Paaua Science Journal

Paper 3

*PaauaSci.J.***2026**, Issue 2 , 32-91

NANOPARTICLES IN NIGERIA: A MINI REVIEW

Emmanuella. O. Adio[1], Favour K. Aoko[1], Opeyemi. S. Oyetunji[2], Anthony. W Ojewumi[2] and Anthony. B. Ojekale[1]

[1]Department of Biochemistry, Lagos State University, Badagry Express Way, Ojo Lagos, [2]Department of Botany, Lagos State University, Badagry Express Way, Ojo Lagos, Nigeria.

Correspondence: emmanuellaadio@gmail.com

DOI: https://doi.org/10.65760/paaujs.v1i2.3

Received 09-03-2026 **Accepted 03**-09-2026 **Published on line 11**-09-2026

Abstract

Nanotechnology has emerged as a rapidly advancing field of science and technology due to the unique properties exhibited by materials at the nanoscale. Nanoparticles, typically ranging between 1 and 100 nanometers in size, possess distinctive physical, chemical, optical, and mechanical properties that differ significantly from those of their bulk counterparts. These properties have stimulated extensive global research and have led to the development of innovative applications across various sectors including medicine, agriculture, environmental remediation, and industrial manufacturing. In recent years, interest in nanotechnology research has also increased in Nigeria as researchers and institutions explore its potential to address pressing societal and environmental challenges. This review examines the fundamental concepts of nanoparticles, including their classification, physicochemical properties, and common synthesis methods such as top-down, bottom-up, and green synthesis approaches. The paper further reviews the current state of nanoparticle research and applications within the Nigerian context, highlighting contributions from universities, research institutes, and emerging scientific initiatives. Particular emphasis is placed on the use of nanoparticles in healthcare, agriculture, environmental management, and industrial development. Despite the growing interest in this field, several challenges continue to hinder the advancement of nanotechnology in Nigeria, including limited infrastructure, inadequate funding, insufficient technical expertise, and low public awareness. Nevertheless, ongoing research efforts and the availability of natural resources suitable for green synthesis present promising opportunities for the expansion of nanotechnology research and innovation in Nigeria.

Keywords: Nanoparticles, Nanotechnology, Nigeria, Nanomaterials

Introduction and literature review

1.0 Background 1.1 Background of review

Nanoparticles are extremely tiny particles that fall within the range of 1-100 nanometers in size. It's completely undetectable by the human naked eye unless using an electron microscope. Due to their large surface area compared to its volume, nanoparticles exhibit significantly unique physical and chemical characteristics such as optical properties, high reactivity, magnetic properties, thermal properties etc.(Saravanakumar, 2017). Aside from having unique properties, nanoparticles also vary in size and dimension and this in turn causes its properties to change as it approaches the atomic scale. i.e., its property is dependent on its size. The emergence of nanotechnology would be incomplete without mentioning Richard Feynman, where he laid the theoretical appliance of nanotechnology in 1959 during his lecture "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics" where he suggested that the entire Encyclopedia Britannica could be written on the head of a pin if we could manipulate individual atoms (Toumey, 2008). This was largely speculative until the year 1985 and 1991 where fullerenes and carbon nanotubes were found respectively. These discoveries served as a global proof that carbon atoms could be rearranged into structures with electrical conductivity and mechanical strength far superior to steel and has also paved way for the revolutionizing in the electronics and aerospace industries. This global emergence has paved way for the production of materials at nanoscale alongside more intensive research on how and why these materials behave differently in their bulk form. Following this path, Nigeria isn't left out, researchers in Nigeria have begun carving out their own niche in this field focusing heavily on biomedical applications and environmental remediation, alongside emerging work in energy and biosensors, mostly leveraging local biomaterials.

1.2 Overview of Nanoparticles

As established earlier, nanoparticles are extremely tiny particles that fall within the range of 1-100 nanometers in size. The word 'nano' is derived from the Greek word 'nanos', which means 'dwarf' or 'little'. Nanoparticles are not a uniform group; they can be classified based on their chemical composition and their dimensionality (Saravanakumar, 2017).

Based on Dimensionality, they are categorized as:

-Zero-dimensional Nanoparticles (0D): Zero dimensional nanoparticles are tiny particles in which all three dimensions of its material are within the nanometer scale. Examples include quantum dots, fullerenes, and metallic nanoparticles (such as gold and silver nanoparticles)(Ali Assim Adul-Rasool, 2024). Due to their small and compact size, alongside their large surface area, they exhibit unique electrical and optical properties making them useful in drug delivery and sensing applications.

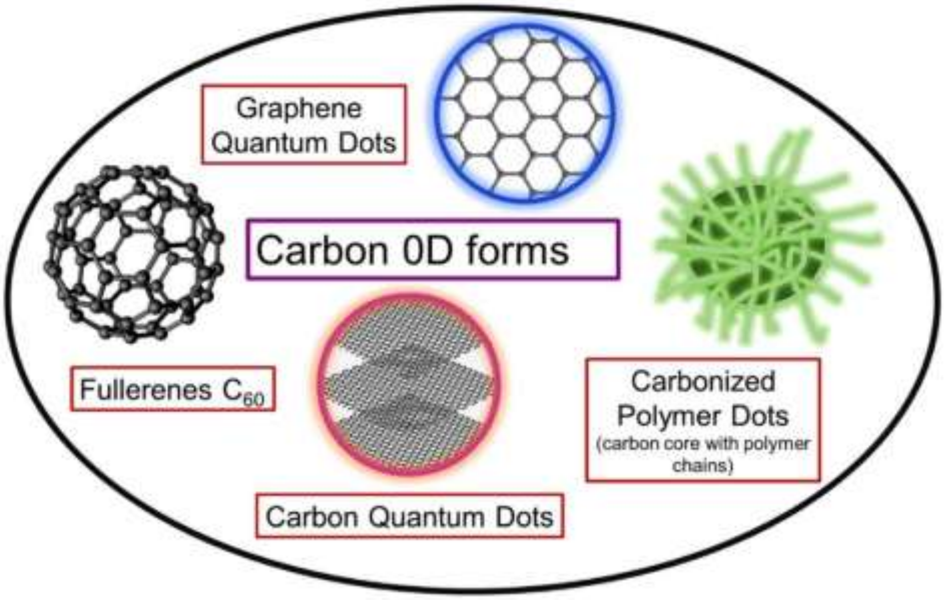

Fig. 1. Schematic representation of carbon types in 0D form (Jani, 2020)

-One-dimensional Nanoparticles (1D)

One dimensional nanoparticles are particles in which two dimensions of its material are within the nanometer scale, while the third dimension extends beyond 100nm, (Ali Assim Adul-Rasool, 2024) thus creating elongated shapes such as; nanotubes, nanowires, nanotube or nanofiber. Due to their special properties such as their great mechanical strength and electrical conductivity, these nanostructures are known to be useful in electronic and biosensor systems.

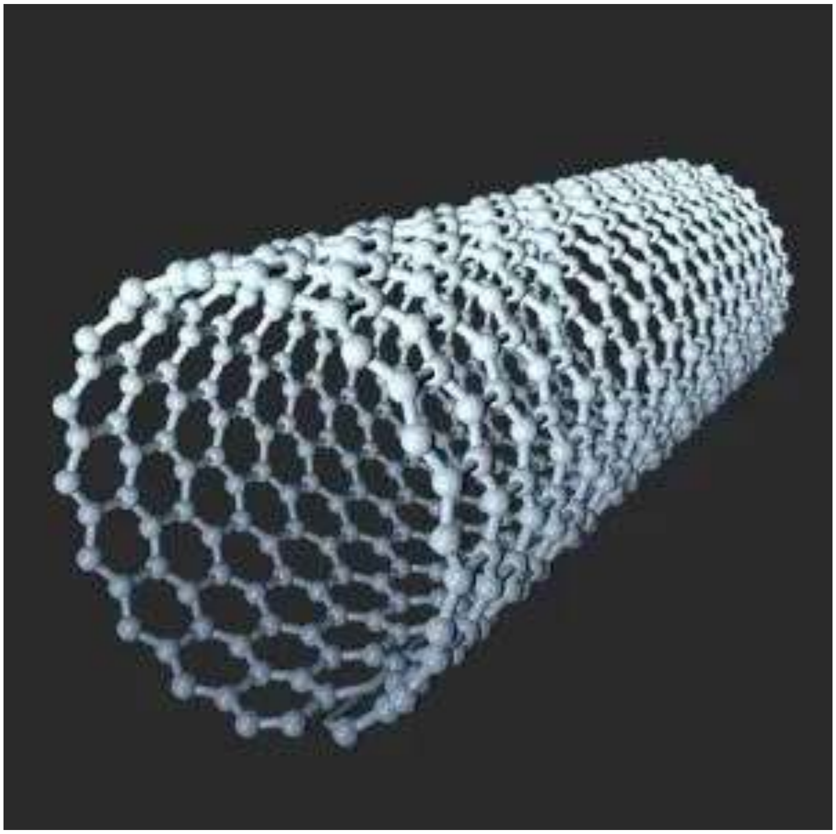

Fig. 2. Illustration of a carbon nanotube. Ren, G. (2025, April 2). carbon nanotube. Encyclopedia Britannica.

