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Nanotechnology has undergone significant advancements since the 1980s, leading to a surge in nanobased synthesized and marketed products. This technology holds substantial promise across various sectors, including biomedicine, pharmaceuticals, farming, and agro-food industry. The foundation of nanotechnology lies in nanoparticles, which are in the range of 1–100 nm. NPs are categorized as inorganic, organic, ceramic, or carbon-based, with inorganic NPs being subdivided into metal and metal oxide types. Nanoparticle synthesis generally uses two major approaches: top-down and bottom-up methods. This review covers chemical, physical, and eco-friendly synthetic methods. In addition, qualitative and quantitative characterization techniques were used. Qualitative methods include Fourier transform infrared spectroscopy (FT-IR), UV–Vis spectrophotometry, scanning electron microscopy (SEM), X-ray diffraction (XRD), and atomic force microscopy (AFM), whereas quantitative techniques include transmission electron microscopy (TEM), high-angle annular dark-field imaging (HAADF), and inductively coupled plasma (ICP) analysis. This review examines various nanoparticle production methods and their applications, focusing on the increasing role of nanotechnology in agriculture and biomedicine, which directly and indirectly impacts human health. Given the broad scope and complexity of these applications, further research is essential to clarify the mechanisms involved and determine which safe nanomaterials may be viable for market introduction.

Keywords: Nanotechnology, Nanoparticles, Biomedical, Pharmaceuticals, Agriculture, Nanoparticle synthesis, Characterization techniques, Safe nanomaterials

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INTRODUCTION

Nanotechnology has been an exciting area of research for nearly a century. Richard P. Feynman first introduced the idea in his 1959 lecture, "There's Plenty of Room at the Bottom." This technology allows the creation of various nanomaterials, including many types of nanoparticles. NPs are tiny particles ranging in size from 1 to 100 nanometers and can have different shapes, such as 0D, 1D, 2D, or 3D. Researchers have reported that the small size of these particles influences the physical and chemical properties of materials, such as how they interact with light. Unlike simple molecules, nanoparticles have a complex structure composed of three distinct layers,

Nanotechnology is an advanced field that has achieved impressive results when combined with biotechnology, medicine, agriculture, and the food industry (Sozer & Kokini, 2019). Its use in biological, agricultural, life sciences and medicine has shown great potential for improving agricultural productivity and human health. Today, nanotechnology is used in many areas, including food, agriculture, Information technology (IT), robotics, aerospace, energy, the environment, biotechnology, medicine, healthcare, and textiles. This evolving field significantly impacts the global economy, drives innovation, and affects many aspects of daily life (Umbrello & Baum, 2018). The synthesis and use of nanoparticles in biological applications depend on their size, shape, surface features, and physicochemical properties, which vary based on how they are made (Akter et al., 2018).

Organic Nanoparticles

Examples include ferritin, micelles, dendrimers, and liposomes, which possess desirable characteristics, including nontoxicity, biodegradability, and, in some cases, a hollow structure, as observed in micelles and liposomes. Owing to their heat and light sensitivity (Tiwari et al., 2008), these nanoparticles, also known as nanocapsules, are particularly well suited for drug delivery applications. Owing to these properties, they are widely utilized in targeted drug delivery. Often referred to as polymeric nanoparticles, organic nanoparticles commonly take the form of nanospheres or nanocapsules (Mansha et al., 2017). In one type, known as matrix particles, the entire structure is solid, while the spherical outer layer can adsorb other molecules; in the other type, the particles encapsulate a solid core.

Inorganic nanoparticles

Compared with organic nanoparticles, inorganic nanoparticles, which lack carbon, are considered safe, biocompatible, hydrophilic, and generally more stable. They are categorized mainly into metal and metal oxide nanoparticles (Altammar, 2023).

Metal nanoparticles

Metal nanoparticles are created through a synthesis process in which constructive or destructive techniques rely on metal precursors to create pure metal nanoparticles. Notable for their unique optoelectronic properties, metal nanoparticles exhibit plasmon resonance characteristics, which are influenced by their morphology (Dreaden et al.,2012). Metal nanoparticles can be made from various metals such as lead, gold, iron, aluminum, silver, cobalt, zinc, cadmium, and copper, each of which has unique optical and electrical properties (Salavati et al., 2008). These nanoparticles, which are usually between 10 and 100 nm in size, have special properties due to their small size and specific properties.

Metal oxide nanoparticles: Metal oxide nanoparticles are created to improve the properties of their metal equivalents. For example, iron nanoparticles can be oxidized to form iron oxide nanoparticles, which are more reactive and efficient than pure iron. This enhanced reactivity makes metal oxides such as zinc oxide, silicon dioxide, iron oxide, aluminum oxide, cerium oxide, titanium oxide, and magnetite particularly useful in a wide range of applications (Tai et al., 2007).

Ceramic nanoparticles: Commonly known as nonmetallic solids, are produced by heating and cooling by heating and cooling, and different forms, including polycrystalline, amorphous, porous, dense, or hollow structures, can be used (Sigmund et al., 2006). Ceramic nanoparticles are widely used in industries such as dye photodegradation, photocatalysis, catalysis, and photography due to their versatile structures (Thomas et al., 2015).

Biological Nanoparticles (bionanoparticles): Biological nanoparticles, also known as bionanoparticles, are naturally occurring particles formed within biological systems, with at least one dimension between 1 and 100 nm. They are categorized into intracellular structures, such as magnetosomes, and extracellular structures, such as lipoproteins and viruses. The examples of bionanoparticles include magnetosomes, exosomes, ferritin, lipoproteins, and viruses. Nanomaterials are divided into one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) categories. They can exist in single, fused, or hybrid forms and may have spherical, tubular, or irregular shapes. The common types of nanomaterials include nanotubes, nanowires, nanofibers, quantum dots, and fullerenes (Karunakaran, 2023).

