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Advances in Nanotechnology: From Fundamental Science to Practical Applications

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Abstract

Nanotechnology refers to manipulating physical matter at length scales typically below 100 nm, which has become a disruptive scientific field with applications throughout the areas of medicine and health care, agriculture, electronics, environmental science, and materials engineering. Improvements in nanomaterials and nanoscale devices allow for enhanced performance in targeted delivery of pharmaceuticals. Nanosensors facilitate real-time monitoring of environmental pollutants, 'smart' packaging, and implementation of sustainable or green agricultural practices. The use of engineered nanoparticles in targeted drug delivery protocols are becoming increasingly possible for specific types of disease, as well as imaging of diseases prior to the use of traditional diagnosis methods (e.g., MRI). Additionally, nanosensors enable detection of environmental pollutants in real time while providing continual (and automatic) feedback to research facilities and the public about the condition of their surrounding air and water. Finally, the inclusion of nano-enabled agricultural inputs (e.g., nanofertilizers and nanopesticides) into agriculture are expected to increase crop yield while simultaneously reducing the number of chemical residues left in the ecosystem. Other innovations demonstrate the fast pace of innovation in this industry, such as the production of uniform metal nanoparticles for disease diagnosis and quantum AI technology for identifying gene mutations in humans. This review provides a snapshot of the current applications and trends, but also offers information on some key issues facing the industry, such as potential toxicity concerns, environmental dangers, and a need for a regulatory framework to ensure that nanotechnology can be implemented safely.

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Introduction

Nanotechnology, a field of engineering and science, primarily concentrates on the development of materials, electronics, and systems through atomic and molecular manipulation (Sim & Wong, 2021). The word "nano" comes from Greek and means "dwarf"; one nanometer is one billionth of a meter (Szczyglewska *et al.,* 2023). Because nanoscale size is extremely small, the way materials behave is very different from how they behave when they are large. The new and different ways that materials exhibit properties at the nanoscale (optical, mechanical, electrical, and chemical) can be attributed to several factors, including increased surface area, quantum effects, and molecular interactions, which is why nanotechnology is an interdisciplinary field that includes physics, chemistry, biology, engineering, and materials science. The concept of nanotechnology as it is understood today was first articulated by Richard Feynman in 1959 during his lecture titled "There is Plenty of Room at The Bottom," where he outlined how it would be possible to manipulate individual atoms and molecules (Toumey, 2008). However, it wasn't until many years later, with the creation of advanced analytical instruments (e.g., STM, Scanning Tunnelling Microscopy and AFM, Atomic Force Microscopy), that real breakthroughs in nanotechnology were made and research into nanotechnology exploded (Zhang *et al.,* 2013). Nanotechnology continues to attract global interest over the past few years as it can be used in an astonishing variety of applications across multiple industries (Figure 1). In medicine, nanotechnology has developed the ability to deliver specific drugs to targeted sites, create new methods for diagnosing patients, and produce innovative therapies including cancer treatment and tissue engineering (Jin *et al.,* 2020).

In agriculture, researchers are studying how to use nanotechnology in applications such as nanofertilizers and nanopesticides as well as developing "smart" systems for delivering nutrients to crops to maximize the effectiveness of the nutrients, improve crop yields, and reduce pollution from nutrient runoff (Mridha *et al.,* 2025). In addition, nanotechnology is helping create smaller, faster, and more energy efficient electronic devices (Salaudeen *et al.,* 2024). Materials based on nanotechnology are also finding use in the energy and environmental sectors for things like managing garbage, making renewable energy, cleaning up drinking water, and lowering pollution levels in the air (Beni & Jabbari, 2022). Researchers have found that nanotechnology-based solar cells, fuel cells, and energy storage devices have improved their efficiency and sustainability through the use of nanotechnology (Wang *et al.,* 2022). In addition, nanotechnology has generated advanced materials that exhibit superior strength, durability, and weight properties in comparison to conventional materials. These materials are currently employed in a diverse array of industries, including aerospace, construction, and automotive manufacturing (Hirankittiwong *et al.,* 2025; Feizbahr & Pourzanjani, 2024; Weng, 2025). Nanotechnology has enormous potential, however, there are numerous issues with regards to toxicity, environment, ethics, and health risk. Responsible development, regulation, and assessment of risk will allow for a safe and sustainable use of this technology. This paper will explore the contemporary applications of nanotechnology, with emphasis on recent advancements and opportunities/challenges presented by this field of modern science and technology.

Classification of nanoparticles

Nanomaterials are generally classified as substances that have a minimum of one dimension falling between the 1-100 nm range and are classified separately from bulk (non-nanomaterial) substances due to their unique or enhanced physicochemical characteristics. Because nanomaterials can exist with many structural, compositional, synthetic methodology, and functional differences, they can be systematically classified (Figure 3) to assist in understanding their physical, chemical, and application-based characteristics by grouping similar substances, thus helping facilitate material selection, assess toxicity, develop regulatory infrastructure, and enable or encourage sustainable use.

Nanomaterials can be classified in various categories, including dimensionality, chemical/compositional origin, and structural morphology.

Classification Based on Dimensionality

Dimensionality classification relates to the number of dimensions of each individual nanomaterial dimension that fall into the nanoscale range (Figure 2). Dimensionality classification is of significant importance to nanomaterials as dimensionality directly affects surface area to volume ratio, electronic structure, optical properties, mechanical properties, and other properties of nanomaterials (Mekuye & Abera, 2023).

Zero-Dimensional (0D) Nanomaterials

A zero-dimensional nanomaterial (or ball) will have all three (x, y, z) of its dimensions within the nanoscale range and none outside the nanoscale range of ten nanometres or less.

They may also be either amorphous or crystalline and can be either single or polycrystalline and demonstrate morphological diversity (variety in form and shape) and may be metal or ceramic materials.

Examples: Metal nanoparticles (Au, Ag, Fe), quantum dots, nanoclusters.

Characteristics

- Extremely high surface area-to-volume ratio
- Size-dependent optical and electronic properties
- High surface energy and reactivity

Applications: 0D nanomaterials are widely used in drug delivery systems, bioimaging, sensors, catalysis, and optoelectronic devices. Quantum dots, in particular, exhibit tunable fluorescence and are extensively used in biomedical imaging and light-emitting devices.

One-Dimensional (1D) Nanomaterials

One-dimensional nanomaterial (or needle) would have two of its three (x,y,z) dimensions in the nanoscale, and one of its three (x,y,z) dimensions outside the nanoscale range of ten nanometers or less. They may also be either amorphous or crystalline and can be either single or multi - crystalline and chemically pure or impure and either as an individual material or as an element of a composite material (i.e., metal, ceramics, and polymer). 1D nanoparticles may be either metal or ceramic or polymeric in nature.

Examples: Carbon nanotubes, nanowires, nanorods, nanofibers.

Characteristics

- High tensile strength
- Superior electrical and thermal conductivity
- Anisotropic properties

Applications: 1D nanomaterials are extensively used in nanoelectronics, energy storage devices, sensors, and as reinforcing agents in nanocomposites. Carbon nanotubes are particularly valued for their exceptional mechanical strength and electron transport capabilities.

Two-Dimensional (2D) Nanomaterials

2D nanomaterials consist of materials that have the shape of a plate and have two dimensions that exceed the nanometer scale, whereas 1D (x) nanomaterials are measured in range between 1-100 nm. 2D nanomaterials may either be amorphous or crystalline; aggregated using a variety of chemical compositions; and be deposited onto substrates or incorporated into a surrounding matrix material. A substrate can be metal or a polymer.

Examples: Graphene, nanosheets, nanofilms, transition metal dichalcogenides (MoS_2, WS_2).

Characteristics:

- Extremely large specific surface area
- High electron mobility
- Excellent mechanical flexibility

Applications: 2D nanomaterials are widely applied in flexible electronics, energy conversion devices, membranes, and sensors. Graphene has attracted considerable attention due to its remarkable electrical conductivity and mechanical strength.

Three-Dimensional (3D) Nanomaterials

3D nanomaterials or Bulk nanomaterials are classified as nanomaterials that do not fall under the nanoscale range along any dimension. Therefore, all three dimensions of a single 3D nanomaterial have dimensions greater than 100 nm; however, since 3D nanomaterials consist of blocks of nanomaterials, which are all in the nanometer range of size (1–100 nm), therefore all of the dimensions of a 3D nanomaterial consist of three arbitrary dimensions of size greater than 100 nm long. A 3D nanomaterial can be a particle or a dispersed particle mixture, or it could be a bundle comprised of many individual nanowires and nanotubes, and/or a stack of many different types of nanomaterials having either a 0D, 1D, 2D structural component that are in close proximity to one another forming interfaces or related material combinations.