-Two-dimensional Nanoparticles (2D)

Two dimensional nanoparticles are particles in which one of its dimensions is within the nanometer scale, while the remaining two dimensions are significantly larger and extend beyond the nanometer scale.(Bawoke Mekuye, 2023). Examples include graphene, nanosheets, nanofilms, nanoplatelets, and nano clays, which are used in various applications such as electronics and sensor devices.

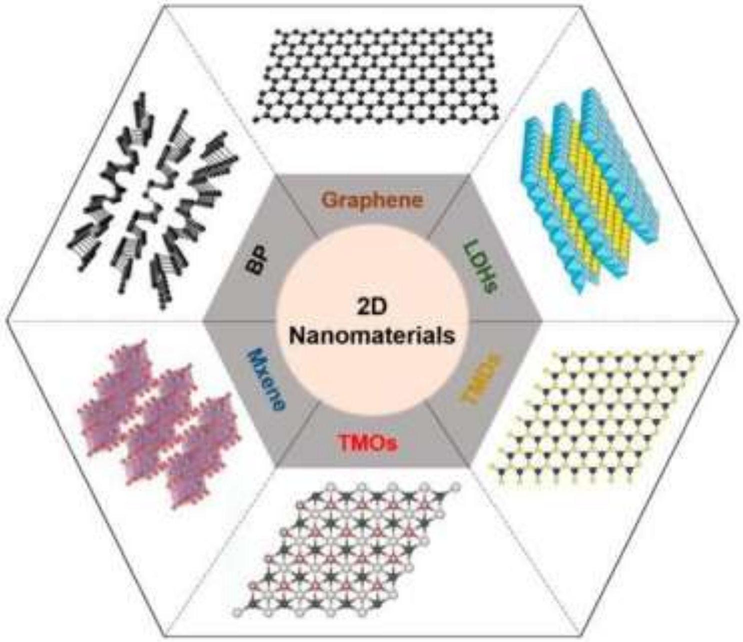

Fig. 3. Schematic illustration of representative 2D nanomaterials. LDH, layered double hydroxide; TMD, transition metal dichalcogenide; TMO, transition metal oxide; BP, black phosphorus.(Woo Yeup Jeong, 2021)

-Three-dimensional Nanoparticles (3D)

Three dimensional nanoparticles are nanostructured materials in which all of its dimensions are not within the nanometer scale, but extend beyond it. Unlike zero-, one-, and two-dimensional nanomaterials, 3D nanoparticles do not have quantum confinement in any specific direction, however, the bulk materials within its structure are composed of individual blocks that are within the nanometer scale hence the reason they exhibit unique nano properties. Examples include fullerenes, liposomes, dendrimers, nano-cubes and nanocages. These 3D- materials possess unique properties such as high surface area, enhanced mechanical strength, and improved chemical stability, making them suitable for applications in catalysis and energy storage.

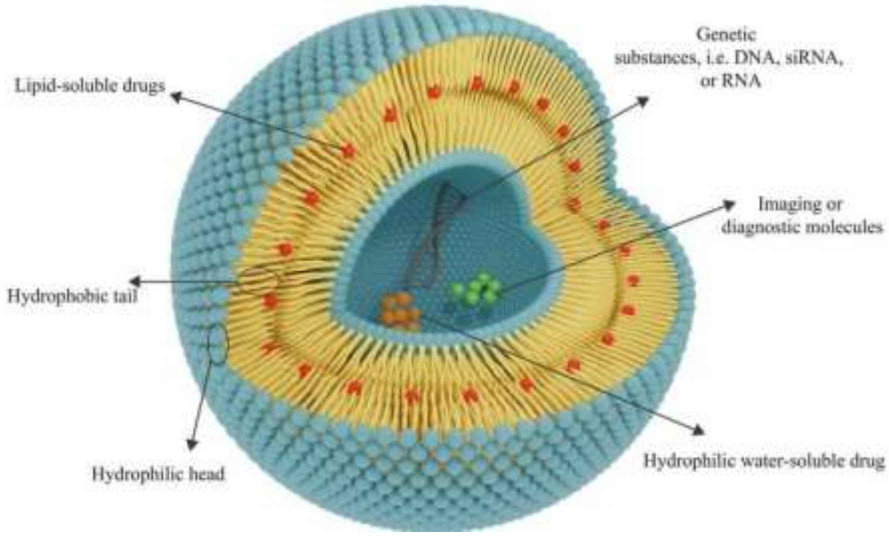

Fig. 4. The general structure of the liposomes.(Esfandiar, 2021)

Based on Chemical Composition, they are generally classified into three major forms:

Inorganic Nanoparticles

Inorganic nanoparticles are tiny particles within the nanometer scale which are not made up of carbon. They are classified into metal and metal oxide nanoparticles.

-Metal based Nanoparticles:

Metal nanoparticles are solid particles within the nanoscale that are formed from their metal counterparts through destructive or constructive methods(Saravanakumar, 2017). One of their notable properties is their unique electrical characteristics due to a well-known Localized Surface Plasmon Resonance (LSPR). (Rajiv Gandhi, 2021). Aside from this unique property, they also exhibit unique physicochemical properties, such as enhanced optical, electrical, catalytic, and magnetic characteristics, which differ significantly from their bulk metal counterparts. The most common types of metal nanoparticles are aluminum (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag) and zinc (Zn).

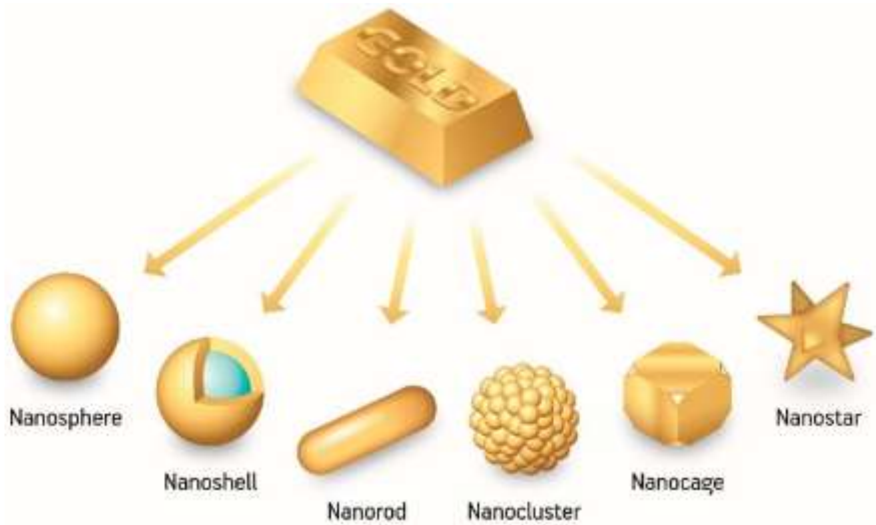

Fig. 5. Representative scheme of the most common gold nanoparticle assemblies and morphologies(Freitas de Freitas, 2018) ***-Metal Oxide Nanoparticles:***

Metal oxide nanoparticles are particles within the nanoscale. They are composed of basic metal oxides such as zinc oxide (ZnO), calcium oxide (CaO), and titanium dioxide (TiO_2). They exhibit unique physicochemical properties, which are different from their bulk counterparts due to their reduced size and large surface area.(Negrescu, 2022). Another unique feature of metal oxide nanoparticles is that, because oxidizing metals generally enhances their ability and durability, metal oxides with nanostructures within the nanoscale produces materials with unique properties such as enhanced reactivity, conductivity, magnetic, and catalytic activity.

