaterials are graphene and carbon nanotube due to their high conductivity, mechanical flexibility, and chemical stability. The recent advancements in sensor design also demonstrate the connection between nanoparticle-based sensing systems and micro/nanoelectronics’ platforms to be used in biomedical and environmental settings [91]. Although they have these benefits, such issues as stability over the long term, scalable fabrication, and reduced environmental effects remain the spheres of active research. Subsequently, there are future directions of nanomaterial-enhanced electronics and sensors in the direction of multifunctional nanocomposites, high-performance integration, and data-driven sensor networks to monitor real-time and smart device systems.

Other applications of nanoparticles

Nanoparticles have been extensively used in the remediation of the environment and water treatment because of their outstanding adsorption, catalytic, and surface reactiveness qualities that allow water systems to be purified of contaminants like heavy metals, organic waste, and pathogens [92]. Metal and metal oxide nanoparticles such as iron oxide (Fe_3O_4), titanium dioxide (TiO_2), and zinc oxide (ZnO) are highly selective in water purification by binding to a wide range of pollutants and accompanying adsorptive sequestration as well as catalytic degradation of toxic dyes, pharmaceuticals, and persistent organic pollutants. Bao et al. demonstrated that the tyrosine kinase non-receptor 1 (TNK1) promotes atherosclerotic inflammation by activating the Tyk2/STAT1 pathway in macrophages. This identifies TNK1 as a promising therapeutic target, where nanoparticle-mediated gene silencing (e.g., shRNA delivery) could potentially mitigate plaque inflammation and progression [93]. The use of nanoparticle-doped materials including zeolite begins to increase the efficiency of contaminant removals by incorporating both high surface area and specific adsorption processes of the heavy metals and organic contaminants [94]. In addition to water purification, nanoparticles are useful catalysts in industrial chemical reactions because they require less energy and greater conversion efficiencies than bulk catalysts. Nanoparticle catalysts and supports find use in energy-related processes, such as enhancing the production of hydrogen through the splitting of water and the enhancement of advanced fuel conversion technologies as a part of renewable energy systems [95]. Also, silver and iron nanoparticles, among other nanomaterials, have antimicrobial and biocidal activity that is used in environmental clean-up plans to minimise microbial contamination of soil and water. Despite the enormous improvements in efficiency and scalability that these applications demonstrate, such issues as the stability of nanoparticles, their possible ecotoxicity, and the implementation in large scale are the topics of ongoing research. In general, the introduction of nanoparticles in the environment and industrial areas highlights their transformative nature in solving the global problems of pollution, resource shortage, and sustainable energy [92].

Current gaps and future perspective of nanoparticles

Nanoparticles are set to play a major role in the future of many industries, particularly in the medical, energy sector, and automotive. Nanoparticles can be utilised in the medical fields to deliver the drugs straight into the tumor areas, and this may help in decreasing the side effects of chemotherapy. On the same note, they are applicable to specific cells in the body; thus, diagnoses and treatments of diseases can be highly accurate. The nanoparticles can also be utilised in the automotive industry to produce lighter and more efficient materials for use in car bodies, which can result in increased fuel efficiency and a decrease in emissions. Nanoparticles may also be applied in the energy industry to develop more efficient solar panels and batteries, which will enable the more efficient storage and use of renewable energy. Lastly, nanoparticles could be employed to design superior material to be used in common devices, e.g., sensors, smartphones, etc., which would enable us to engage in more purposeful interaction with the world around us [96]. Nevertheless, there are still issues, such as insufficient knowledge of both long-term toxicity, environmental impact, and biocompatibility and the inability to produce in large scale reproducibly. Standardised testing protocol and regulatory standards are not well developed. Future studies ought to be conducted on green and scalable synthesis procedures, comprehensive toxic globulin research, creation of multifunctional nanoparticles, regulatory frameworks, and integration of hybrid nanoparticles for improved performance. Solving these loopholes will bring safe, sustainable, and efficient application of nanoparticles in industries.

Conclusion

Nanoparticles have become an important focus in modern nanoscience and nanotechnology because of the distinctive properties arising from their extremely small size. At the nanoscale, materials often behave differently from their bulk counterparts. Their high surface-to-volume ratio, increased reactivity, and unique electrical, optical, and catalytic properties make nanoparticles highly useful for many scientific and industrial purposes. Depending on their composition, nanoparticles are generally classified into inorganic, organic, and carbon-based types, each offering specific characteristics suited to applications. Several methods have been developed for nanoparticle synthesis, including physical, chemical, and biological approaches. Physical methods such as mechanical milling and laser ablation enable nanoparticles to be produced without extensive use of chemical reagents. Chemical methods, on the other hand, provide better control over particle size, shape, and composition. More recently, biological or green synthesis techniques using microorganisms, plant extracts, or enzymes have attracted considerable interest because they are environmentally friendly, cost-effective, and reduce the use of hazardous chemicals. Because of distinct physicochemical characteristics, nanoparticles have found applications in a wide range of fields, including agriculture, medicine, catalysis, sensing technologies, energy storage, and environmental remediation. Nanoparticles can help improve crop productivity, enable more efficient drug delivery systems, enhance catalytic efficiency, and assist in the removal of environmental pollutants. These capabilities highlight their growing role in addressing many scientific, technological, and environmental challenges. However, despite these promising developments, several issues still need to be addressed. Concerning toxicity, environmental safety, large-scale production, and long-term stability remain important research topics. Future studies should therefore focus on developing greener synthesis methods, improving nanoparticle biocompatibility, establishing standardised protocols for toxicity evaluation, and designing scalable production strategies. Addressing these challenges will help ensure the safe and effective use of nanoparticle-based technologies and support their translation into practical applications.

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