Examples: Nanocomposites, nanoporous materials, nanostructured bulk materials.

Characteristics:

- High porosity and surface area
- Improved mechanical and thermal stability
- Enhanced functional performance

Applications: 3D nanomaterials are used in catalysis, energy storage, drug delivery matrices, and advanced structural materials.

Classification Based on Chemical Composition

The classification of nanomaterials can also be done based on their chemical composition and is one of the most common options since they strongly influence their physical and chemical properties (e.g., stability, reactivity, toxicity, potential uses). Depending on their elemental/molecular make-up, nanomaterials are generally divided into 5 categories: carbon-based, inorganic, organic, composite or biological nanomaterials.

They all have different functional characteristics and are used in a variety of applications, such as electronics, medicine, agriculture, energy, and environmental remediation (Suhas *et al.,* 2026).

Carbon-Based Nanomaterials

Carbon-based nanomaterials are nanomaterials that contain only carbon atoms, which can be arranged in many different configurations and therefore form the basis of all carbon-based nanomaterials. All carbon-based nanomaterials have excellent mechanical strength, good electrical conductivity, good chemical stability, and tunable optical properties.

Major types include

- Fullerenes (C_{60}, C_{70})
- Carbon nanotubes (single-walled and multi-walled)
- Graphene and graphene oxide
- Carbon nanofibers
- Carbon quantum dots

The sp^2 hybridization of carbon atoms gives carbon-based nanomaterials higher electrical and thermal conductivity compared to the other categories; therefore, carbon-based nanomaterials are excellent candidates for use in the production of nanoelectronics, energy storage devices, sensors, and drug delivery systems. An example of a high-performance carbon-based nanomaterial is graphene, which is a material of great interest due to its high surface area and mechanical strength and excellent carrier mobility. Graphene is a very attractive nanomaterial for use in the fields of catalysis and biomedicine.

Inorganic Nanomaterials

Inorganic nanomaterials are nanomaterials that are made from metal, metal oxide and/or semiconductor elements. The characteristics of inorganic nanomaterials include high thermal stability, high catalytic activity and excellent optical properties; therefore, inorganic nanomaterials have numerous applications in both the industrial and the biomedical fields.

Metal-Based Nanomaterials

Metal nanoparticles are typically synthesized from noble or transition metals and show size-dependent optical, electrical, and catalytic properties.

Examples:

- Gold (Au)
- Silver (Ag)
- Iron (Fe)
- Copper (Cu)

In antimicrobial applications, imaging techniques, diagnostic methods and catalytic reactions, nanoparticles of gold and silver are most common because of their substantial surface plasmon resonance spectrum manifesting from the particles and good bio-compatibility of these particles (gold/silver) makes them enormously valuable in medical applications.

Metal Oxide Nanomaterials

Nanomaterial formed from the combination of Oxygen atoms with metal cations are described as metal oxide nanomaterials.

Metal oxide nanomaterials exhibit high degree of chemical stability combined with significant photocatalytic ability.

Examples:

- Zinc oxide (ZnO)
- Titanium dioxide (TiO_2)
- Iron oxide (Fe_3O_4, Fe_2O_3)
- Silicon dioxide (SiO_2)

The primary applications for metal oxide nanomaterials include environmental clean-ups, nanofertilizers, sunscreens and photocatalysis; zinc oxide (ZnO) and titanium dioxide (TiO_2) nanoparticles are specifically noteworthy as they both possess substantial levels of UV-blocking capabilities and biological resistance (or antibacterial or germicidal) properties.

Semiconductor Nanomaterials

Semiconductor (semiconductor) nanomaterials can exhibit variable electronic and optical behaviours depending on size due to quantum confinement phenomenon.

Examples:

- Cadmium sulfide (CdS)
- Cadmium selenide (CdSe)
- Zinc sulfide (ZnS)

Semiconductor nanoparticles are frequently utilized in optoelectronic devices, solar cell technologies, and imaging/biological imaging applications.

Organic Nanomaterials

Organic nanomaterials primarily comprise carbon-based materials (such as polymers and surfactants), and possess characteristics of biocompatibility, biodegradability and lower toxicity than their non-organic counterparts.

Major forms include:

- Polymeric nanoparticles
- Dendrimers
- Nanogels
- Micelles

Because of their controlled release characteristics, high surface functionalisation ability, and low toxicity, organic nanoparticles are commonly used in drug delivery, gene therapy and tissue engineering applications.

Composite Nanomaterials

Composite nanomaterials consist of two or more separate nanomaterials combined together to result in compounds that possess property of synergy (or synergistic) properties not typically found in either of the materials alone.

Examples:

- Polymer–metal nanocomposites
- Carbon–metal oxide composites
- Core–shell nanostructures

These materials have shown increased mechanical strength, thermal stability and multiple functions to make them suitable for catalysis, energy storage, agriculture and biomedicine. Core-shell nanocomposites are also beneficial because they offer better stability and controlled functional performance.

Biological and Bio-Inspired Nanomaterials

Biological nanomaterials are produced from biological sources such as plant, bacteria, fungi and biomolecules. In addition, these nanomaterials are eco-friendly and very biocompatible.

Examples:

- Liposomes
- Protein nanoparticles
- Virus-based nanoparticles
- Green-synthesized metal nanoparticles

Biological nanomaterials have seen an increase in use in medical field, nano-medicine, agriculture and environmentally sustainable industries because they are less toxic and have eco-friendly synthesis methods.

Classification Based on Origin

Natural and artificial nanoparticles are the two groups into which nanomaterials are divided based on origin (Cho *et al.,* 2022; Khan & Hossain, 2022).

Natural nanomaterials

Nanomaterials found in nature can take many forms, which include but are not limited to viruses, proteins, clay-type minerals (e.g., clays) and natural colloids (e.g., milks, bloods) (liquid colloids); fog (aerosol); gelatins (gel); mineralized natural matter (e.g., shells); natural mineralized materials like coral and bones; many insects' wings (e.g., butterflies); opals; spider silk; leaves of lotus plants; feet of geckos; volcanic ash; and ocean sprays.

Artificial nanomaterials

Examples of man-made nanomaterials include carbon nanotubes and quantum dots (QDs) which have been created on purpose with exact mechanical processes or methods of manufacture. Depending on the composition of their structural make-up, nanomaterials can also be classed into three categories: metal Recontent-based, dendrime, or composites.

Synthesis of nanoparticles

The nanoparticles may be synthesized by different physical, chemical, and biological processes depending on the size and application of the nanoparticles. For instance, physical processes such as laser ablation, evaporation-condensation, and ball milling are used for the synthesis of nanoparticles. These processes are effective in controlling the size of nanoparticles but may require high energy and specialized equipment for the synthesis of nanoparticles (Iravani, 2011; Sangeetha *et al.,* 2020). On the other hand, the synthesis of nanoparticles by the sol-gel process, reduction, co-precipitation, and microemulsion processes is quite popular because the size of the nanoparticles may be controlled by the above processes (Rao *et al.,* 2004). Among the above processes, the reduction process is widely used for the synthesis of metallic nanoparticles such as gold and silver nanoparticles (Iravani *et al.,* 2011; Mohanpuria *et al.,* 2008). In recent years, the biological synthesis of nanoparticles has gained much attention due to the eco-friendly and sustainable synthesis of nanoparticles. In this synthesis route, the biological molecules such as plant extracts and microorganisms are used as reducing and stabilizing agents for the synthesis of nanoparticles (Iravani, 2011).

Plant-mediated synthesis is also an important one because it is easy and does not require the use of toxic solvents (Ahmed *et al.,* 2016). In the same way, bacteria, fungi, and algae have also been reported as effective biological systems for the synthesis of nanoparticles. The synthesis technique also has a significant impact on the properties of nanoparticles. For example, the size and stability of nanoparticles are important for their application (Sangeetha *et al.,* 2020). Therefore, the selection of the synthesis technique is an important factor for the synthesis of nanoparticles for use in health care, biotechnology, and agriculture.