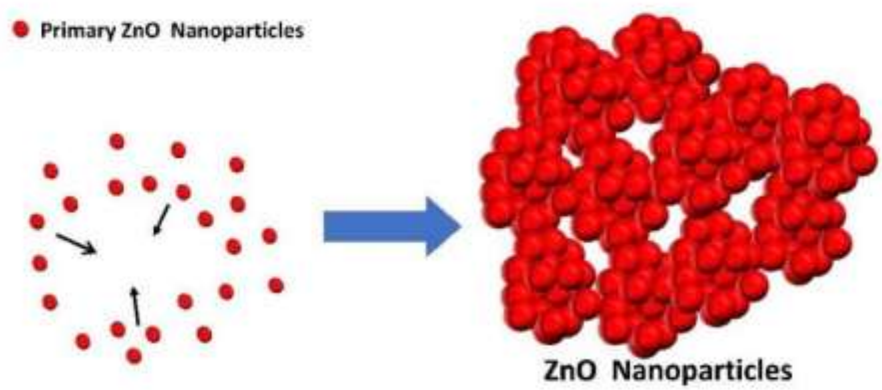

Fig. 6. Aggregation of primary ZnO particles in forming raspberry-like structure.(Khairul Basyar Baharudin, 2021)

Organic nanoparticles

Organic nanoparticles are particles within the nanoscale that are biodegradable and non-toxic, and are synthesized from organic materials such as polymers, lipids, or proteins. Examples of organic nanoparticles include micelles, dendrimers, and liposomes.(Khan, 2022). Micelles and liposomes have a hollow core, which are known as nano capsules, and they are sensitive to heat and radiation. Because of these unique features, organic nanoparticles are a suitable option for medicinal drug delivery. Their drug-carrying capacity and delivery methods involve either entrapping the drug or absorbing the drug, which affects both their application and efficiency. This allows drugs to be delivered to specific areas of the body, a process known as targeted drug delivery.(Saravanakumar, 2017)

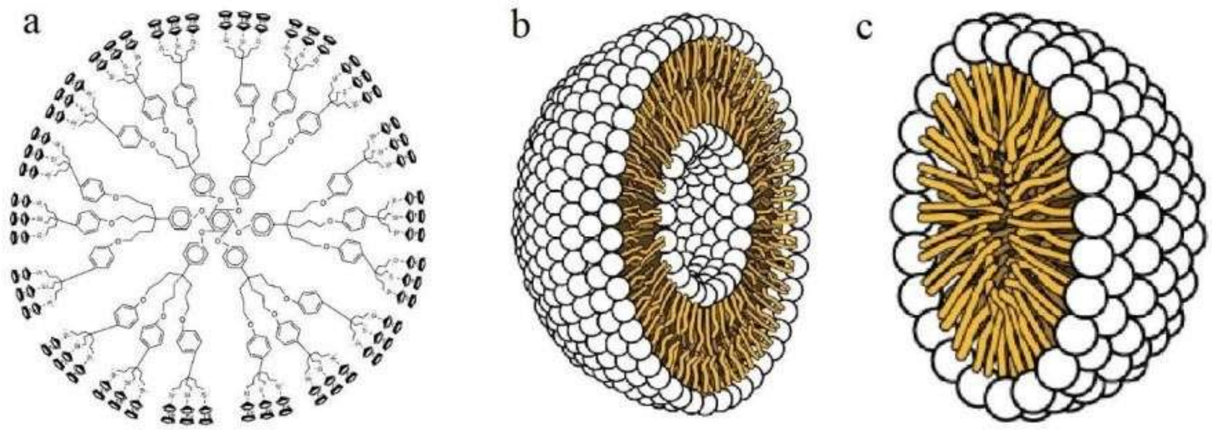

Fig. 7. Organic nanoparticles: a – Dendrimers, b – Liposomes and c – micelles (Saravanakumar, 2017)

Carbon-based nanoparticles

Carbon based nanoparticles are nanoparticles completely made up of carbon which exist within the nanoscale. Carbon based nanoparticles have potential uses in energy storage and energy production.(Saravanakumar, 2017). Due to the numerous allotropic forms of carbon, such as diamond, graphite and fullerenes, carbons within the nanoscale exhibit enhanced unique properties. Examples of carbon-based nanoparticles include fullerenes, graphene and carbon black. Graphene which one of the most popular carbon-based nanoparticles consists of a single layer of atoms arranged in a honeycomb arrangement on a two-dimensional sheet. This two-dimensional arrangement gives graphene exceptional mechanical, electrical, and thermal properties compared to other carbon allotropes.(Khan, 2022)

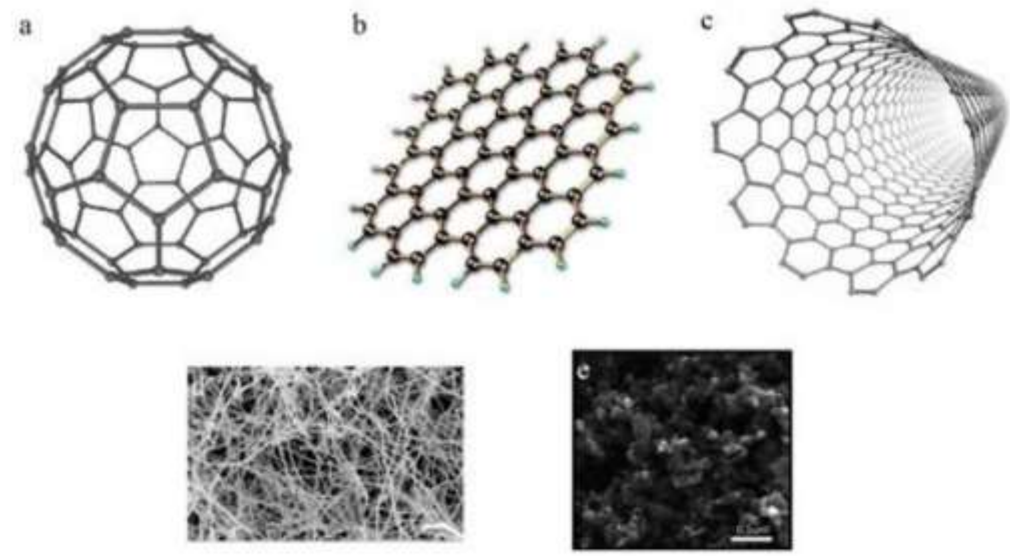

Fig. 8. Carbon based nanoparticles: a – fullerenes, b – graphene, c – carbon nanotubes, d – carbon nanofibers and e – carbon black

1.3 Significance of Nanoparticles in Nigeria

Nigeria as a developing country faces numerous challenges in important sectors such as healthcare, agriculture, energy, and environmental management.Nanoparticles serve as a promising solution to these problems due to their unique physical and chemical properties, alongside their wide range of applications.(Ejeta, 2017). In healthcare, nanoparticles help improve drug delivery, treatment efficiency (antimicrobial treatments) and overall, proper diagnostics which have been proven to be more effective for diseases such as tuberculosis and malaria. For Nigeria, the use of nanoparticles synthesized from local biomaterials or plant extracts looks promising as it is cost-effective. In agriculture, nanoparticles provide a transformative approach to farming in Nigeria by replacing traditional farming practice (e.g., use of cow dung) with nano-fertilizers and nano-pesticides which have proven to be efficient and cost-effective, thus promoting food security and employment. Nanoparticles like zinc and silver oxide have been shown to boost the yield of major food crops (e.g., rice)(Igiebor, Ikhajiagbe, & Asia, 2023). Similarly, in environmental management, nanoparticles offer a wide range of alternatives to traditional cleanup methods in Nigeria by providing a cost-effective and faster remedy to industrial pollution and water purification. These materials, particularly nano-Zero Valent Iron (nZVI), are used to treat soil and water contaminated by oil spills and poisonous chemicals like Trichloroethylene (TCE). (Okonkwo, Edoziuno, & Orakwe, 2020) However, despite these advantages and availability of natural resources, Nigeria faces significant challenges in utilizing the full potential of nanoparticles. This is due to the fact that major research, development and patent of nanomaterials are concentrated in developed countries and multinational corporations, thus, limiting funding and technical expertise in Nigeria.(Ejeta, 2017)