One-dimensional nanomaterials

The prefix "nano" represents the scale of 10^9, signifying one billionth of a unit and resulting in materials with dimensions on the nanoscale, such as thin films (Hickey et al., 2013). Nanomaterials derived from this scale have diverse applications across fields such as chemistry, pharmaceuticals, electronics, and engineering (Gopi et al., 2016).

Two-dimensional nanomaterials

Two-dimensional (2D) nanostructures have two dimensions beyond the nanoscale range, with distinctive shapes, making them essential building blocks in the construction of nanodevice components (Jibowu, 2016).

Three-dimensional (3D) nanomaterials

The functionality and performance of 3D nanomaterials are largely influenced by their shape, size, dimensions, and morphology, which serve as fundamental parameters for their various applications (Sreelakshmy et al., 2016). Compared with bulk materials, nanomaterials have distinct shapes, giving them unique properties that make them ideal for use in areas such as biomedicine, catalysis, fuel cells, solar cells, and magnetic data storage. There are two main methods for synthesizing nanomaterials: the "bottom-up" and "top-down" approaches. Different synthesis techniques allow the creation of nanomaterials with varying sizes and structures. These shapes are usually categorized by their dimensionality: 0D (isotropic structure), 1D, 2D, and 3D (anisotropic structure). Depending on their size and structure, nanoparticles can have solid or mesoporous/hollow forms, as illustrated in Figure 1.

Synthesis of nanoparticles

There are several techniques for synthesizing metallic nanoparticles, such as physical, chemical, and biological methods. Physical methods are beneficial for nanoparticle synthesis but have the drawback of high energy consumption. In contrast, chemical synthesis can produce toxic byproducts and unwanted reactions. Biological synthesis, involving microbes such as bacteria, fungi, and yeast, as well as plant-mediated methods, plays an important role, especially for applications against pathogens, cancers, skin diseases, and diabetes (Nasrollahzadeh et al., 2019). Among these methods, plant extract-based synthesis is particularly popular because of its eco-friendly and cost-effective nature compared with other methods (Recio-Sanchez et al., 2019). Synthesis techniques are broadly classified into two main categories.

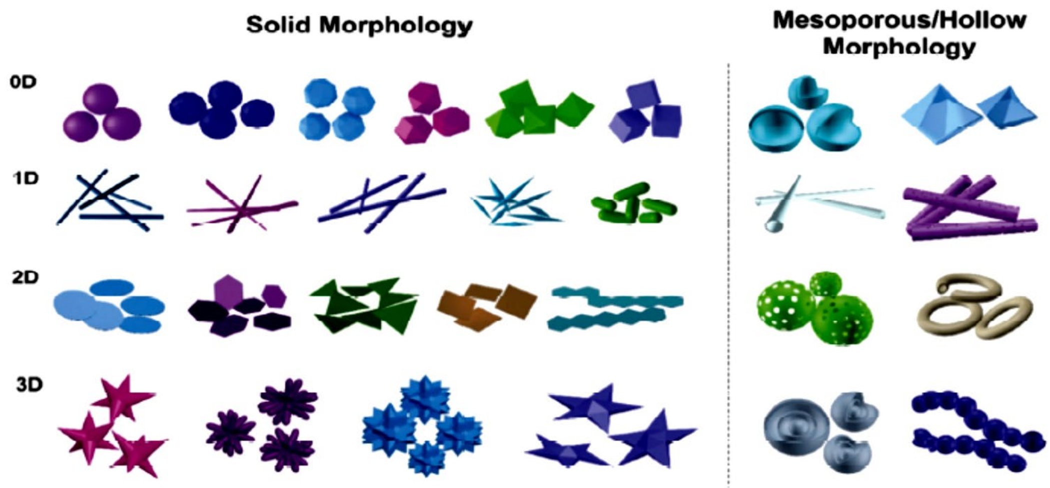

Figure 1. Typical morphologies of solid and mesoporous/hollow nanoparticles with 0D, 1D and 2D shapes and other 3D complex structures [Wu, 2016].

Top-Down Synthesis

This technique uses a reductive approach, where larger molecules or bulk materials are broken down into smaller components, which are then converted into nanoparticles. Key examples of top-down methods include grinding, milling, and physical vapor deposition (Iravani, 2011).

Thermal decomposition method

It is an endothermic process where heat induces chemical decomposition. The heat breaks the chemical bonds in the compound.

Mechanical technique/ball grinding technique

The production of nanoparticles from bulk materials can be achieved through a cost-effective approach. Ball milling represents one of the most straightforward mechanical techniques for this purpose. This method operates through attrition, whereby kinetic energy is imparted from the grinding medium to the material undergoing reduction (Joy, 2022).

Lithographic methods

Lithographic techniques are classified as top-down approaches that primarily facilitate the creation of micron-sized features. However, these methods require a significant amount of energy and costly equipment (Fruncillo, 2021).

Laser Ablation

Laser ablation synthesis in solutions is a simple technique for producing nanoparticles from various solvents. The process involves the use of a laser beam to irradiate different metals immersed in a solution, creating a plasma that results in the formation of nanoparticles (Amendola et al., 2009).

Sputtering

Sputtering refers to the deposition of nanoparticles through the ejection of particles from a source material (Shah et al., 2006). Annealing plays a crucial role in the deposition of thin nanoparticle layers. Several factors, such as temperature, layer thickness, annealing duration, and substrate type, influence the size and shape of nanoparticles.

Bottom-Up Method

The bottom-up approach, called the constructive method, is the opposite of the top-down technique. In this approach, nanoparticles are created from simpler substances. Bottom-up methods include chemical vapor deposition (CVD), sol-gel processes, spinning, pyrolysis, and biological synthesis (Khan, 2022).