In general, there are two main ways to make nanoparticles: the top-down technique and the bottom-up approach (Figure 4). The top-down method breaks materials down into nanoparticles by using physical or mechanical means. The top-down approach often uses methods like laser ablation, mechanical machining, lithography, and sputtering. These techniques are utilized to break down materials into nanoparticles (Rao *et al.,* 2004; Sangeetha *et al.,* 2020). Although the top-down approach has the advantage of controlling the size and shape of nanoparticles, the high-energy processes involved may result in particle defects and irregular size. On the other hand, the bottom-up approach involves the synthesis of nanoparticles by employing physical and/or chemical transformations.

Techniques such as sol-gel synthesis, reduction synthesis, co-precipitation synthesis, hydrothermal synthesis, and biological synthesis are common in the bottom-up approach (Iravani, 2011). This approach has the advantage of controlling the size and characteristics of nanoparticles because nanoparticles are synthesized at the molecular level. Recently, the bottom-up approach has been given more attention compared to the top-down approach because of the use of green synthesis. Techniques such as the use of biological molecules and plants are considered environmentally friendly and cost-effective for the synthesis of nanoparticles (Ahmed *et al.,* 2016).

Nanotechnology and Its Applications

Nanotechnology is a very important branch of the science and technology world, which is extremely influential, as this branch of technology can help in the development of technology as well as benefit the world in a number of ways. The branch of science concerned with the manipulation, design, and usage of materials at the nanoscale is referred to as nanotechnology. The ability to manipulate materials at the nanoscale is what enables the development of new products and systems with greater functionality, efficiency, and performance than what is achievable without the usage of nanotechnology. Nanotechnology has been utilized in numerous different industries and has found wide usage in the fields of health, electronics, engineering, agriculture, and energy technologies (Mohammad *et al.,* 2022). Due to the interdisciplinary character of nanotechnology, it has greatly contributed to accelerating scientific discoveries and technological advancements that could not have been achieved using conventional methods.

Applications of Nanotechnology in Electronics

The incorporation of newer nano-scale materials and devices in contemporary electronic devices has altered the design and production of electronic devices through the incorporation of better electrical, optical, and mechanical properties in the constituent parts used in their production (Musa *et al.,* 2025). At the nano-scale size, the constituent parts have better properties such as increased surface activity, conductivity, and sensitivity, thus providing better means for signal transmission through the use of chemical and biological sensing technologies. This has led to the production of biosensors that are extremely sensitive and can detect a variety of biological and/or chemical agents or substances. Due to their small size and high surface area to volume ratio, nanomaterials require less material to be used but can achieve significantly higher efficiencies than are achieved using conventional bulk materials (Joudeh & Linke, 2022). Nanotechnology has had a significant role in advancing computer and electronic devices. In particular, it has allowed for the manufacture of smaller, lighter, and more energy-efficient devices. Current electronic devices demonstrate better processing speeds, larger capacity for data storage and enhanced reliability. Nanoscale conductor materials have now substituted for traditional conductor materials used to assemble electronic components, resulting in more safety and cost-effective production processes. In addition to improving computer systems performance — such as improving how quickly they start up, how long a device retains data and displaying a higher resolution image on its screen — the overall system has benefited from advances made through nanotechnology. Nanomaterials, like quantum dots have enabled much greater brightness and contrast in advanced display systems while also improving energy savings; Nanoscale components have led to the development of hearing aids with greater responsiveness, memory storage devices with higher density, and smaller types of electronic systems capable of being used in portable devices (Chauhan *et al.,* 2023). Collectively, these innovations are saving power and increasing the use of electronic devices. Nanoelectronics has resulted from demand for smaller and denser components and is a precise branch of engineering that manufactures and operates devices at nanometer sizes. At the nanoscale, electronic processes differ significantly from those at larger dimensions owing to quantum confinement effects and the dominant influence of atomic-scale interactions. Understanding and manipulating phenomena on a nanoscale is essential for developing next generation of electronic products; therefore, nanoelectronics will open up new avenues for industry to continue developing high performance, small footprint, and intelligent electronic systems into the future (Payal & Pandey, 2022).

Applications of Nanotechnology in Medical and Healthcare

The application of nanotechnology in medicine and healthcare relies greatly on nanometers-sized materials and devices that can interact with biological systems, such as cells and tissues, at their molecular and subcellular levels. Nanomaterials, then, are highly specific and sensitive, which lead to highly precise interactions with the molecular structures occurring naturally in the human body; for example, nanomedicine (the science applying nanotechnology) is an advanced and innovative aspect of nanotechnology in healthcare, consisting of the observation, treatment, and modulation of biological systems through engineered nanostructures and nanodevices (Kazi *et al.,* 2025). Modern diagnostics and therapeutic sciences have benefited greatly from this new scientific field, as many of today's most significant breakthroughs in diagnostic and therapeutic sciences represent significant advancements in our ability to perform interventions at the molecular level (Kurul *et al.,* 2025). A significant issue in healthcare today is how to deliver drugs and other therapeutic agents throughout the body in an efficient and targeted manner. Nanotechnology has developed into a promising alternative in the area of pharmaceutical development, with the drug delivery system being the most important nanotechnology development in medicine (Sim & Wong, 2021). Numerous therapeutic strategies have been developed and reported that use nanotechnology-based drug delivery systems, including the use of nanoparticles as the pharmacological agent and/or the delivery vehicle for the controlled and targeted delivery of drug substances. The use of nanocarriers to deliver drugs will enhance a drug's therapeutic potential by increasing stability and/or bioavailability and by decreasing the systemic toxicity level of the drug (particularly of drugs that are poorly soluble or degrade quickly in the body) (Islam *et al.,* 2025). The use of polymer-based nanocapsules to deliver medications based on external factors such as pH, temperature, and electric charge can allow for site-specific release, for instance, in a tumor, which can limit the effects of medication on healthy tissue and thus improve the effectiveness of medication (Chu *et al.,* 2022). Nanomedicine is a burgeoning field that continues to assist the development of medical diagnostic tests, methods, and clinical instruments. Nanotechnology advances biologic processes, thus allowing for disease identification, prevention, and treatment with a very high level of accuracy. Some of the advancements that have been made possible by the use of nanotechnology in the field of medicine include improved imaging and diagnosis for the early detection and treatment of diseases, improved knowledge and treatment for heart diseases by focusing on the detection and treatment of plaque in the arteries, and the regeneration of bone and nerve tissues (Chohan *et al.,* 2024).

Applications of nanotechnology in energy

Nanotechnology has contributed significantly in the development of new ways of improving alternative energy technologies as well as traditional energy sources in order to meet the ever-growing need for energy in the world (Hussein, 2015). The application of nanotechnology in energy includes a wide range of different areas, including creating more efficient catalytic processes to produce fuel from petroleum-based feedstock, improving combustion efficiency and reducing friction in engines and power plants, resulting in reductions in total fuel consumed (Hosseinzadeh-Bandbafha *et al.,* 2023). The development of carbon nanotube-based membranes and scrubbers for the efficient removal of carbon dioxide from the emissions of power plants is also an achievement of the application of nanotechnology, and the development of low-cost and easy-to-install nanostructured solar cells for the conversion of solar radiation into electrical energy is an additional example of the potential of the application of nanotechnology in the energy sector (Ibekwe *et al.,* 2025). The incorporation of carbon nanotubes in the structure of wind turbine blades makes it possible to increase the length, weight reduction, and mechanical strength of the blades, and the incorporation of flexible piezoelectric nanowires in fabrics and thin-film solar cells may enable the generation of portable energy (Attaf, 2024). Around the world, researchers are concentrating on finding alternatives to existing fossil fuel-type energy solutions by developing new technologically advanced energy options. The goal of creating alternative energy resources will be to back up some of the common forms of energy production (i.e., petroleum, coal, hydropower, natural gas, etc.) with a sustainable, renewable energy solution. Currently, most alternative energy technologies are used for small-scale energy production (like solar panels or wind turbines), but many experts believe these technologies will be able to produce large amounts of energy in the future. During the next 10–20 years, nanotechnology (i.e., using nanomaterials, such as carbon nano-tubes) will begin to affect how energy is transferred & distributed throughout the world. For example, power and energy usage may be optimized through better fuel utilization within transportation systems, reducing use of gasoline for long distance trips. In addition, the added strength and smaller amount of space required by nanoparticle-based construction materials will result in less physical space needed for electric energy transmission lines and natural gas pipeline systems, compared to traditional construction materials (Hussein, 2015). The energy sector, which involves energy generation, storage, and use, is one of the largest contributors to environmental damage and thus has an enormous environmental footprint. There are still many challenges to be addressed before we can create a completely sustainable energy system; however, ongoing research in energy nanotechnology will mitigate these negative effects on our planet. Energy is one of the main priorities for the EU's Seventh Framework Programme (FP7), which has placed an emphasis on the fast-tracking of affordable solutions to create a sustainable energy economy. This research is expected to result in much better access to energy, both in homes and in automobiles, in the twenty-first century (Omietimi *et al.,* 2023). Researchers are now starting to explore the possibilities of using recent breakthroughs in the nanoscale as possible alternatives to the traditional Complementary Metal-Oxide-Semiconductor (CMOS) technology, especially in the development of communication systems. In this regard, the use of quantum dot cellular automata technology has enabled the design of low-power consumption, high-speed, and compact digital circuits, especially in memory design. In contrast, digital circuits built using CMOS technology have higher power consumption, take up more space, and experience more leakage current than those built with quantum dot cellular automata technology (Alharbi *et al.,* 2024). Apart from using nanotechnology in traditional energy applications, new energy-based medical therapies have been developed for treating cancer using this technology. In particular, energy-based approaches for treating cancer are designed to help reduce some of the toxic side effects related to conventional chemotherapy and to allow for greater precision in treatment of the disease. Because of the rapid progress being made in this particular field, the current research being done is focused on how to increase precision in targeting therapies, as well as how to use these therapies in combination with one another. Some of the promising energy-based therapies being evaluated for treating cancers include: cryoablation, high-intensity focused ultrasound (HIFU), microwave therapy, radiofrequency (RF) ablation, photodynamic therapy, and alternating magnetic field (AMF) therapy. These energy-based therapeutic methods provide a way to destroy unhealthy tissue while reducing the risk of systemic side effects, infection, and the need for major surgery.