1.4 Relevance of Nanotechnology

Nanotechnology is a field of science that deals with materials at the nanoscale level, typically around 1–100 nanometers. It has become quite relevant in today's world because it involves the manipulation of matter at the atomic level to create distinct materials with unique and superior properties. It focuses on the structural synthesis and modification of materials at the nanoscale. Nanotechnology has several branches, including nanomaterials, nanoelectronics, nanorobotics, and nanophysics. Nanoparticles are considered a core component of nanotechnology because they serve as the building blocks of nanomaterials, and most nanotechnology applications depend on them. These materials are believed to have a major impact on healthcare, electronics, and many biological systems. Take, for example, major diseases such as diabetes mellitus, cancer, autoimmune diseases, and cardiovascular diseases. These diseases have become serious global concerns. Although we have synthetic drugs to manage these conditions, they often come with unwanted side effects, which can even lead to additional diseases. While some patients do get better, others become worse. As a result, scientists and researchers have begun to look for alternatives through nanotechnology. One particular branch of nanotechnology that shows a lot of promise is drug delivery, specifically nanoparticle-based drug delivery. One of the major problems in treating many diseases is drug delivery to the infected cells. Instead of drugs targeting only the specific cells causing the problem, the drugs often affect both the diseased and healthy cells. However, with nanotechnology based drug delivery, drugs can be directed to target only the specific cells responsible for the disease. For instance, in the case of cancer, researchers are currently looking for alternatives to reduce the hair loss and damage to healthy cells caused by chemotherapy. This is where nanotechnology comes in, drug delivery systems are being developed to target cancer cells more selectively while sparing healthy ones. However, this technology is still under development and it is believed that nanotechnology has the potential to alleviate many of these treatment-related drawbacks. Nanotechnology has also revolutionized material manufacturing by producing materials that are stronger and lighter. For example, carbon nanotubes are used in aerospace applications to improve structural strength and boost energy efficiency. Environmentally, nanoparticles are used in water purification through photocatalytic materials such as titanium dioxide, which help degrade pollutants and improve air and water filtration.

1.5 History of Nanotechnology Development Globally

The development of nanotechnology did not occur suddenly but evolved gradually through several scientific discoveries and technological advancements across different fields of science. Although the term nanotechnology became widely used only in the late twentieth century, the concept of manipulating materials at extremely small scales had been discussed much earlier. Scientists gradually realized that when materials are reduced to the nanoscale, they begin to exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts. These observations laid the foundation for the emergence of nanotechnology as a distinct scientific discipline (Bayda et al., 2019).

One of the earliest theoretical discussions that contributed to the development of nanotechnology was presented by physicist Richard Feynman in 1959 during a lecture titled “There’s Plenty of Room at the Bottom.” In this lecture, Feynman proposed the idea that it might one day be possible for scientists to manipulate individual atoms and molecules to create extremely small structures and devices. He described how information could potentially be stored in very small spaces and suggested that miniature machines could be designed to perform tasks at microscopic levels (Feynman, 1959). Although the technology required to achieve such ideas did not exist at that time, Feynman’s lecture introduced a new way of thinking about materials and inspired future research into nanoscale science.

Despite the conceptual ideas proposed in the 1950s, practical progress in nanotechnology only became possible after the development of advanced microscopy techniques that allowed scientists to observe materials at atomic resolution. A major breakthrough occurred in 1981 with the invention of the scanning tunneling microscope (STM) by Gerd Binnig and Heinrich Rohrer. The STM enabled scientists to visualize individual atoms on the surface of materials by measuring the tunneling current between a conductive probe and the sample surface. This instrument allowed researchers to study surface structures with unprecedented accuracy and opened new opportunities for exploring nanoscale materials (Nobel Prize Outreach, 1986).

Shortly after the development of the STM, another important instrument known as the atomic force microscope (AFM) was introduced in 1986 by Binnig, Quate, and Gerber. Unlike STM, which can only analyze conductive materials, AFM can examine both conductive and non-conductive surfaces by measuring the interaction forces between a probe and the sample surface. This made it possible for scientists to study a wider range of materials, including biological samples, polymers, and nanostructured materials (Binnig et al., 1986). The development of these scanning probe microscopes significantly advanced nanotechnology research because they provided scientists with the ability to observe and manipulate materials at extremely small scales.

Another important milestone in the history of nanotechnology occurred in 1985 with the discovery of fullerenes, a new form of carbon composed of sixty carbon atoms arranged in a hollow spherical structure known as buckminsterfullerene (C_{60}). This discovery was made by Harold Kroto, Robert Curl, and Richard Smalley during experiments involving carbon vaporization. The discovery demonstrated that carbon atoms could form stable nanoscale structures with unique chemical and physical properties (Kroto et al., 1985). This finding generated significant interest in nanoscale carbon materials and later earned the researchers the Nobel Prize in Chemistry in 1996.

Further progress in nanotechnology occurred in 1991 when Japanese scientist Sumio Iijima discovered carbon nanotubes while studying carbon materials using electron microscopy. Carbon nanotubes are cylindrical nanostructures formed from rolled graphene sheets and are known for their exceptional strength, electrical conductivity, and thermal stability (Iijima, 1991). Due to these remarkable properties, carbon nanotubes quickly became one of the most extensively studied nanomaterials in modern materials science.

During the late 1990s and early 2000s, nanotechnology research began to expand rapidly across the world. Governments and scientific institutions increasingly recognized the potential of nanotechnology to transform several industries. One of the most influential programs supporting nanotechnology development was the United States National Nanotechnology Initiative (NNI) launched in 2000. The initiative coordinated federal research funding across multiple agencies and helped accelerate research and innovation in nanoscale science and engineering (National Nanotechnology Initiative, 2000). Similar national research programs were later introduced in Europe, Japan, China, and other parts of the world, leading to significant global investment in nanotechnology research.

As research efforts increased, nanotechnology began to move beyond theoretical and laboratory studies toward practical applications in many areas of science and technology. In medicine, nanoparticles have been explored for applications such as targeted drug delivery, diagnostic imaging, and disease treatment. These technologies aim to improve the effectiveness of treatments while minimizing side effects associated with conventional therapies (Malik et al., 2023). In electronics, nanotechnology has enabled the development of smaller and more efficient semiconductor devices, which play a crucial role in modern computing and communication systems. Nanotechnology has also contributed to advancements in energy and environmental technologies. Nanomaterials are increasingly used in solar cells, batteries, and supercapacitors to improve energy conversion efficiency and storage capacity. In addition, certain nanoparticles are used in water purification and pollution control processes due to their high surface area and strong adsorption properties (National Nanotechnology Initiative, n.d.). These developments demonstrate the versatility of nanotechnology and its potential to address global challenges related to energy sustainability and environmental protection.

Furthermore, nanotechnology has significantly influenced materials science and engineering. Nanostructured materials often possess improved mechanical strength, enhanced chemical stability, and better thermal resistance compared to traditional materials. These properties have led to the development of advanced materials used in aerospace engineering, construction, and manufacturing industries (Bayda et al., 2019).

Overall, the development of nanotechnology reflects a gradual progression from theoretical ideas to practical technological innovations. Beginning with early conceptual discussions about atomic manipulation and advancing through discoveries such as fullerenes and carbon nanotubes, nanotechnology has evolved into a multidisciplinary field with widespread global importance. Today, nanoparticles play a central role in many nanotechnology applications due to their unique size-dependent properties. Understanding the historical development of nanotechnology provides important context for examining current research on nanoparticles and their growing relevance in different parts of the world, including emerging research efforts in Nigeria.