Chemical vapor deposition (CVD) method

The chemical vapor deposition (CVD) method involves the formation of a thin film of gaseous reactants on a substrate. This happens in a reaction chamber, where the gas reacts with the heated substrate (Bhaviripudi et al., 2007).

Sol-gel method

The sol-gel method is named "sol," meaning a liquid containing tiny solid particles, and "gel," which refers to a solid structure within a liquid. This method is popular for making nanoparticles because it is simple.

It uses a suitable chemical solution as a starting material, often involving metal oxides and chlorides (Ramesh, 2013).

Spinning

NPs can also be synthesized through spinning techniques. This process uses a spinning disc reactor (SDR), which features a rotating disc that allows for the control of various physical parameters, such as temperature. To prevent unwanted chemical reactions and eliminate oxygen, the reactor is filled with nitrogen or other inert gases (Dell'Era, et al., 2019).

Pyrolysis

Pyrolysis is one of the most employed industrial methods for nanoparticle synthesis. In this technique, the precursor is placed in a high-pressure furnace to produce nanoparticles (Kammler et al., 2001). Sometimes, lasers or plasmas are used instead of flames to reach high temperatures, making evaporation easier (D'Amato et al., 2013).

Plant extracts

Various plants can be utilized to reduce and stabilize nanoparticles. Many researchers have used biological methods to create metal or metal oxide nanoparticles in various plant parts, such as leaves, stems, roots, and fruits. The extracts from these plants contain various biomolecules, such as proteins, coenzymes, and carbohydrates, which facilitate the reduction of metal salts into nanoparticles. This eco-friendly approach offers a sustainable alternative to traditional methods that may pose hazards to living organisms.

Biological synthesis

Biological synthesis uses plant extracts and microorganisms, such as bacteria and fungi, to create nanoparticles.

Bacteria

Bacteria can reduce metal ions, making them suitable for nanoparticle synthesis (Iravani, 2014). Various bacterial species have been employed to give up metallic and other novel nanoparticles.

Fungi

The use of fungi for the biological synthesis of metal or metal oxide nanoparticles is also an effective method that yields well-defined morphologies. Fungi are utilized for nanoparticle synthesis because of their intracellular enzymes, which facilitate this process (Mohanpuria et al., 2008). Compared with bacteria, fungi generally produce greater quantities of nanoparticles.

Yeast

Yeasts, which are unicellular microorganisms, constitute approximately 1,500 reported species. Numerous scientists have documented the synthesis of nanoparticles using yeast. Significant efforts have been made to control the shapes of these nanoparticles. The shape of nanoparticles is typically determined by thermodynamic or kinetic factors during their dispersion, which are influenced by temperature and supersaturation levels in the reaction dispersion. On the other hand, kinetically controlled shapes with different sizes are achieved by altering the reaction conditions according to nucleation theory. In such processes, the growth of nuclei leads to the formation of nanoparticles with anisotropic shapes. Thus, the balance between thermodynamic and kinetic factors plays a critical role in defining the final shape of nanoparticles (Aya, et al., 2024).

Factors affecting the shape control of nanoparticles

Supersaturation Refers to the concentration of monomers or their ratios in the system when multiple monomers are involved. According to classical nucleation and growth theory, supersaturation plays a critical role in regulating the rates of nucleation and subsequent growth. Therefore, it is a key factor affecting nanoparticle shape. Supersaturation is directly influenced by the precursor concentration and the concentration or ratio of reducing agents. For example, increasing the ascorbic acid concentration as a reducing agent has been shown to affect nanoparticle shape.

The impact of pH Altering the pH through the addition of acids or bases (such as H+, OH-, or NH3) can modify the chemical states of species in the dispersion, leading to the formation of coordination bonds between ions and the precursor monomer, resulting in complex formation. Consequently, pH is a critical parameter in controlling the shape of nanoparticles.

Factors affecting nanoparticle synthesis

Solvent The selection of a solvent is a critical factor in nanoparticle synthesis, especially when solvents with various functional groups, such as ionic liquids, are employed. These solvents improve coordination with precursor monomers, which benefits both thermodynamically and kinetically controlled nanoparticle synthesis by increasing supersaturation. Furthermore, the use of different solvent mixtures and compounds can provide enhanced control over the shape of nanoparticles.

Temperature Temperature is a key thermodynamic variable in reaction dispersion. Increasing the reaction temperature not only increases supersaturation but also accelerates the reduction rate of the precursor agent. Elevated temperatures promote faster thermodynamically controlled nucleation and growth, thus shortening the overall reaction time.

Surfactants and additives Owing to their high free energy at the nanoscale, nanoparticles have a natural tendency to agglomerate, forming larger particles with irregular and undesirable shapes. To mitigate this, surfactants and additives are used to reduce the surface energy of nanoparticles, aiding in the formation of desired shapes. Additionally, these agents create stable layers on nanoparticle surfaces, protecting agglomeration. Agglomeration poses significant challenges in maintaining the nanoscale size of nanoparticles, which is critical for various applications. To mitigate agglomeration, surface modification methods have been developed, leading to the emergence of surface engineering. This field explores techniques that enable nanoparticles to retain their nanoscale dimensions.

Three primary methods have been proposed for maintaining nanosized nanoparticles

Mechanical force surface modification can be achieved through mechanical forces, typically involving external shear or impact forces. This process induces chemical changes on the nanoparticle surface, resulting in either branching from organic chain compounds or the creation of protective layers that promote effective dispersion.

Ultrasonic impact techniques are widely utilized in chemistry because of their effectiveness in dispersing particulate structures and synthesizing compounds.

High-energy approaches These techniques utilize plasma radiation, electrical discharge, and infrared or ultraviolet waves to modify the surfaces of nanoparticles. By employing these strategies, researchers aim to increase the stability and functionality of nanoparticles in various applications.