Most of these types of therapy are performed in an outpatient setting and are minimally invasive, using localized temperature changes to destroy malignant cells (Alharbi *et al.,* 2024). Due to the rapid depletion of non-renewable energy sources, the past few years have seen an increase in interest in renewable energy technologies for the sake of cleaner and healthier environments. Researchers have been examining multiple types of renewable energy systems (e.g., supercapacitors, batteries, solar cells, fuel cells, and wind turbines) and how they can be used to convert one type of energy into another. The use of nanomaterials and nanostructures in these systems has significantly improved their functionality and efficiency. However, these new technologies have raised questions about their safety for both the environment and human health when it comes to exposure to nanomaterials (Alharbi *et al.,* 2024). Nanostructured devices and components with dimensions of less than 100 nm are opening up new possibilities for the efficient harvesting, storage, and transfer of energy. The sun provides huge potential for solar energy, which is generated by nuclear fusion processes, and this resource has not yet been utilized to its fullest extent. The amount of solar power available is expected to far exceed the global needs for primary energy today. As a result, much research has been conducted on the development of solar collection technologies based on nanomaterials. As such, a variety of nanomaterials have been incorporated into solar collectors, fuel cells, photocatalysis, and photovoltaic systems to improve energy conversion efficiency and overall system performance (Farajollahi, 2025).

Application of Nanotechnology in Modern Textiles

Nanotechnology is characterized by manipulating materials at an atomic and molecular level, or nano-scale (approximately 1–100 nm). Nanotechnology enables a high level of control over the structural and physical characteristics of Materials. The advancements made through Nanoscience have resulted in high-quality material creation and have had a dramatic impact on the area of textile science using nano-engineering to develop new and improved polymer and textile materials. Nanotechnology has made a significant improvement in the performance of textiles by providing additional functional properties to them. Traditional textile finishing processes have typically focused on aesthetics and basic surface characteristics. However, the advances made in textile finishing films with nanotechnology allow for long-term durability improvements in functionality for an entire range of in-use textiles. Examples of modern-day textile characteristics that have been enhanced by nanotechnology include antimicrobial properties; UV protection; water resistant properties; wrinkle resistant properties; flame retardant properties; and stain resistant properties; without loss of comfort or flexibility. Nanotechnology allows the introduction of nanomaterials into textiles by using physical, chemical or biological processes to increase properties thereof, such as quality, durability, and cost effectiveness. Nano-engineered textiles are widely available for use in a variety of industries and end-uses including safety apparel, smart textiles, sanitary products, and high-performance athletic wear such as bullet-resistant clothing or multifaceted textiles; using nano-engineering for natural fiber types like cotton to economically improve performance and extend service life of textiles are particularly common. In addition to providing safety from chemicals and heat, nanotechnology helps create industrial protective textiles that protect workers from flames, biological hazards and particulate matter. Nanotechnology has led to the creation of new fibers and coatings, which provide better resistance, durability, and comfort for users in difficult work environments (Syduzzaman *et al.,* 2023).

Nanotechnology's use in textiles also created many new uses for textiles, for example, as conductive textiles, antibacterial textiles, wearable sensor textiles, and light-emitting textiles, as well as electronic components directly incorporated into the fabric. The use of these new textiles has expanded their use into a variety of industries, for example, healthcare, defense, electronics, and wearable technology (Prasad *et al.,* 2024). In summary, nanotechnology has modernized the way textiles are produced and their application to create very durable, versatile and high-quality textile products. Not only does nanotechnology present a great deal of opportunity for innovation and potential economic growth, the focus of future advances will be on creating sustainable, reliable and regulatory compliant nanotechnology solutions while ensuring that the essential properties of textiles are not compromised (Gouda, 2013; Qian, 2004).

Application of Nanotechnology in Agriculture

Nanotechnology has become an important tool in today's agriculture, enabling precise, efficient and sustainable ways of managing agricultural inputs/resources through the manipulation of materials at the nanoscale; therefore providing innovative means of enhancing the productivity of crops, increasing the efficiency of nutrient use, Protecting plants from biotic and abiotic stresses and reducing the adverse environmental effects resulting from the conventional methods of agriculture (Chaudhary *et al.,* 2025). Nutrient management via Nano-fertilizers is one the most exciting ways in which Nanotechnology can help with agriculture. The creation of nano-fertilizers enables a systematic and targeted way of applying nutrients to plants thereby greatly reducing nutrient losses through leaching, evaporation or fixing within the soil. The increased availability and efficiency in uptake help in the growth of crops while also providing the advantage of reduced rates of Fertilizer application (the rate of nutrient application), compared to using conventional fertilizers (Table 1). Zinc, Iron, Copper, and Silica in nanoparticle forms are also being studied for their ability to address the deficiency of Micronutrients in the crop and also help in the metabolic process in plants (Kumar *et al.,* 2025). Nanotechnology is also being used extensively for crop protection; therefore, nanoparticles can enhance the efficacy of nano-pesticides and nano-herbicides through improved penetrability, controlled release and increased stability of active ingredients. The application of pesticides/herbicides targets a specific area and hence allows for a reduced amount to be used, thereby reducing off-target effects and the contribution to environmental pollution by such chemical compounds. The engineering of nanoparticles into pesticides/herbicides also ensures that there is no degradation of such compounds by light, temperature, or microorganisms, thereby extending their period of usage (Chen *et al.,* 2025; Yousef *et al.,* 2023). The application of nanotechnology to improve soil health and water management is proving to be very beneficial for both areas. Nanoparticles affect soil structure and help to capture moisture, as well as provide a way for soil to hold nutrients; especially sand-based or degraded soils. Soil amendments such as soil conditions based on nanoscale materials and hydrogels, are ways to maximize water use efficiency and assist with crops in their ability to survive during times of drought stress. The incorporation of nanotechnology into irrigation systems will also improve the purification and monitoring of the water supply used for irrigation, thus allowing for safe and efficient water use in agriculture (Mustapha *et al.,* 2025; Pandey, 2024). Nanotechnology is being applied in agricultural sensing as well as precision farming today (Shaikh *et al.,* 2021). Real-time monitoring of soil moisture, nutrient content, plant health, pest intensity, as well as environmental factors, can be carried out through the application of nano-sensing technology.

This smart sensing technology can also help in efficient use of resources through data-driven decision-making, which can lead to optimized use of labour as well as resources, thus helping to achieve this goal through maximum productivity as well as zero wastage. Nanotechnology is also beneficial for the post-harvest management of food and food security. Antimicrobial-nanoparticle coatings and nanomaterial packaging can provide growers with ways to extend the shelf life, reduce waste, and retain nutritional content of food products. Antimicrobial nanoparticles are particularly important in reducing food spoilage after harvesting, especially during transport and storage (Gidado *et al.,* 2025). In conclusion, it is evident that nanotechnology is providing tremendous opportunities for the achievement of sustainable agricultural intensification. The key to using nanotechnology sustainably in agriculture is to protect the environment, ensure economic viability, and follow legal requirements. Future research should concentrate on advancing safe nanotechnology and techniques that enhance agricultural productivity while safeguarding soil and human health.