1.6 Unique Physicochemical Properties of Nanoparticles

Nanoparticles exhibit physicochemical characteristics that differ significantly from those observed in bulk materials. These differences are largely attributed to their nanoscale dimensions, increased surface area relative to volume, and quantum-related phenomena that become prominent at very small particle sizes. According to (Khan et al 2019), when materials dimensions are reduced between 1 and 100 nm, a larger fraction of the atoms becomes exposed on the particle surface. As a result, nanoparticles often demonstrate enhanced chemical reactivity and altered physical behavior compared with larger particles. As explained by (Joudeh and Linke 2022), these nanoscale phenomena give rise to several unique properties that are rarely observed when the same materials exist in their conventional bulk form.

The most important physicochemical properties of nanoparticles include:

Optical Properties

One of the most distinctive features of nanoparticles is their unique interaction with light. Metallic nanoparticles, particularly those composed of gold and silver, exhibit localized surface plasmon resonance (LSPR). (Kelly et al. 2003) explain that this phenomenon occurs when conduction electrons on the nanoparticle surface oscillate collectively in response to incident electromagnetic radiation. These oscillations produce noticeable absorption and scattering of light at particular wavelengths. The optical behavior of nanoparticles is strongly influenced by factors such as particle size, morphology, and the surrounding medium. For example, variations in the size of gold nanoparticles can shift their absorption spectrum, resulting in different visible colors in colloidal suspensions. This tunable optical behavior makes nanoparticles particularly useful in biomedical imaging, biosensors, and photothermal therapies used in cancer treatment.

Magnetic Properties

Magnetic behavior also changes significantly when materials are reduced to nanoscale dimensions. Many nanoparticles composed of iron oxide, cobalt, or nickel exhibit a phenomenon known as superparamagnetism.(Kolhatkar et al.2013) note that in superparamagnetic nanoparticles, each particle behaves as a single magnetic domain that can rapidly respond to external magnetic fields.

Unlike bulk magnetic materials that retain magnetization after the removal of an external magnetic field, superparamagnetic nanoparticles lose their magnetization when the field is removed. (Joudeh and Linke 2022) highlight that this property is particularly beneficial in biomedical applications because it prevents particle aggregation. As a result, magnetic nanoparticles are widely used in targeted drug delivery, magnetic resonance imaging (MRI), and magnetic separation techniques.

Mechanical Properties

At the nanoscale, materials often demonstrate improved mechanical properties when compared with their bulk counterparts. According to (Wu et al. 2020), the reduced size of nanostructures can lead to enhanced hardness, elasticity, and tensile strength due to the decreased presence of structural defects.

Nanoparticles are frequently added to composite materials as reinforcing agents to enhance their mechanical performance. For example,nanoparticles such as graphene, silica, or carbon nanotubes when embedded within polymers or ceramics, can significantly enhance the material's strength and durability. This makes nanomaterials valuable in high-performance coatings, aerospace materials, and advanced construction applications.

Thermal Properties

Thermal properties of materials can also change significantly at the nanoscale. (Khan et al. 2019) report that nanoparticles often exhibit reduced melting points compared with bulk materials because surface atoms require less energy to rearrange. This phenomenon becomes more pronounced as particle size decreases.

Nanoparticles can also improve heat transfer when dispersed in liquids. Such suspensions, commonly referred to as nanofluids, have been shown to possess higher thermal conductivity than conventional fluids. These enhanced thermal properties make nanoparticles useful in applications such as cooling systems, heat exchangers, and energy-related technologies.

Electronic Properties

Electronic behavior in nanoparticles is strongly influenced by quantum confinement effects. When electrons are confined within extremely small dimensions, their energy levels become discrete rather than continuous. (Khan et al. 2019) explain that this change alters the electrical conductivity and optical properties of nanoscale materials.

Semiconductor nanoparticles known as quantum dots are a well-known example of materials that exhibit sizedependent electronic properties. By controlling the size of these particles, scientists can adjust their bandgap and optical emission characteristics. This tunability has made quantum dots useful in light-emitting diodes, solar cells, and biological imaging systems.

Catalytic Properties

Nanoparticles also demonstrate remarkable catalytic properties due to their extremely large surface area. (Cuenya 2010) explains that the high proportion of surface atoms in nanoparticles increases the number of active sites available for chemical reactions.

Metal nanoparticles such as platinum, palladium, and gold are widely used as catalysts in industrial chemical processes and environmental remediation. Their high surface reactivity enables them to accelerate chemical reactions more efficiently than bulk catalysts. This enhanced catalytic activity has led to their use in fuel cells, pollutant degradation systems, and chemical synthesis.

1.7 Methods of Nanoparticle Synthesis

The synthesis of nanoparticles is an important aspect of nanotechnology because the method used during preparation greatly affects the size, shape, structure, and properties of the nanoparticles produced. Different methods have been developed over time to produce nanoparticles with controlled characteristics for different applications. The synthesis method chosen often determines the stability, uniformity, and performance of the nanoparticles, which is why it is an important consideration in nanoparticle research and development (Joudeh & Linke, 2022).

Nanoparticle synthesis methods are generally grouped into three major approaches:

- Top-down approach
- Bottom-up approach
- Green synthesis

These approaches differ mainly in the way nanoparticles are formed. In the top-down approach, larger materials are broken down into nanosized particles. In the bottom-up approach, nanoparticles are built up from atoms, ions, or molecules. Green synthesis, on the other hand, focuses on producing nanoparticles through environmentally friendly means, often using biological materials such as plant extracts and microorganisms (Ealias & Saravanakumar, 2017).

Top-Down Approach

The top-down approach involves the production of nanoparticles by reducing bulk materials into smaller particles at the nanoscale. This method usually depends on physical or mechanical processes that gradually break down larger structures into nanoparticles. It is one of the earliest approaches used in nanoparticle production and is still widely applied in many areas of nanotechnology (Patil et al., 2021).

-Mechanical Milling

Mechanical milling is widely regarded as one of the commonly used top-down techniques for nanoparticle synthesis. In this method, bulk materials are introduced in a milling chamber together with hard balls made of steel or carbide. As the chamber rotates, repeated collisions occur between the balls and the material, which causes the bulk material to break down into smaller particles. With continuous milling, nanoparticles can eventually be produced. The final size of the particles depends on factors such as the speed of milling, time of milling, and the ratio of the balls to the material (Patil et al., 2021).

Nanolithography

Nanolithography is another top-down method used to produce nanostructures with controlled size and pattern. It involves creating nanoscale features on surfaces using techniques such as electron-beam lithography or X-ray lithography. This method is mostly used in electronics and semiconductor production where precise nanoscale structures are needed. Although it offers good control, it is often expensive and requires specialized equipment (Ealias & Saravanakumar, 2017).

-Laser Ablation

Laser ablation is a top-down method in which a high-energy laser beam is focused on the surface of a solid material. The intense energy causes atoms or clusters to be removed from the target surface, and these later condense to form nanoparticles. This method is useful because it can produce relatively pure nanoparticles without the need for many chemical reagents. However, it still requires costly equipment and controlled operating conditions (Patil et al., 2021). Generally, top-down methods are useful for producing nanoparticles from bulk materials, but they may lead to surface defects and sometimes poor control of particle uniformity. They also tend to require higher energy input and sophisticated equipment (Abuzeid et al., 2023).

Bottom-Up Approach

The bottom-up approach involves the creation of nanoparticles through the assembly of smaller building units such as atoms, ions, or molecules. Instead of breaking down larger materials, this method builds nanoparticles from the molecular level upward. Because of this, bottom-up techniques often produce nanoparticles with better uniformity and fewer structural defects than top-down methods (Abuzeid et al., 2023).

-Sol-Gel Method

The sol–gel process is widely recognized as an important bottom-up technique used in the synthesis of nanoparticles. In this method, precursor compounds are dissolved in a solution and then undergo hydrolysis and condensation reactions to form a colloidal suspension known as a sol. As the reaction continues, the sol gradually forms a gel containing nanosized particles. This method is commonly used in the synthesis of metal oxide nanoparticles because it allows good control over particle composition and size (Ealias & Saravanakumar, 2017).