Characterization of the Nanoparticles

Qualitative Analysis

Fourier Transform Infrared Spectroscopy (FTIR) FTIR is utilized to identify the biomolecules responsible for the capping, reduction, and stabilization of nanoparticles.

UV–Vis Spectrophotometry This technique characterizes nanoparticles of various metals ranging in size from 2 to 100 nm, typically using wavelengths between 300 and 800 nm. This technique helps determine the formation and stability of nanoparticles in aqueous solutions.

Scanning electron microscopy (SEM) SEM uses electrons instead of light to produce images that characterize the shape, size, morphology, and distribution of synthesized nanoparticles.

X-ray Diffraction (XRD) XRD is employed to determine the atomic structure of materials. It serves both qualitative and quantitative purposes, including determining the crystal structure and calculating the size of crystalline nanoparticles.

Atomic Force Microscopy (AFM) AFM is used to study the shape, size, and surface area of synthesized nanoparticles.

Quantitative analysis

Transmission electron microscopy (TEM) TEM is utilized to examine the particle size at the nanoscale and assess the crystal structure.

Annular Dark-Field Imaging (HAADF) HAADF allows for the study of how nanoparticles interact with bacteria, providing insights into the size distribution of nanoparticles in contact with various bacterial types.

Inductively Coupled Plasma (ICP) Spectrometry ICP-MS was used to determine the metal concentrations in both the deionized and original nanoparticle solutions. Techniques such as inductively coupled plasma–mass spectrometry (ICP-MS) and inductively coupled emission spectroscopy (ICP-ES) are employed to measure the resulting metal concentrations.

Applications for nanomaterials

Application of Nanomaterials in Agriculture

Nanomaterials have significant potential applications in agriculture aimed at enhancing crop productivity and improving soil health. This section highlights advancements in nanofertilizers, nanopesticides, nanobiosensors, and nanoenabled remediation of contaminated soils.

Nanofertilizers Over the past fifty years, crop yields—especially those of cereals—have significantly increased, playing a vital role in addressing global nutritional demands. This improvement has been largely driven by the extensive use of chemical fertilizers. However, the effectiveness of these fertilizers is often compromised by losses from volatilization and leaching, resulting in environmental pollution and increased production costs (FAO, 2017). As a result, there is a growing focus on creating alternative strategies for sustainable nutrient management. Nanotechnology provides innovative approaches to reduce nutrient loss, develop slow-release fertilizers, and improve the bioavailability of nutrients that are typically difficult to access. Nanofertilizers can act as direct nutrient sources or function as carriers or additives by integrating with minerals. Additionally, they can be engineered by encapsulating nutrients within nanomaterials (Kah et al., 2018).

Nanopesticides Agricultural pesticides are extensively employed in large-scale farming, and ongoing studies have focused on creating more potent and precise mixtures. Nonetheless, only a tiny fraction (approximately 0.1%) of the pesticides used manage to hit their targets, with the majority causing pollution in the environment. The broad application of these substances has adversely affected species not intended to be targeted and has also resulted in the development of resistance in a variety of pests, including weeds, insects, and diseases (Rai and Ingle, 2012). While biopesticides can mitigate some of the adverse effects linked to synthetic pesticides, their effectiveness is frequently limited by environmental factors. Nanopesticides show promise as alternatives, offering gradual decomposition and controlled delivery of active components when combined with suitable nanomaterials. This approach improves long-term pest control and decreases reliance on synthetic substances, thereby reducing environmental hazards. In contrast to traditional pesticides, nanopesticides exhibit distinct characteristics that increase their overall effectiveness (Kah et al., 2018).

Progression of nanoparticles in soil Soil, which contains natural colloids along with organic and inorganic components, can contain nanoparticles (NMs), affecting how they are spread between the solid and liquid parts of soil systems (Ben-Moshe et al., 2010). However, there is a lack of information on how nanoparticles behave and what happens to them in the soil, mainly because most research has concentrated on water environments. As a result, our understanding of how nanoparticles act in soil is mostly based on studies performed with soil in a liquid form.

Effects of nanomaterials on soil microbes Soil microorganisms serve as effective indicators of soil quality, significantly influencing soil health, particularly in terms of soil organic matter dynamics and nutrient cycling (Dinesh et al., 2012). Nanomaterials (NMs) tend to localize within soil macroaggregates (ranging from 2–53 µm), where they come into direct contact with a substantial portion of the microbial communities, as approximately 40–70% of total soil bacteria reside in these macroaggregates (Vottori-Antisari et al., 2013).

Nanomaterials in plants The utilization of nanoparticles at precisely calibrated concentrations has demonstrated their efficacy in increasing the germination, establishment, development, and productivity of diverse plant species. Furthermore, nanoparticles have been found to increase plant resistance to both biotic and abiotic stresses by facilitating the expression of genes associated with stress tolerance (Van Aken, 2015) and the production of proteins related to the stress response.

Transport and Distribution Processes The processes through which nanoparticles are absorbed and distributed within plants are multifaceted. NPs can penetrate the root epidermis through a series of complex processes, eventually reaching the vascular bundle (xylem), stele, and leaves (Figure 2) (Tripathi et al., 2017). To cross the intact cell membrane, nanoparticles utilize size-specific pores present on the membrane (Rico et al., 2011). Before entering the stele, nanoparticles passively diffuse through the apoplast of the endodermis (Judy et al., 2012). The primary mechanism of uptake involves active transport in conjunction with various cellular activities, such as signaling, recycling, and regulation of the plasma membrane (Tripathi et al., 2017).