Applications of Nanotechnology in Food and Packaging

Nanotech has been established as a cutting-edge technology within food and packaging, providing increasing levels of quality, safety and long-term stability for food products. The integration of nano-materials to either food systems or to packaging materials provide improved functional properties while offering consumers greater protection. The incorporation of smart packaging technologies that incorporate nano-sensors, as well as nano-materials, is able to track the condition of the food products in real-time. Nano-sensors are able to track changes in the temperature, humidity, pH levels, and the presence of gases like ammonia and carbon dioxide, all of which indicate the spoilage and degradation of the food product from the original state (Ramezani *et al.,* 2025). Some of the smart packaging technologies have the ability to change their colors, thus indicating whether the food product is spoiled or not. These technologies are thus very important for the average consumer or the retailer as a means of determining whether the food is spoiled or not. Additionally, nano-sensors have the ability to track the presence of microbial contaminants and toxins in the food products, even at very low levels. This indicates the significance of the incorporation of nano-technologies in the field of food safety while in storage and while being transported. Nanotechnology is also very important in the improvement of the barrier properties of the packaging materials. Nano-composites, such as nano clay, nano-silica and graphene-based products, are used to create better barrier performance for gas permeation (i.e., O_2, CO_2 and moisture). The reduced barrier performance prevents food spoilage primarily due to oxygen and moisture present in the atmosphere which induces oxidation, microbial growth and moisture loss. Therefore, food products will remain fresh for a longer duration of time which leads to reduced food waste; it also leads to an overall improved supply chain efficiency (Ashfaq *et al.,* 2022). In addition, antimicrobial nanoparticles such as silver and zinc oxide may be used in food packaging films to prevent the growth of pathogenic microbes. Nanotechnology facilitates the quick detection of foodborne pathogens. Nano biosensors and nano-biochips can identify pathogens like E. coli, Salmonella, and Listeria in food within a few minutes.

Due to the extraordinary sensitivity, accuracy, and the speed of the results compared with non-nano materials, such devices are useful in the prevention of the outbreak of diseases caused by foodborne illnesses and the assurance of the observance of food safety regulations (Akbari-Alavijeh *et al.,* 2025). Nano-encapsulation is the incorporation of bioactive compounds into a nanoparticle. Bioactive compounds include vitamins, antioxidants, probiotics, and essential oils. These nutrient delivery systems with nano-encapsulation technology are advantageous in the protection of nutrients from degradation in the presence of light, heat, and oxygen. In addition, the nutrient delivery system with nano-encapsulation is advantageous in the controlled release of nutrients in the gastrointestinal system. This improves the absorption of the nutrient. Therefore, nano-encapsulation technology is useful for creating functional foods and nutraceuticals with improved nutritional benefits (Arratia-Quijada *et al.,* 2024).

Applications of Nanotechnology in Environmental Management

Nanotechnology is an important aspect in the protection and preservation of the environment. Nanomaterials are highly reactive because of their large surface area compared to their volume.

These characteristics have enabled nanotechnology to be effective in pollution control and waste management. Recent developments in the field of Nanotechnology have improved existing technologies in water treatment processes. One of the developments is the ability to design nano-filters and nano-membranes that have the ability to effectively remove a variety of heavy metals in water. Some examples include arsenic, lead, and mercury. In addition, nano-carbon tubes, graphene oxide, and nano-alumina have been used in the effective adsorption of harmful ions in water. Furthermore, owing to the high antimicrobial properties, nanoparticles like titanium dioxide and silver have been used in the effective killing of harmful bacteria, viruses, and protozoans in water. This helps in the effective purification of water using faster methods with minimal concentration of contaminants compared to existing water filters (Elhenawy *et al.,* 2024). In addition to the use of nanomaterials in water purification, they are used in the reduction of air pollution by capturing harmful gases in the air. For example, titanium dioxide nanoparticles can be utilized due to their strong photocatalytic properties; hence, they have the ability to break-down nitrogen oxides, sulphur dioxide, and volatile organic compounds when exposed to light. Similarly, nanofiber filters have been incorporated into the mechanics of air purification systems in order to trap ultrafine particles, allergens, and microorganisms. These technologies are helping in the improvement of the quality of indoor and outdoor air quality and are thus directly contributing to the prevention of respiratory problems caused by poor air quality (Saleem *et al.,* 2022). The remediation of contaminated soils or soil pollution can also be carried out using nanotechnology. Zero-valent iron nanoparticles are used for the degradation of harmful organic substances such as pesticides and solvents. These nanoparticles are small enough to penetrate deep into the contaminated soils and react with the toxic substances, breaking them down into harmless substances. This is thus more efficient and cost-effective compared to other remediation processes (Xue *et al.,* 2018). Nanomaterials have great potential for managing oil spills in ocean waters. Nano sponges can absorb or extract oil from the water using magnetic nanoparticles; they have a very high capacity for absorption. Both the magnetic nanoparticles and the hydrophobic nano-sized materials can be reused after extracting the oil, with magnetic nanoparticles requiring only magnetic fields to separate the absorbed oil from the particles (Avila *et al.,* 2014).

Applications of Nanotechnology in Construction and Materials

Nanotechnology has significantly changed the construction industry, leading to improvements in the strength, durability, and overall performance of building materials (Macías-Silva *et al.,* 2024). The addition of nanoparticles to building materials makes them more resilient to environmental factors, which increases their lifespan of use. The new technology advancements involve sustainable practices in building designs, while at the same time, there is a reduced need to maintain such constructions. Adding nano-silica to concrete has been seen to make it more robust. Due to their small size, nano-silica can occupy the pores in the cement paste. This leads to the creation of calcium silicate hydrate gel, which is essential for concrete's strength. Therefore, concrete with nano-silica is more durable, less permeable, and less likely to crack than regular concrete. Moreover, it has been proven that concrete that is enhanced by nano-materials is resilient to environmental degradation and chemical attacks and hence is the most appropriate choice for long-lasting infrastructure (Althoey *et al.,* 2023). Nanotechnology has led to the development of self-healing construction materials used to automatically repair cracked construction materials. Microcapsules or nano-sized healing agents contained within concrete will release repair materials when they are activated by cracks. Furthermore, such nanomaterials as nano-calcium carbonate and nano-silica enhance and speed up the curing process, as they will accelerate the curing of crack-sealing agents. These self-healing mechanisms will greatly reduce the amount of structural damage, service life of buildings and bridges, and the need for continued maintenance (Jiang *et al.,* 2024). Another area where nanotechnology is being utilized is to develop coatings that prevent corrosion on metal surfaces. Buildings, bridges, etc., are highly prone to corrosion, as they have to face harsh environmental conditions all the time. Nanotechnology is also helping in increasing the durability and corrosion-resistance of these structures. Coatings contain nanoparticles, such as nano-zinc oxide, nano-titanium dioxide and graphene that improve the adhesion of coatings to surfaces; provide coatings with improved barrier properties; and provide coatings with improved resistance to chemical penetration. The application of nanotechnology-based coatings will result in an increase in the longevity of steel reinforcements, as well as other types of metallic construction materials (Rathish, 2013).

The use of nanomaterials, for example, carbon nanotubes, graphene, and nano composites, is being employed for the production of lightweight yet high-strength construction materials (Macías-Silva *et al.,* 2024). These nanomaterials possess high mechanical strength, flexibility, and thermal stability when compared with other construction materials. The reduction of weight in construction materials is bound to reduce the loads in the structure while maintaining strength, hence increasing energy efficiency.

Applications of Nanotechnology in Cosmetics

Nanotechnology has significantly improved the cosmetic industry, particularly in how well products work, how long they last, and how well they work with other ingredients. Currently, nano-sized titanium dioxide (TiO_2) and zinc oxide (ZnO) are common in sunscreen products.