-Chemical Vapour Deposition

Chemical vapour deposition is another bottom-up method used to produce nanoparticles and thin films. In this process, gaseous precursor compounds react on a heated surface and form solid nanomaterials. The properties of the nanoparticles formed depend on factors such as temperature, pressure, and gas concentration. This method is widely used in electronics and catalysis because it can produce nanoparticles with good purity and uniformity (Ealias & Saravanakumar, 2017).

-Hydrothermal and Related Methods

Hydrothermal synthesis is also a bottom-up approach in which chemical reactions take place in sealed containers under high temperature and pressure. This method is especially useful for producing crystalline nanoparticles with controlled morphology. Other related bottom-up methods include spray pyrolysis and atomic or molecular condensation, which are also used to build nanoparticles from smaller chemical units (Abuzeid et al., 2023). In general, bottom-up methods are preferred when uniformity and better control of nanoparticle properties are needed. However, they often require careful control of reaction conditions such as temperature, pH, and precursor concentration (Joudeh & Linke, 2022).

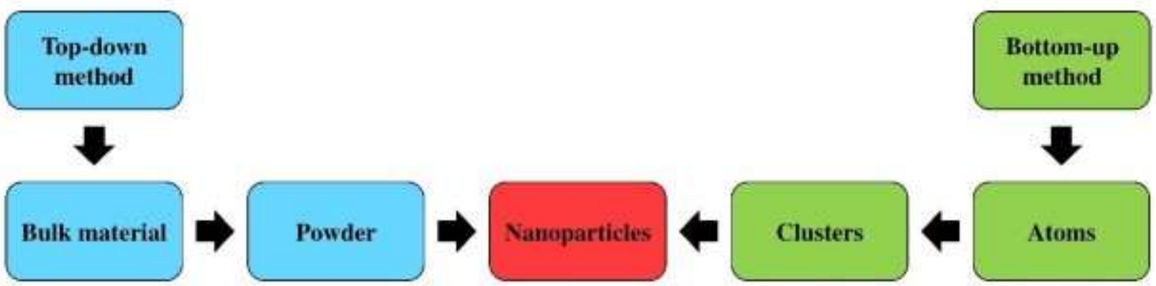

Fig. 9. Synthesis process

Green Synthesis

Green synthesis is an environmentally friendly method for the production of nanoparticles. It was developed as a response to the environmental and health concerns linked to many conventional physical and chemical synthesis methods. In green synthesis, biological materials such as plant extracts, microorganisms, fungi, algae, and agricultural waste are used as reducing and stabilizing agents during nanoparticle formation (Osman et al., 2024).

-Plant-Mediated Synthesis

Plant-mediated synthesis is one of the most common forms of green synthesis. Plant extracts contain many natural compounds such as flavonoids, phenols, terpenoids, and proteins that can reduce metal ions into nanoparticles. These same compounds can also help stabilize the nanoparticles formed, preventing them from aggregating. This method is widely preferred because plant materials are readily available, inexpensive, and easy to handle (Osman et al., 2024).

-Microbial Synthesis

Microbial synthesis involves the use of bacteria, fungi, or algae to produce nanoparticles. These microorganisms contain enzymes and biomolecules that can convert metal ions into nanosized particles. This method is considered eco-friendly and useful for biomedical applications because the nanoparticles produced often show good biocompatibility. However, the process may sometimes be slower than plant-mediated synthesis and may require stricter biological control (Osman et al., 2024).

Green synthesis has gained much attention in recent years because it reduces the use of toxic chemicals, lowers energy consumption, and supports sustainable nanotechnology. Even though it may still face challenges such as variability in particle size and slower reaction rates, it remains an important and promising method for nanoparticle production (Abuzeid et al., 2023).

Table 1: Differences Between Nanoparticle Synthesis Methods

Method	Principle	Examples of Techniques	Advantages	Limitations
Top-down approach	Breaking bulk materials into nanosized particles	Mechanical milling, nanolithography, laser ablation	Useful for direct size reduction from bulk materials	High energy requirement, costly equipment, possible surface defects
Bottom-up approach	Building nanoparticles from atoms, ions, or molecules	Sol-gel, chemical vapour deposition, hydrothermal synthesis	Better control of size and structure, fewer defects	Requires careful control of reaction conditions
Green synthesis	Using biological materials to produce nanoparticles	Plant extracts, bacteria, fungi, algae	Eco-friendly, cost effective, less toxic	Slower reaction rate, possible variation in particle size

2.0 DEVELOPMENT

2.1 Development of Nanotechnology in Nigeria

The development of nanotechnology in Nigeria has gained gradual momentum over the past two decades, driven mainly by academic research, government interest, and growing awareness of its potential applications in science, medicine, agriculture, and industry. Although Nigeria is still at an emerging stage compared to developed countries, recent studies indicate a steady increase in nanoparticle-based research outputs across Nigerian universities and research institutes (Friday *et al.,* 2025). Research efforts in Nigeria have largely focused on the synthesis, characterization, and application of nanoparticles, particularly metal and metal oxide nanoparticles such as zinc oxide (ZnO), silver (Ag), titanium dioxide (TiO2), and magnetic nanoparticles. These studies are predominantly conducted within academic settings, where nanotechnology is integrated into chemistry, physics, material science, and biomedical research programs (Nnaji *et al.,* 2024). The use of locally available raw materials and plant extracts has further encouraged the adoption of green synthesis approaches, making nanoparticle research more accessible and environmentally sustainable. Government and institutional support has also contributed to the growth of nanotechnology in Nigeria. Agencies such as the National Agency for Science and Engineering Infrastructure (NASENI) and the Federal Ministry of Science, Technology and Innovation have promoted nanoscience research through policy frameworks and limited funding initiatives. These efforts aim to enhance technological innovation, local manufacturing, and capacity building in advanced materials research (Muhammad *et al.,* 2023). Despite these advancements, the development of nanotechnology in Nigeria faces several challenges. These include inadequate funding, limited access to advanced characterization equipment, and insufficient collaboration between academia and industry. As a result, many nanoparticle studies remain at the laboratory stage, with minimal translation into commercial or industrial applications (Akinsipo, 2025). Nevertheless, recent reviews highlight increasing interdisciplinary collaborations and a growing number of publications suggesting a positive trajectory for nanotechnology development in Nigeria (Friday *et al.,* 2025). Overall, while nanotechnology in Nigeria is still developing, ongoing research activities, policy support, and the adoption of cost-effective synthesis methods indicate significant potential for future growth and innovation.

2.2 Research Institutions and Laboratories

Nanotechnology research in Nigeria is emerging through a combination of university research groups, dedicated research units, and national science agencies that contribute to the synthesis, characterization, and application of nanoparticles. These institutions not only promote scientific investigation but also support capacity building and knowledge exchange across disciplines. A leading force in Nigerian nanotechnology is the Nanotechnology Research Group (NANO+) at Ladoke Akintola University of Technology (LAUTECH), Ogbomoso. Formed in 2014, this group has consistently advanced nanoscience research by organizing international conferences, training scholars, and publishing extensively on nanoparticle synthesis, applications, and sustainable development strategies (LAUTECH Nanotechnology Research Group, n.d.; Guardian Nigeria reports). Their annual conferences bring together researchers from Nigeria and abroad to share findings and build collaborations, helping to strengthen the national research network in nanotechnology (Salau, 2025) Guardian Nigeria reports). The success of the group has also contributed to the establishment of the Centre for Nanoscience and Nanotechnology Research (CEENANO) at LAUTECH, aimed at deepening research capacity and serving as a hub for advanced materials investigation (LAUTECH Nanotechnology Research Group, n.d.). At the national level, the National Agency for Science and Engineering Infrastructure (NASENI) plays a critical role in coordinating nanotechnology research and infrastructure development. NASENI's Centre of Excellence in Nanotechnology and Advanced Materials focuses on the design, synthesis, and application of nanomaterials for various sectors including medicine, agro-nanomaterials, and advanced materials for industrial use. The center is equipped with state-of-the-art instrumentation such as scanning electron microscopes, spectrometers, and nanolithography systems, enabling high-precision research and development activities (NASENI Centre of Excellence in Nanotechnology and Advanced Materials, n.d.). Collaboration between NASENI and university groups like LAUTECH's NANO+ has been highlighted as a strategic effort to deepen nanotechnology-driven research in Nigeria (Salau, 2025). Within academia, specialized research units have also emerged. For example, the Drug Delivery and Nanotechnology Research Unit (RUNDD) at the University of Nigeria, Nsukka focuses on pharmaceutical applications of nanotechnology, particularly targeted drug delivery systems. This unit brings together postgraduate students and faculty to advance research in controlled-release systems and nanoparticlemediated drug targeting, addressing health challenges through nanomedicine innovation (University of Nigeria Nsukka, n.d.). Several universities contribute to the broader nanotechnology research landscape in Nigeria through materials science, chemistry, and interdisciplinary research groups. Although not always exclusively labeled as "nanotechnology laboratories," institutions such as Federal University of Technology, Minna and others with strong science and engineering faculties often incorporate nanoparticle research within their materials, chemistry, and engineering departments (Nanotechnology Experts listings). Similarly, interdisciplinary materials and nanoscience groups explore nanomaterials' properties and applications, demonstrating the breadth of research interest across Nigerian institutions (ICEESR Materials and Nanoscience Group, n.d.). Collectively, these research institutions and laboratories illustrate Nigeria's growing capacity in nanotechnology. By fostering training, expanding infrastructure, and encouraging collaborative research, they are central to the continued development of nanoparticle research and its translation toward practical solutions for national challenges.