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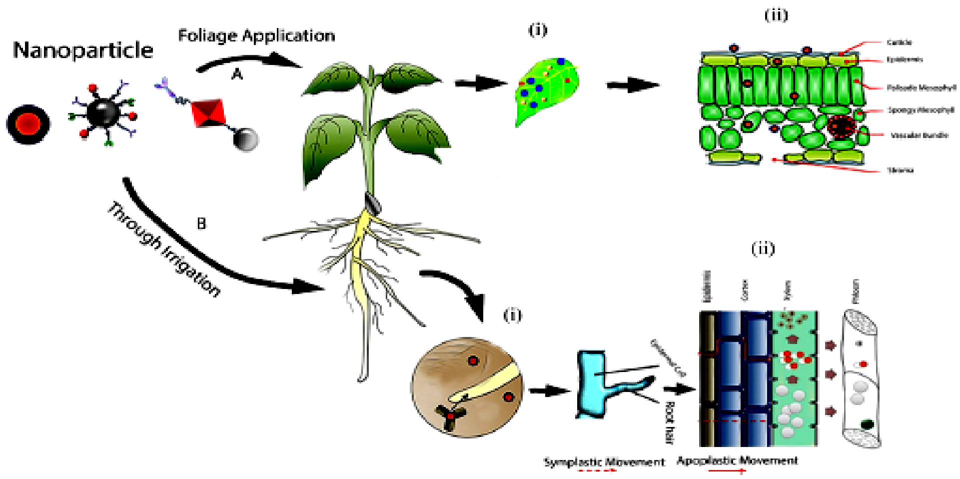

Figure 2. Uptake and translocation mechanisms of nanoparticles in plants through leaves and roots. (A) Uptake of the nanomaterial by foliage application: (i) the nanomaterial penetrates the leaf cuticle; (ii) it enters the palisade and spongy mesophyll through the epidermis layer and finally penetrates into vascular bundles; (B) the nanomaterial is taken up by plant roots when it is applied through irrigation; (i) the nanomaterial penetrates the root hairs; and (ii) it enters the xylem and phloem through the epidermis and cortex via apoplastic and symplastic pathways.

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Impact on the environment The environmental impact of nanoparticles is a crucial area of study, as they can have both direct and indirect effects on ecological systems. Research into silver nanoparticles has been particularly prolific, highlighting their potential benefits across various fields while also raising concerns about their toxicity. The environmental toxicity of silver nanoparticles is influenced by their composition, concentration, and form, as well as the specific properties of the soils in which they are present (McKee et al., 2019). Once released into the environment, nanoparticles can disperse widely, but their impact may be mitigated by changes in their structure, properties, and mobility.

Application in biomedicine

Metallic nanoparticles, especially Ag nanoparticles, are recognized for their ability to affect bacteria and fungi and have other therapeutic properties (Meva et al., 2019). Owing to their significant potential, the biological synthesis of silver nanoparticles from plant materials has gained traction. These nanoparticles are being explored for applications in treating various diseases, including diabetes and cancer.

AgNPs as Antimicrobial Agents The antibacterial characteristics of engineered silver nanoparticles (AgNPs) have gained significant recognition. Biogenic, green-synthesized metallic nanoparticles are particularly appealing because of their rapid efficacy (Parmar et al., 2019). Numerous medicinal plants have been utilized to synthesize these nanoparticles, which have demonstrated notable activity against microbes. Compared with other metals, silver ions are more toxic to various microorganisms and act on microbial membranes and cellular structures through mechanisms such as membrane disruption and reactive oxygen species generation, ultimately leading to cell death. AgNPs have also been shown to be effective against several viruses, including Tacaribe virus (TCRV), influenza A/H1N1, human immune-deficiency virus (HIV-1), recombinant respiratory syncytial virus (RSV), hepatitis B virus (HBV), murine norovirus (MNV)-1, and monkeypox virus.

Potential therapeutic applications of AgNPs in cancer Metallic nanoparticles are emerging as promising agents in cancer therapy. Their primary therapeutic application lies in reducing the size or dosage of conventional drugs. Even at low concentrations, silver nanoparticles can induce DNA damage and chromosomal aberrations without causing cytotoxic effects (Habas and Shang, 2019).

Nanoparticles in Diabetes Nanotechnologies play a vital role in enhancing therapeutic efficacy for diabetes management. Various nanotechnology-based methods have been developed, including layer-by-layer techniques, smart tattoos, carbon nanotubes, and quantum dots (Cash and Clark, 2010).

Application as a chemical catalyst In chemical reactions, metals such as nickel, lead, silver, and platinum serve as effective catalysts. However, below 200 °C, gold does not facilitate the dissociative adsorption of hydrogen and oxygen on its surface (Yang and Chen, 2017).

Applications for Nanoparticles in Food and Agriculture

Nanotechnology has introduced innovative techniques for water filtration and desalination that offer economic advantages. In the food industry, nanotechnology has led to the development of new functional materials and instruments for food preservation and biosecurity. For instance, Bayer has created airtight plastic packaging utilizing nanotechnology to enhance food preservation. Additionally, nanotechnology enables genetic modifications in crop plants.

Applications for energy harvesting

Given the nonrenewable nature of fossil fuels (Yadav et al., 2015), their limitations for future energy needs are increasingly recognized. Consequently, researchers are shifting their focus toward more sustainable resources that are readily available and can generate renewable energy at lower costs. In nanomedicine, tiny materials and electronic sensors at the nanoscale are used for diagnosing, monitoring, and preventing diseases. A key area is drug delivery (Figure 3A), where nanoparticles are used to target and deliver drugs to specific cells such as cancer cells, reducing damage to healthy cells. For example, chemotherapy drugs are packed into nanoparticles for targeted cancer treatment. Another exciting area is the use of quantum dots for diagnosing and treating cancer, which are still being developed but show promise. Additionally, iron oxide nanoparticles with magnetic properties are used to find tumors by attaching special antibodies to them, which then light up with MRI to visualize the tumor's location (Nikalje, 2015). Additionally, the field of nanovaccines is rapidly advancing owing to new nanotechnology tools and an expanded understanding of polymeric drug delivery. Developed by scientists, nanovaccines consist of synthetic polymer nanoparticles carrying tumor-associated proteins that are recognized by the immune system, increasing the ability of the body to combat cancer (Figure 3B).