These materials can protect against UVA and UVB radiation. This is done by reflecting and scattering the harmful rays of the sun. Nano-titanium dioxide (TiO_2) and zinc oxide (ZnO) possess the characteristic of transparency, thereby eliminating the typical white residue. These diminutive particles facilitate even application on the skin, enhancing the efficacy of these formulations in UV ray blockage while simultaneously contributing to a visually pleasing aesthetic (Sitinjak *et al.,* 2025). This is because nanotechnology has allowed active ingredients such as vitamins (Vitamin C and E), retinol, and antioxidants to be nano-encapsulated, meaning that these active ingredients have been placed inside small particles. Nano-encapsulation protects these active ingredients from breaking down when exposed to light and oxygen. Furthermore, nano-encapsulation enables these active ingredients to penetrate deeper into the skin, thus making them more effective in eliminating fine lines, wrinkles, and damage on the skin. This is due to controlled release ingredients that ensure that they last longer and are more effective in formulation (Pan *et al.,* 2025).

Cosmetic and dermatological products have become more effective due to the application of nanotechnology in the form of nano-carriers such as liposomes, niosomes, and solid lipid nanoparticles. This has enabled an improvement in the skin penetration of such products through the skin's barrier function, as well as a targeted approach to delivering such products to a particular skin layer. This has enabled a reduced amount of such products to achieve a more effective result, which has reduced irritation as well as improved safety (Albakr *et al.,* 2024).

Applications of Nanotechnology in Defence and Security

Nanotechnology significantly enhances defense capabilities. The unique mechanical, optical, and chemical properties of nanomaterials have led to the creation of highly sophisticated security equipment, protective gears, and stealth devices (Rahman, 2025). Nanotechnology is creating innovative ways to detect explosives using nanomaterials. Due to the use of nanoparticles, there is an increase in surface area, which is available for chemical reactions with analytes, thus enabling high sensitivity while detecting small amounts of explosives (Chavan *et al.,* 2023). These devices have been used in various military operations, such as airports, borders, etc., with the purpose of enhancing security levels and protecting against terrorist activities. Carbon nanotubes, Graphene, etc., have been used to create highly strong armor materials, which can be used to create protective gears. This type of gear ensures impact resistance and durability while reducing the overall mass and thus increasing the mobility and comfort for military personnel without compromising the overall safety of the mission (Zelelew *et al.,* 2026). The coating developed through nanotechnology is likely to help in reducing the visibility of military assets to radar and infrared detectors by absorbing radar and infrared energy.