2.3 Types of Nanoparticles Studied in Nigeria

In Nigeria, researchers have investigated a diverse range of nanoparticles, reflecting both global trends in nanotechnology and local research interests. These studies mainly focus on metal nanoparticles, metal oxide nanoparticles, and nanocomposites, often using green (biogenic) synthesis methods that employ plant extracts as reducing and capping agents. This approach is popular because it is cost-effective, environmentally friendly, and accessible for researchers in Nigerian laboratories.

Metal Oxide Nanoparticles

A major focus of Nigerian nanoparticle research has been on metal oxide nanoparticles, especially zinc oxide (ZnO). ZnO nanoparticles are widely studied because of their antibacterial, photocatalytic, and environmental remediation properties. For example, researchers in Nigeria have successfully synthesized ZnO nanoparticles and used them for applications such as wastewater treatment, demonstrating the material's effectiveness in reducing turbidity and contaminants in wastewater systems (Nnamdi Azikiwe University research, 2025). In addition, ZnO nanoparticles have been integrated into nanocomposite materials such as ZnO-polyaniline (PANI) composites, enhancing their photocatalytic ability to degrade organic pollutants (Ali *et al.,* 2025). Other metal oxide nanoparticles studied in Nigeria include iron oxide nanoparticles (Fe3O4), synthesised using plant extracts like Prosopis africana, which have potential applications in magnetic materials and environmental science (Ekwumemgbo *et al.,* 2025). Additionally, research on titanium dioxide (TiO2) nanoparticles via sol-gel methods highlights interest in photocatalytic and industrial applications (Nigerian Journal of Technology, 2025).

Noble Metal Nanoparticles

Silver nanoparticles (AgNPs) are another well-studied class in Nigerian nanoscience. AgNPs are known for their strong antimicrobial properties, useful in biomedical and environmental contexts. Nigerian researchers have synthesized AgNPs using green methods from plant materials such as Moringa oleifera leaves, demonstrating effective production and potential antimicrobial uses (Moses et al., 2025). Additionally, studies on the delivery and antimicrobial mechanisms of AgNPs contribute to understanding their interactions with bacterial cells and therapeutic applications (Idris et al., 2025).

Other Metal Nanoparticles

Copper nanoparticles (CuNPs) have been investigated through green synthesis using seed extracts from neem, baobab, and black seed, highlighting their optimization and antibacterial potential (Shehu *et al.,* 2025). These CuNPs demonstrate that research in Nigeria is expanding beyond traditional metals like silver and zinc into other transition metal nanoparticles with diverse functional properties.

Nanocomposites and Functionalised Nanoparticles

Nigerian research also includes nanocomposite materials, where nanoparticles are combined with other phases to achieve enhanced properties. For instance, ZnO-PANI nanocomposites are explored for enhanced environmental remediation due to improved surface area and photocatalytic activity (Ali *et al.,* 2025).

Nanocomposites broaden the functional utility of base nanoparticles by integrating conductive or polymer components.

Green and Eco-Friendly Synthesis

Across many Nigerian studies, green synthesis is a common theme. Plant extracts from locally available species such as Jatropha curcas have been used to produce ZnO nanoparticles with notable antibacterial properties (Ovonramwen *et al.,* 2025). This bio-mediated synthesis approach not only minimizes the use of hazardous chemicals but also aligns with sustainable and environmentally safe nanotechnology practices in Nigeria.

2.4 Notable Research Findings

Recent nanoparticle research in Nigeria has yielded important scientific insights and practical findings, particularly in environmental remediation, antimicrobial activity, and functional nanocomposite development. These studies not only highlight the potential applications of nanoparticles but also demonstrate how Nigerian research is contributing to global nanoscience trends.

Environmental and Wastewater Treatment Advances

One of the most significant findings from Nigerian research involves the use of zinc oxide (ZnO) nanoparticles for wastewater treatment. A study conducted at Nnamdi Azikiwe University investigated the mechanochemical synthesis of ZnO nanoparticles and assessed their ability to treat restaurant wastewater. The results showed that treatment with ZnO nanoparticles significantly reduced turbidity (from 377 mg/L to 52 mg/L) and decreased levels of sulphates, nitrates, phosphates, and heavy metals--leading to a notable improvement in water quality (e.g., reduction in total dissolved solids and biological/chemical oxygen demand) (Billik *et al.,* 2025). These findings suggest ZnO nanoparticles can play a transformative role in improving water quality and environmental health in urban settings where wastewater management is a major challenge. Further research has also emphasised ZnO-polyaniline nanocomposites (ZnO-PANI) as advanced materials for environmental cleanup. Compared with individual ZnO nanoparticles, these nanocomposites exhibited enhanced surface area and improved photocatalytic properties, suggesting they may more efficiently degrade stubborn organic contaminants in wastewater. Increased surface area and porous structure were confirmed through electron microscopy and BET analysis, indicating strong potential for scalable environmental applications (Ali *et al.,* 2025).

Antimicrobial Properties and Biomedical Potential

A major area of nanoparticle application in Nigeria has been their antimicrobial efficacy, particularly against multidrug-resistant pathogens. For example, ZnO nanoparticles synthesized using Chromolaena odorata leaf extract demonstrated significant antibacterial activity against multidrug-resistant clinical isolates, including both bacterial and fungal pathogens. Detailed characterization (using XRD, SEM, EDX, FTIR, and BET) confirmed that the nanoparticles' high surface area contributed to their enhanced antimicrobial effects, pointing to their potential use in antimicrobial surface coatings and treatments (Okorie et al., 2025). Similarly, nanocomposites involving metal oxides and natural materials such as carbonized Moringa oleifera leaves have been shown to possess selective antibacterial activity, particularly against Gram-positive bacteria like Staphylococcus aureus.

These ZnO-carbonized Moringa composites revealed a porous morphology and high crystallinity, which helped inhibit bacterial growth in laboratory assays (Ogbeide *et al.,* 2025). Other studies focusing on green synthesis methods have further established that plant-mediated ZnO nanoparticles can effectively inhibit common pathogenic bacteria (e.g., E. coli, Klebsiella pneumoniae, Pseudomonas aeruginosa), demonstrating how locally sourced biological agents can be used to produce potent antibacterial materials (Ovonramwen *et al.,* 2025).

Nanocomposite Materials and Functional Enhancements

Research in Nigeria has also explored nanocomposite materials that combine different phases to improve functionality. ZnO/PANI nanocomposites, for instance, showed enhanced photocatalytic properties compared with standalone ZnO nanoparticles, due to strong interfacial contact and increased surface area, which facilitate more efficient charge separation. This feature is essential for advanced photocatalytic degradation of environmental pollutants and suggests scalable approaches for wastewater treatment technologies (Ali *et al.,* 2025).