Another notable application in nanomedicine involves the use of fullerene-based "buckyballs," nanomaterial that helps reduce inflammation from allergies by fighting free radicals. Additionally, nano shells have been developed to selectively target and destroy cancer cells through infrared heating, sparing healthy cells from damage. In trauma care, aluminosilicate nanoparticles exhibit significant benefits due to their water-absorbing properties, promoting rapid clot formation and reducing bleeding. Nanotechnology also plays an essential role in antimicrobial treatments; for instance, silver nanoparticles are employed to eliminate microbes from wounds. Some nanoparticles, such as nitric oxide-releasing nanoparticles embedded in wound creams, specifically target infections. Upon application, these nanoparticles release nitric oxide gas, which effectively kills bacteria (Adnan, 2010). Nanotechnology also plays an essential role in antimicrobial treatments; for instance, silver nanoparticles are employed to eliminate microbes from wounds. Some nanoparticles, such as nitric oxide-releasing nanoparticles embedded in wound creams, specifically target infections. Upon application, these nanoparticles release nitric oxide gas, which effectively kills bacteria (Adnan, 2010). Nanotechnological applications will be effective in the creation of a sustainable environment. The most important ones are studies on hydrogen energy. One of these studies focused on a generator powered by light that cleans the air while generating hydrogen fuel. With the nanoparticles present in the catalyst of the device, hydrogen fuel is produced as the dirty air is cleaned (Verbruggen et al., 2017) (Figure 4).

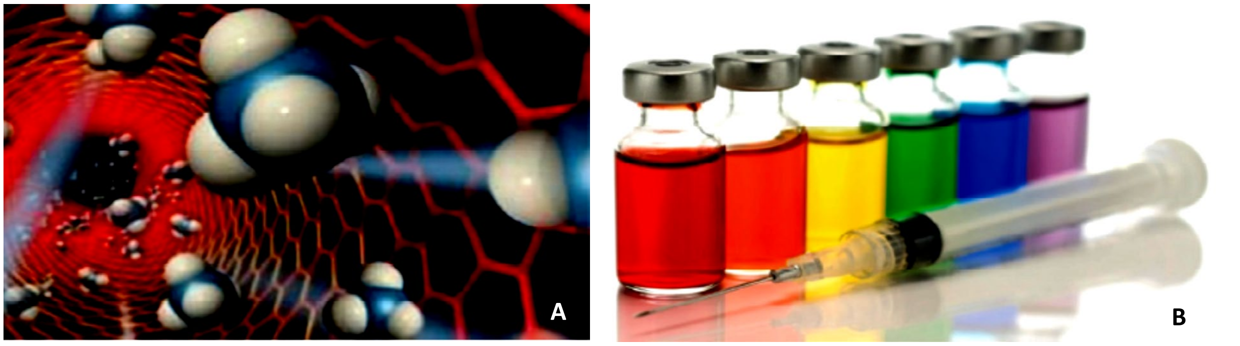

Figure 3 A: Drug delivery, B: Nanoparticle vaccinations (This image is published at https://id-ea.org/researchers-explore-new-class-of-syntheticvaccines/ and retrieved from Google Images.).

Figure 4: A light-powered generator- potable water- Thin, flexible and light filaments textiles. (This image is published at http://www.nanowerk.com/nanotechnology-news/newsid=45064.php and retrieved from Google Images.)

Storage of this produced hydrogen gas as fuel and hydrogen buses is the best example of this. However, to promote the use of this energy, first, it is necessary to store hydrogen at high density and in a safe way. However, storing high-density hydrogen is a difficult and expensive task. Today, scientists have shown that hydrogen can be stored at very high capacities in carbon nanotubes and molecules that are functionalized by transition elements (Pt, Pd, Ti, V, etc.). Hydrogen-powered automobiles can become more common with this discovery, which will lead to environmentally friendly fuel consumption. In this way, a solution can be found for clean air and alternative energy needs.

Another important development in the energy industry has occurred in studies on battery life. Scientists have used highly conductive nanowires, which are thousands of times thinner than human hair, in batteries to increase battery life. These wires create a large surface area, therefore providing a larger storage capacity; in this way, more electrons can be transferred. However, studies have shown that these wires are very fragile and cannot be recharged many times. A group of researchers coated nanowires inside a manganese dioxide and plexiglass-gel electrode to eliminate this problem. The safety and durability of this mixture are revealed through testing over more than 200,000 cycles. As a result of these tests, the batteries did not lose capacity, and the used nanowires did not breakdown (Thai, et al., 2016). This study is expected to significantly prolong the life of commercial batteries. With such developments, smartphones, computers, cars and other battery-powered vehicles may not need their batteries replaced.

Applications in water treatment processes are another important implementation of nanotechnology. Nanomaterials such as nanomembranes, carbon nanotubes, nanoclays and aluminum fibers are being used for water treatment applications. These materials are inexpensive, portable and easily cleanable systems. Nanofilters can eliminate precipitates, chemical waste, charged particles, bacteria and other pathogens, such as viruses, from water. In addition, they can also eliminate toxic trace elements such as arsenic and viscous liquid contaminants such as oil (OECD, 2004). Nanotechnology plays a crucial role in water treatment processes, utilizing various nanomaterials such as nanomembranes, carbon nanotubes, nanoclays, and aluminum fibers. These materials are cost-effective, portable, and easy to maintain. Nanofilters can remove a wide range of contaminants from water, including chemical residues, charged particles, bacteria, and viruses. They also effectively eliminate toxic trace elements such as arsenic and address viscous liquid pollutants such as oil (OECD, 2004).