Figure.1 Various applications of Nanotechnology

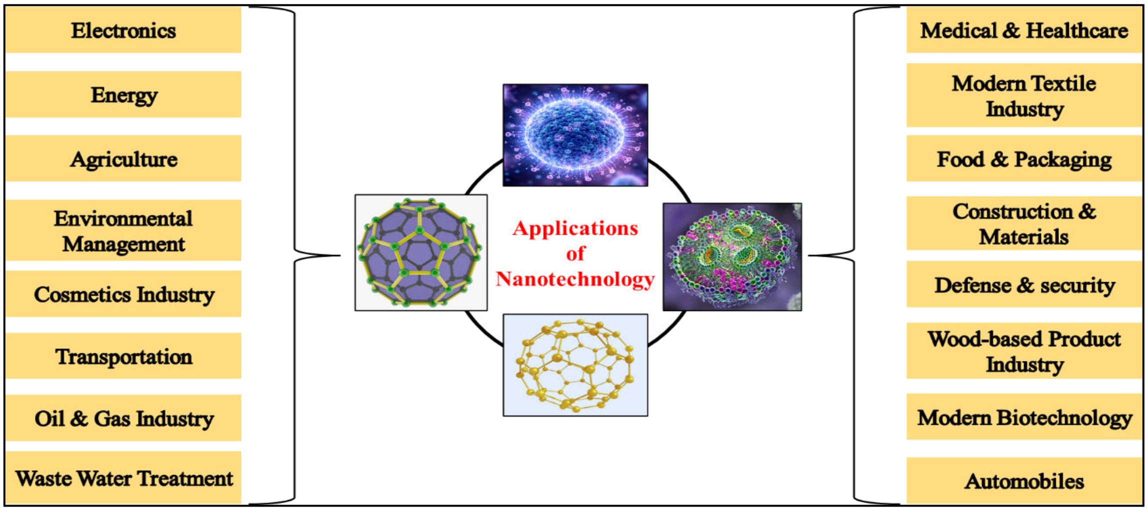

Figure.2 Classification of Nanomaterials Based on Dimensionality

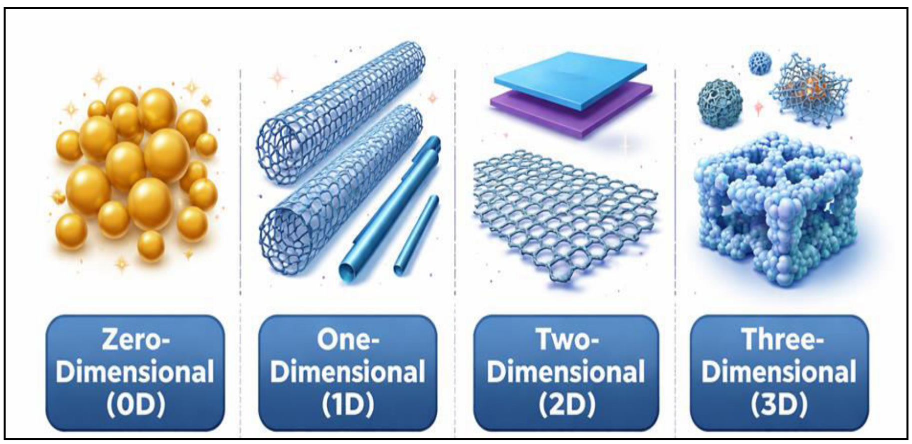

Figure.3 Classification of Nanomaterials

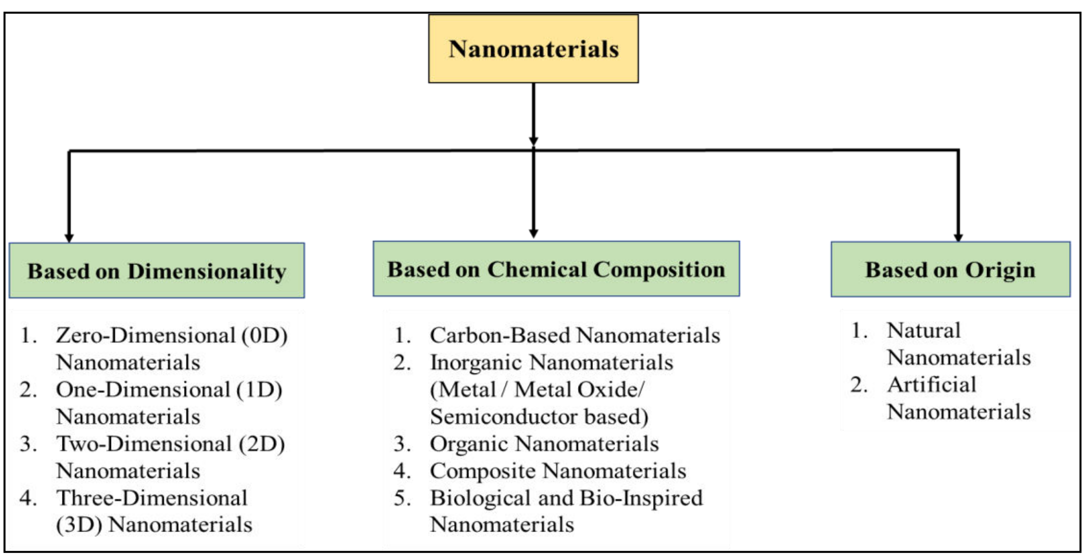

Figure.4 Approaches of nanoparticles synthesis

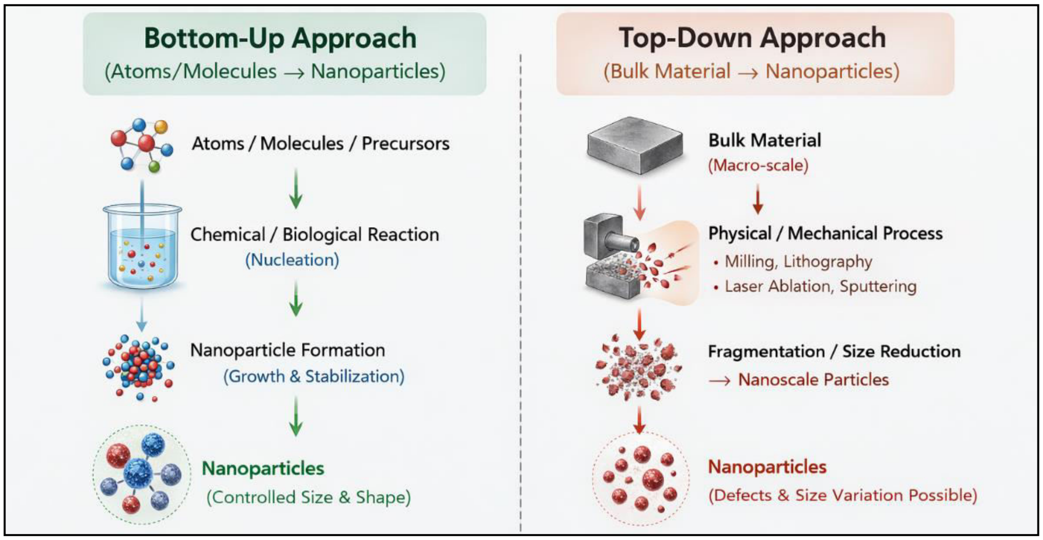

Table.1 Nanoparticles as substitute of chemical fertilizer

Nanoparticle Used	Substitute fertilizer	Advantages	Reference
Liquid Nano-Urea (nano-nitrogen particles, ~20–50 nm)	Conventional granular urea (N fertilizer)	• Nutrient use efficiency up to 85–90% (vs. 30–40% in conventional), • Drastically reduces N losses via leaching, volatilization, and runoff, • Controlled foliar release for targeted delivery throughout crop life cycle.	Upadhyay *et al.*, 2023
Zinc Oxide Nanoparticles (ZnO NPs, ~30–100 nm)	Conventional zinc sulfate ($ZnSO_4·7H_2O$)	• Superior bioavailability and Zn uptake in neutral/alkaline soils, • Increases grain Zn content by 7.9–20%, germination (up to 22%), root/shoot elongation, chlorophyll content, and yield, • Lower application rate (5 mg/kg soil or 100 mg/L foliar) with minimal runoff and better retention than bulk $ZnSO_4$, • Additional stress mitigation and microbial biomass support.	Singh *et al.*, 2021
Hydroxyapatite Nanoparticles (nHAP)	Traditional phosphorus fertilizers (e.g., superphosphate or rock phosphate)	• Slow/controlled P release with high solubility and uptake, • Improves maize growth, yield, rhizosphere activity, and salt tolerance, • Reduces P leaching and	Zhang *et al.*, 2026

		environmental pollution.	
Nano-zeolites (nano-porous zeolite carriers loaded with nutrients)	Conventional NPK fertilizers (urea, monoammonium phosphate, etc.)	• Extended slow release, fixes NO_3^- and NH_4^+ in soil, • Cutting losses from leaching, volatilization, and denitrification; • Boosts nutrient use efficiency, soil water retention, cation exchange capacity • Reduce environmental impact.	Yadav *et al.,* 2023

Table.2 Nanoparticles used in Biotechnology with specific applications

Nanoparticles	Applications	Advantages	Reference
Gold Nanoparticles (AuNPs)	Targeted drug delivery, photothermal therapy, bioimaging, gene transfection, biosensing	Tunable optical properties (surface plasmon resonance), biocompatibility, easy functionalization, multiplex imaging, radio sensitization	Zahdeh *et al.,* 2025
Silver Nanoparticles (AgNPs)	Antimicrobial activity, biosensors, bioimaging, pathogen detection, drug delivery	Strong antibacterial/antiviral properties, surface modifiability, plasmon resonance for sensing, effective against multidrug-resistant bacteria	Sati *et al.,* 2025
Magnetic Nanoparticles (e.g., Fe_3O_4, superparamagnetic iron oxide)	Targeted drug delivery, magnetic hyperthermia, MRI contrast enhancement, antibacterial activity, cell tracking	Super para-magnetism for external magnetic guidance, biocompatibility (especially green-synthesized), synergistic antibacterial effects under magnetic fields	Chand, 2025
Quantum Dots (QDs, e.g., GZCIS/ZnS, Cd-based or carbon QDs)	Bioimaging, biosensing, targeted chemo-radiotherapy, gene delivery, multiplexed cellular labeling	High quantum yield, photostability, size-tunable fluorescence for multi-color imaging	Abrishami *et al.,* 2024
Zinc Oxide Nanoparticles (ZnO NPs)	Antimicrobial applications, drug delivery, biosensing, tissue engineering scaffolds, wound healing	Photostability, high surface area, potent antimicrobial activity, biocompatibility in healthcare formulations	Lebaka *et al.,* 2025
Mesoporous Silica Nanoparticles (MSNs)	Drug/gene delivery carriers, tissue engineering, controlled release systems	High porosity for loading therapeutics, tunable pore size, surface functionalization for targeting	Harish *et al.,* 2022
Carbon-based Nanoparticles (e.g., CNTs, graphene)	Tissue engineering scaffolds, biosensors, drug delivery, gene therapy, photothermal therapy	Excellent mechanical/electrical properties, high sensitivity in biosensors, support for cell growth and differentiation	Yucer *et al.,* 2025

The nanostructure of the coating used for military vehicles, aircraft, and equipment ensures improved security and strategic advantage in defense applications (Agbogo *et al.,* 2025).

Applications of Nanotechnology in Transportation

Nanotechnology has significantly influenced the expansion of the transportation sector, particularly through the application of materials that are lightweight, resilient, and energy-conserving. The utilization of nanotechnology has facilitated the manufacture of vehicles with reduced weight, thereby improving fuel efficiency; this is especially evident in the incorporation of carbon nanotubes, graphene, and nanocomposite materials in the fabrication of components for both automotive and aeronautical applications. This results in reduced carbon footprint because lighter vehicles require less fuel to run. Vehicles have a variety of nano-engineered coatings applied to surfaces to improve endurance of surfaces against scratches, resistance against corrosive elements and easier cleaning due to self-cleaning properties. These coatings extend the time until maintenance is necessary. Nanoparticles in size such as Molybdenum Disulphide used in nanoparticles-based lubricants, as well as nanoparticle-based boron, help to decrease friction and wear in engines or mechanical systems thus enhancing performance while prolonging service life. In terms of aerospace, strength and weight are achieved through the use of nanocomposites resulting in a smaller overall weight and thus greater payload capabilities and enhanced fuel efficiency for aircraft. Nanotechnology assists the current electric vehicle marketplace by providing technology to enhance battery and supercapacitor performance by providing greater energy storage, higher charge rates, and longer useful life for electric vehicle batteries and/or supercapacitors. Nanotechnology is an important part of making transportation systems more efficient, eco-friendly, and long-lasting (Cestino *et al.,* 2024; Shafique and Luo, 2019).

Application of Nanotechnology in Wood-Based Product Industries

Nanotechnology has been integrated into the wood-based industry to provide greater lightweight properties and increased durability, as well as multiple functional uses. With the growing focus on the environment, there has also been a rise in the interest of sustainable and biodegradable nanomaterials (nanoscale materials), particularly nanocellulose, which comes from lignocellulosic biomass derived from forests. Because there is an abundance of cellulose available in forests, there is also a growing supply of cellulose being converted into nanocellulose and used for high quality industrial applications (Jasmani *et al.,* 2020). In addition to providing a wide variety of uses as a substrate, stabilizing agent or electrode, nanocellulose has many applications in electronics, sensors, batteries, food systems, pharmaceuticals and cosmetics. For example, in wood products, nano-particles such as nano zinc oxide and nano titanium dioxide can be incorporated into coatings that can impart greater durability to such products against UV light, as well as a protective function against water, etc. Moreover, nanoencapsulation technology can also be utilized in wood preservatives to enhance their penetration efficiency as well as to reduce their leaching out, which in turn can provide greater resistance to decay caused by fungi as well as insects (Li *et al.,* 2022). The contribution of wood-based industries to many countries is greatly beneficial to their economic growth. Forest biomass is an available and sustainable resource that can be utilized to obtain high-value products through eco-friendly nanomaterials. Additionally, the positive properties of wood, such as strength-to-weight ratio, renewability and aesthetics, make wood widely used in construction. Unfortunately, wood is prone to microbial degradation and dimensional instability as a result of moisture fluctuations, limiting its utility for a wider range of applications. Structural integrity and compatibility with coatings and adhesives are degrading due to fungal attack as well as the hygroscopic swelling and shrinkage associated with dimensional instability in the material. Nonetheless, the advancement of nanomaterials science has allowed for the production of lignocellulosic nanoparticles, as well as modified surfaces and bulk wood composites using nanotechnology to address these limitations. The use of advanced nanotechnology in addition to traditional chemical impregnation techniques will improve surface hardness, abrasion-resistant properties, dimensional stability and overall durability in addition to producing high-performance woods with greater strength than what is currently available. In addition, the commercial interest in cellulose, hemicellulose and lignin as biopolymers produced from wood-derived materials is increasing due to their potential to be used as renewable replacements for petroleum-based materials. By supporting the development of new products, including those created through 3D printing processes, biopolymers and novel composite materials made from wood are important components of advanced electronic and energy systems. Ultimately, due to their abundance, sustainability, nanofibrillar structure, and the ability to self-assemble, cellulosic nanomaterials will play a major role in industrial development in the future (Jasmani *et al.,* 2020).

Applications of Nanotechnology in Drilling Engineering in the Oil and Gas Industry

There are many different methods of creating nanoparticles, including solvent evaporation, nanoprecipitation (salting-out), emulsion or mini-emulsion polymerization electrohydrodynamic atomization and supercritical fluid processing. Solvent evaporation is commonly used to make nanoparticles because it involves making emulsions with evaporative solvents then using diffusion processes to create nanoscaled particles. You can use a variety of methods, like high-speed homogenization, magnetic stirring and temperature control, to create particles in a controlled manner.

Nanoparticles have a wide range of uses, including drug delivery, imaging, solar energy and petroleum engineering. In the oil and gas industry, nanoparticles improve drilling efficiency and increase the amount of oil that can be recovered by stabilizing emulsions and foams in addition to altering the wettability of rocks, reducing the viscosity of the oil, lowering the interfacial tension between the oil and other fluids, and minimizing the adsorption of surfactants to the surface of the reservoir. Nanotechnology is increasingly being used to solve technical problems related to improved oil recovery and exploration of unconventional reservoirs. The use of nanotechnology ranges from exploration to drilling, completion, production, refining, and wastewater treatment (Emmanuel, 2024).

Nanosensors can improve the resolution of subsurface imaging, while nanomaterials help to improve the performance of cementing and to enhance interfacial molecular interactions. As the world's population continues to grow, the demand for energy will also continue to grow. Additionally, there is a finite supply of conventional energy resources available.

Nanotechnology will represent a cost effective and efficient means of improving energy extraction and energy production. By enabling material manipulation at the 1–100 nm scale, nanotechnology continues to drive innovation across upstream and downstream oil and gas operations (Alkalbani and Chala, 2024).

Application of nanoparticles in Biotechnology and transgenics

Nanoparticles have been recognized as multifunctional agents in modern biotechnology owing to their physicochemical properties, which include a large surface area, reasonable size, and reactivity (Table 2). Nanoparticles are being increasingly applied as vectors for the delivery of biomolecules, e.g., DNA, RNA, and proteins, into cells. Nanoparticles can easily enter the cell membrane of a plant cell owing to their small size. Nanoparticles are being investigated as alternative vectors for the delivery of biomolecules into plant cells, replacing traditional vectors, e.g., Agrobacterium and biolistics, in transgenic research (Torney *et al.,* 2007). For instance, nanomaterials such as gold nanoparticles and carbon nanotubes have the ability to carry biomolecules, thus entering plant cells. This is a more stable system of delivery, especially for plant cells. Nanoparticles have shown their ability to deliver genome editing tools such as CRISPR/Cas, thus enabling genome editing (Demirer *et al.,* 2019). Nanoparticles have shown their ability to act as biosensors, enabling us to detect transgenic characteristics, pathogens, and metabolites of genetically modified organisms (Goswami *et al.,* 2011). In agricultural biotechnology, nano-formulated fertilizers and pesticides have shown their ability to enhance the uptake of nutrients and protect transgenic plants. Furthermore, magnetic nanoparticles have shown their ability to enhance the purification of DNA and proteins, especially in molecular biology (Raliya *et al.,* 2016). Thus, nanotechnology and genetic engineering have shown their ability to enhance the efficient manipulation of biological systems. With the advancement of research in the field of nanoparticles, efficient approaches for the development of transgenic plants may also be obtained.

Future Prospects

Nanotechnology continues to grow at an exponential rate, with many new areas of research developing quickly. Some of the newest areas in nanotechnology currently being explored include the use of nanorobots for the targeted delivery of drugs; nano-biosensors for real-time monitoring of diseases; the application of quantum dots in both computing and imaging technology; and nanomaterials that can store and convert energy. Another very promising area includes research conducted using nanoenabled agriculture methods for improving precision nutrient delivery to crops and pest control, both of which could revolutionize crop management practices. Lastly, ongoing integration between nanotechnology and biotechnology, artificial intelligence and materials science will lead to the discovery of new applications that were previously thought to have been impossible. The potential market for Nanotechnology products is vast and accelerating in all sectors, including electronics, healthcare, energy, and environmental management. The first commercialized nano-enabled products such as advanced batteries, smart clothing, coatings and sensors, are rapidly approaching large-scale (commercial) production levels. Both start-up companies and existing companies are investing heavily into scaling up manufacturing processes and being able to produce these new products in an efficient and cost-effective manner. As such, Nanotechnology not only represents an area of speculative scientific inquiry but also offers significant potential for economic growth. Nanotechnology has tremendous potential to support sustainable development goals (SDGs) by developing clean energy, purifying water, reducing waste, and utilizing natural resources more efficiently. For example, nanotechnology can improve energy efficiency and purify water using nanocatalysts and nanofiltration systems. Additionally, by lowering the environmental impact of agriculture through the use of nano-fertilizers and nano-pesticides, nanotechnology promotes resource efficiency and precision in managing global problems like climate change, food insecurity, and waste from pollution. The development and implementation of intelligent nanodevice technology, as defined by real-time monitoring, autonomous operating capacity, and self-repair features, is greatly expanding the scope of nanotechnology, especially in the integration of artificial intelligence, robotics, Internet of Things, and 3D printing technologies.

In electronics, the combination of nanotechnology and quantum computing is expected to lead to electronic devices that are not only smaller but also faster and use less energy. Simultaneously, in the field of healthcare, the incorporation of nanotechnology with artificial intelligence facilitates the development of personalized diagnostic tools and treatment strategies, consequently augmenting the quality of patient care. As the field of nanotechnology expands into additional applications, it is critical to establish strong regulatory frameworks to support safety, ethical use, and environmental protection. Therefore, the future of policy development in nanotechnology is expected to focus on standards for characterizing nanomaterials, identifying and mitigating risks from their use, ensuring occupational safety, and developing disposal methods that protect the biosphere. Accordingly, initiatives at the federal level, support from venture capitalists, and international collaboration among peer nations will greatly enhance responsible innovation and commercialization of nanotechnology while achieving a balance between increased technology and appropriate safeguards for society and the environment.

In conclusion, the various sectors in which nanotechnology has been applied, such as health care, food, agriculture, computers, electronics, energy production, use, building, construction, environmental management, etc., illustrate the enormous potential of this technology. The properties of materials and devices on the nanoscale include increased operation ability in terms of tensile strength, electrical conductivity, bioavailability, targeting, etc.; the development of this technology has led to the creation of solutions that might not have existed otherwise. Industry and research have transformed by developing new and innovative nanotechnology applications that lead to greater efficiency, sustainability, and performance. Some of these new ideas include drug delivery systems, using nanotechnology in food and farming, making better electronics, and making methods of storing energy. Nanotechnology has the potential to have a big impact on society. It should be noted that although there are various benefits associated with the use of nanotechnology, there are also potential risks associated with its use in terms of its toxicity, environment, and ethics.

It is essential that we pursue the safe, responsible, and regulated development of nanotechnology, with attention given to ensuring that products made using nanotechnology are environmentally safe, biocompatible, and socially acceptable. The future of nanotechnology will continue to be bright and ever-changing, with continued advancements being seen in research, commercialization, and integration with other advanced technologies. Through fostering interdisciplinary collaboration, sustainable innovation, and well-developed policy frameworks; we can ensure that nanotechnology has a significant positive impact on economic growth, quality of life for individuals, and the long-term sustainability of our planet.

Conflict of Interest Statement

Authors declares no conflict of interest.

Author Contributions

Both the authors conceived the original idea and designed the model and wrote the manuscript.

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