Textile Applications of Nanotechnology

In the textile industry, nanotechnology is predominantly applied in the development of anti-stain and anti-wrinkle fabrics as well as products that resist liquid spills. Researchers have engineered titanium dioxide nanoparticles that react with sunlight to break down dirt and organic matter, allowing fabrics to remain clean when coated with cotton. Various nanoparticles—including clays, metal oxides, carbon black, graphite nanofibers, and carbon nanotubes—are employed to increase the mechanical strength and electrical conductivity of textiles. Notably, carbon nanofibers improve the tensile strength of composite materials, whereas carbon black nanoparticles bolster abrasion resistance and durability. Furthermore, composite fibers reinforced with clay nanoparticles exhibit properties such as flame retardance and ultraviolet protection due to their thermal and chemical resistance (OECD, 2004). A significant advancement in this field is the creation of self-cleaning fabrics; studies have shown that textiles treated with copper and silver-based nanoparticles can autonomously clean themselves when exposed to light (Anderson et al., 2016). Additionally, innovative lightweight filaments capable of generating and storing solar energy are being integrated into textile applications (Figure 5C).

Another important development in textiles is the thin, flexible and light filaments of copper strips that can be woven as textiles and can generate and store electricity from sunlight. These filaments, developed through nanotechnology, have solar cells on one side and energy storing plates on the other side. In the future, our mobile phones will be able to be recharged with clothes made from fabrics woven with these filaments. Maybe we will monitor our heartbeat, body temperature and blood sugar regularly with our clothes. Uniforms produced with nanotechnology will provide convenience for soldiers. Advancements in the textile industry have significantly contributed to the defense sector and are poised to continue doing so. The development of intelligent uniforms and materials through nanotechnology has introduced enhanced protective features. These innovations are not only more durable and longer lasting but also lighter and more resistant than traditional materials. This is expected to lead to increased adoption in military applications (Figure 5A). Future uniforms are expected to feature flexible, washable nanosensors capable of performing a range of functions, including energy generation, body temperature monitoring, alerts for necessary medical interventions, and detection of chemical and biological threats. Moreover, the widespread adoption of all-season, durable, lightweight clothing and footwear is expected to positively impact on the economy by providing financial benefits.

Food Industry and Nanotechnology

The integration of nanotechnology into the food industry is a relatively recent development. It is anticipated to empower food manufacturers to produce products that are not only affordable but also safer, more resilient, and enriched in nutritional value. Moreover, food companies are expected to minimize their consumption of water and chemicals throughout the processes of food preparation and production. For example, a food company has introduced nanosensors into packaging that notify consumers when the food is contaminated or starts to spoil by changing color. Scientists have also developed portable nanosensors capable of identifying pathogens and toxins in food. This advancement facilitates enhanced safety monitoring at various stages, including farming, processing, transportation, and packaging (Figure 5B). Some food manufacturers have also developed plastics infused with clay-based nanoparticles, which serve to inhibit the permeation of oxygen, carbon dioxide, and moisture. This innovation helps maintain the freshness of food and meat products (Mongillo, 2007). Furthermore, researchers have engineered clay nanotubes that can mitigate food poisoning risk by preventing spoilage and bacterial proliferation. Conventional packaging materials permit the flow of water vapor and oxygen, which results in the accumulation of ethylene near food, thereby accelerating its decay. Polyethylene films, particularly those infused with hollow clay nanotubes, are among the most common plastic composites employed for this purpose. Studies indicate that these nanotubes successfully diminish the production of ethylene by restricting the entry of water vapor and oxygen, thus prolonging the shelf-life of various food items (Lavars, 2017).

Figure 5. A: Uniforms produced with nanotechnology, B: Packaging by using nanotechnology (This image is published on http://www.fibre2fashion.com/industry-article/3046/militaryuniform? page=6 and retrieved from Google Images.)

In addition to these protective measures, nanotechnology is being leveraged to create nutritious and functional foods tailored to meet bodily needs while ensuring efficient nutrient delivery. Current scientific efforts are focused on developing on-demand foods that remain inactive until activated by the body, incorporating nanocapsules within them. Another significant advancement in food processing involves the use of nanoparticles designed to increase nutrient absorption (Mongillo, 2007). The food industry continues to witness a surge of innovative applications stemming from nanotechnology.

Nano impact today

A) Nanorobot Doctors over 30 Years

Imagine swallowing a tiny "doctor" capable of navigating through the bloodstream to target any affected cell in the body (Figure 6A). This nanodoctor is highly capable of delivering medication, removing tumors, analyzing tissue, and assisting in the repair of damaged areas. Currently, our treatments are limited by safety measures. For example, when designing an antibiotic, we must ensure that it kills harmful bacteria without harming our own cells. However, a nanorobot that can deliver toxins solely to targeted bacteria would make treatment simpler and more effective. Such nanotechnology could detect diseases before symptoms even appear, allowing easier and earlier treatment. Additionally, organs subjected to wear and tear, such as the liver, kidneys, and brain, could benefit from these nanorobots, which would help repair damaged cells. These robots can precisely place new cells at sites of injury, facilitating tissue regrowth that matches the original process, and then halts the process to prevent tumor formation. In just 30 years, this complex technology could be a reality.

B) Nanospaces

The most difficult problem faced by scientists when they proposed building a space elevator was linked to the material that would be most appropriate to meet such a high demand. In 1991, a Japanese researcher discovered a novel combination of carbon, which he called the 'tube nano', which proved to be breathtaking. The space elevator is designed to send space to satellites. Ultimately, it would make it a tourist attraction, offering the curiosity to travel in space (Figure 6B).

C) Intelligent lens

Nanomachines for therapeutic and diagnostic purposes within the human body are becoming increasingly common, with researchers striving to increase their functionality. This technology is not merely aimed at correcting vision impairments but also includes contact lenses equipped with displays. For example, when navigating an unfamiliar city, these smart lenses can activate and overlay various indicators onto the real-world view, facilitating navigation. The distinction between standard contact lenses and those with integrated displays lies in their incorporation of electrical connections and LED arrays (Figure 6C).

D) Lotus effect

The lotus plant possesses natural resistance against discoloration and soil accumulation, meaning that it remains clean despite its environment. This remarkable plant efficiently spreads light and has high energy efficiency (Figure 6D). Each droplet of water on its surface effectively removes dust and grime. This concept has inspired a startup focused on automotive products. The development of nanocoatings derived from this principle can be utilized in various nanotechnology applications for vehicles, including car services, showrooms, industrial facilities, and underground parking areas. The lotus flower is widely recognized as one of nature's most effective self-cleaning plants, exhibiting a phenomenon known as the lotus effect, which stems from the extreme hydrophobic properties of its leaves. Its leaves feature a delicate waxy coating that repels water, as well as dirt and pathogens. Scientists have created four varieties of silicon-based substances that are ideal for application to solar panels. These substances included a slick hydrophilic coating, a surface with nanoscale textured hydrophilic properties, a slick hydrophobic coating, and a nanotextured hydrophobic surface.

E) Nokia Morph: Transforming the Phone Experience

Nokia has leveraged advancements in nanotechnology to create a groundbreaking device known as Morph, which shows a variety of innovative technologies set to be integrated into mobile devices over the next decade (Figure 6E). This prototype can transform its shape, functioning as anything from a bracelet to a standard phone or even an office desk. Notably, it features a (transparent design), a self-cleaning surface, and the ability to detect and utilize nearby power sources. Displayed at the modern art museum in New York, Morph exemplifies the remarkable adaptability that future mobile devices may offer, highlighting a vision of extreme flexibility in technology.

Future Nanotechnology

Nanotechnology significantly influences the future of technology by enabling the precise manipulation of materials at the nanoscale (less than 100 nanometers). This cutting-edge field offers transformative potential across numerous industries, where it facilitates the development of highly efficient, compact electronic circuits and devices. As advancements in nanotechnology progress, its integration into diverse sectors is expanding, supporting the creation of cost-effective products and fostering substantial opportunities for business innovation. The influence of nanotechnology is expected to spread across every facet of everyday existence, including healthcare, food production, energy, transportation, infrastructure, and textiles. Its application promises to increase safety standards and quality of life through innovative solutions to common challenges. Long-term initiatives by organizations such as NASA's Advanced Concept Institute (ICA) are exploring forward-looking projects that may take decades to actualize. These projects include:

- Molecular machines that can construct objects atom-by-atom
- Superstrong materials, with tensile strengths up to 100 times greater than that of steel, yet significantly lighter
- Conductivity improvements that exceed those of copper
- Dual-functional materials that can act as both conductors and semiconductors based on their atomic arrangement
- Exceptional thermal conductivity enhancements

With ongoing research, the scope of nanotechnology applications is expected to broaden, potentially transforming industries and increasing the global quality of life. In terms of its use in agriculture and biomedicine, nanotechnology has already shown considerable utility. Nanomaterials help plants grow faster, start sprouting sooner during farming, and keep pests away. Nanotechnological advancements in biomedicine have contributed to treatments for cancer, diabetes, and microbial infections. In agriculture, the future of nanotechnology lies in its potential to address key challenges in productivity, sustainability, and food security (Parisi et al., 2015). Nanotechnology in agriculture could soon enable "smart" fields equipped with advanced nanotools for the precise management of agricultural inputs. Nanofertilizers, nanopesticides, and nanobiosensors offer promising solutions for environmental remediation and pollutant detection, reducing the environmental footprint and input costs of agriculture while increasing yields. However, a comprehensive understanding of the environmental fate and impact of nanomaterials remains critical. Collaborative research on nanomaterial properties, ecotoxicity, and species-specific effects is essential for optimizing nanotechnology applications across plant species for sustainable large-scale use.

Figure 6. A: Nanorobots, B: Space elevator, C: Intelligent lens, E: Lotus effect, D:Nokia Morph. A: (This is a featured Picture on Google images http://www.groupin.pk/blog/nanotechnology-a-daily need-in-thefuture/) C: (This is a featured picture on Google images, https://gadgetreport.ro/gadget/tehnologie-sf-devine-realitatecum arata-lentilele-decontact-inteligente-video/). D: (Picture taken from Google https://biomimeticdesign.wordpress.com/2008/08/27/lotus-effect-efecto-lotus/). E: (Picture taken from Google http://www.dreambloggers.com/5068/nokia morph-nanotechnology-phone future-of-mobile-phone-features-specs/).

Outlook

This study highlights recent advancements in nanotechnology, emphasizing its potential applications within medicine and agriculture, which holds promise for future research. This exploration is crucial for elucidating the specific mechanisms by which nanoparticles, nanotechnology, and nanomaterials function across medical, agricultural, and engineering disciplines. Continued research in these areas will be essential to expand methodologies and applications within both biomedical and agricultural sciences.

Emerging challenges

Nanotechnology has great potential for agriculture, but concerns about its safety remain. The use of nanomaterials in farming, water cleaning, and other methods could harm people, the environment, and wildlife. We do not know much about how these tiny particles affect our health over time, especially for workers. This highlights the need for detailed studies on their safety.

AVAILABILITY OF DATA

This investigation offers all the data collected.

AUTHORS' CONTRIBUTION

The author constructed the framework, data collection, data representation, writing, reviewing, and editing.

CONFLICT OF INTEREST

The author proclaims that there is no conflict of interest.

ETHICAL APPROVAL

Not applicable

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