2.5 Government Policies and National Initiatives

The development of nanotechnology in Nigeria has not only been driven by academic research but also through government policies, strategic initiatives, and institutional support frameworks aimed at expanding science, technology, and innovation (STI). Although Nigeria does not yet have a finalized standalone National Nanotechnology Policy, actions by federal agencies, ministries, and innovation ecosystems demonstrate a growing commitment to integrate nanotechnology into national development agendas.

Policy Recognition and Federal Commitment

The Federal Government of Nigeria has long recognized nanotechnology as a critical emerging technology with potential applications across multiple sectors, including health, environment, agriculture, defense, and industrial development. Government leadership has repeatedly emphasised the need for formal policy frameworks and integration of nanotechnology into national science agendas. For instance, during university-based nanotechnology conferences, the Minister of Science and Technology affirmed the government's commitment to supporting research and development in nanotechnology and stressed the importance of synergy between universities, government agencies, and industry for rapid technological adoption and economic impact (Onu, 2020; Onu, 2025). In line with this vision, the Ministry of Innovation, Science and Technology has engaged stakeholders to develop standard operating procedures (SOPs) for chemical and nanotechnology policies, which would provide actionable guidelines for implementation and safe operation across sectors. This initiative, driven through stakeholder consultations, is a step toward a comprehensive National Nanotechnology Policy that supports innovation while addressing safety, health, and environmental considerations.

Institutional Frameworks and Agency Roles

Central to Nigeria's national nanotechnology agenda is the National Agency for Science and Engineering Infrastructure (NASENI). NASENI is mandated to promote research, production, and technology transfer in engineering materials including nanotechnology as part of its broader mission to support technological advancement and indigenous manufacturing capacity nationwide. The agency's mandate explicitly includes nanotechnology research and development, reinforcing its role as the primary federal body backing nanoscience engagement and commercialization.

Under recent government frameworks, NASENI has launched technology transfer and commercialization programmes, attracting significant investment commitments and partnerships in areas related to nanotechnology. For example, government-approved technology transfer programs have drawn over $2 billion in investment commitments and established collaborations with foreign firms, including agreements for establishing technology production facilities in Nigeria. These investments reflect policy efforts to move nanotechnology from laboratory prototypes to market-ready products, expanding Nigeria's industrial base and technological exports.

Support for Research, Collaboration, and Conferences

Beyond institutional mandates, Nigerian government policy has supported research collaboration and advocacy across agencies and universities. The Federal Ministry of Innovation, Science and Technology, national space agencies, and research institutions have collaborated to organise international nanotechnology conferences, bringing together scholars, policymakers, and private sector stakeholders to discuss nanotechnology opportunities within the Fourth Industrial Revolution (4IR) and sustainable development. These conferences contribute to raising policy awareness and fostering cross-sector dialogue necessary for integrating nanotechnology into national strategies.

Linkages With Broader Innovation Initiatives

While specific policies for nanotechnology are being developed, Nigeria's wider innovation ecosystem initiatives also provide indirect support for nanotechnology research and commercialization. For example, national programmes aimed at building technical talent and expanding digital skills--such as the 3 Million Technical Talent (3MTT) Programme--help create a skilled workforce capable of engaging with advanced technologies, including nanoscience and nanotechnology applications. In addition, federal activities through technology incubation, innovation challenges, and partnerships supported by government agencies help strengthen Nigeria's STI landscape, thereby creating environments where interdisciplinary research such as nanotechnology can thrive.

Policy Implications

Although Nigeria does not yet have a fully enacted National Nanotechnology Policy, the government has taken important early steps through stakeholder engagement, institutional support, policy drafting processes, investment frameworks, and research promotion. The Federal Ministry of Innovation, Science and Technology, in collaboration with agencies like NASENI, plays a key role in shaping future nanotechnology governance. These efforts signal a strategic policy direction aimed at harnessing nanotechnology for national development, economic growth, and scientific competitiveness.

3.0 APPLICATIONS OF NANOPARTICLES IN NIGERIA 3.1Medical and Pharmaceutical Applications

Nanoparticles are increasingly being investigated in Nigeria for medical and pharmaceutical uses, leveraging their unique size-dependent properties to enhance antimicrobial activity, drug delivery, diagnostics, and potential therapeutic outcomes. Nigerian research has been particularly active in exploring green synthesis of biocompatible nanoparticles, evaluating their antibacterial and antioxidant effects, and considering their roles in pharmaceutical formulation and therapy.

Antimicrobial and Antibacterial Activity

A major focus of Nigerian research has been the antimicrobial properties of nanoparticles, especially silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnO NPs). This interest aligns with global concerns about antimicrobial resistance and the need for alternative agents capable of combating drug-resistant clinical pathogens. For instance, silver nanoparticles synthesized using the leaf extract of Vernonia amygdalina showed significant antibacterial and antioxidant effects, suggesting potential pharmaceutical applications for managing infections and oxidative stress-related conditions. The green-synthesized AgNPs exhibited effective inhibition against Escherichia coli and Staphylococcus aureus, two common clinical pathogens, indicating their therapeutic promise as antimicrobial agents (Ovenseri *et al.,* 2023). Similarly, AgNPs produced via green methods from Azadirachta indica (neem) leaves demonstrated antimicrobial activity against E. coli, S. aureus, and Candida albicans, supporting their potential for clinical use where conventional antibiotics may fail due to resistance mechanisms (Agbaje *et al.,* 2023). Zinc oxide nanoparticles synthesized using Jatropha curcas leaf extract also exhibited strong antibacterial activity against both Gram-positive and Gram-negative bacteria, reinforcing the biomedical relevance of green-produced metal oxide nanoparticles for combating infectious microbes (Ovonramwen *et al.,* 2025). Moreover, zinc oxide nanoparticles produced from Chromolaena odorata demonstrated antimicrobial efficacy against multidrug-resistant clinical isolates, including both bacterial and fungal species from a Nigerian clinical setting. These nanoparticles' high surface area and tailored morphology significantly enhanced their interaction with microbial cells, suggesting robust applications in infection control and potentially in wound dressings or topical formulations (Okorie *et al.,* 2025).

Drug Delivery and Formulation Innovations

Nanoparticles provide advantageous benefit for targeted drug delivery, improved solubility, and controlled release, which can enhance therapeutic outcomes while reducing side effects. Although the development of clinical nanoparticle-based drug delivery systems within Nigeria remains at an early stage, existing research conducted in the country suggests promising potential for nano-enabled drug delivery platforms. Studies on nanoemulsions describe how nanotechnology-based formulations can improve transdermal and dermal drug delivery, overcoming skin barriers and enhancing therapeutic bioavailability compared with conventional delivery routes (Oyelaja-Akinsipo *et al.,* 2025). Additionally, research globally and reflected in Nigeria's scientific interest suggests that nanoparticles can be engineered to carry pharmaceuticals such as chemotherapeutic agents, vaccines, or antimicrobial drugs directly to target tissues, thereby improving efficacy and reducing systemic toxicity. These drug delivery systems include lipid nanoparticles, polymeric nanoparticles, and nanocarriers tailored for specific therapeutic purposes (Okafor, 2025). For example, nanoparticles designed to deliver loaded drugs--like silver-loaded omeprazole nanoparticles prepared in Nigeria--illustrate early efforts to combine therapeutic agents with nanostructures, potentially enhancing drug stability, targeted action, and clinical effectiveness compared with traditional dosage forms (Patani *et al.,* 2024).

Antioxidant and Therapeutic Effects

Many nanoparticles synthesized in Nigeria also exhibit antioxidant properties, which can have therapeutic implications in conditions involving oxidative stress. Nanoparticles with high surface area and functional phytochemical capping agents can scavenge free radicals effectively, demonstrating potential utility in pharmaceutical antioxidant formulations (Ovenseri *et al.,* 2023).

Challenges in Clinical Translation

While these findings are promising, authors note that nanotoxicology and safety assessment are critical considerations before clinical use can be widely adopted. Studies emphasize the importance of understanding nanoparticle interactions with biological systems, potential cytotoxicity, and long-term health effects to ensure safe therapeutic applications (Abubakar *et al.,* 2025).

Plant-Mediated Silver Nanoparticles in Therapeutic Research

Recent studies have further investigated the therapeutic potential of plant-mediated silver nanoparticles synthesized from locally available plant extracts. This approach integrates the medicinal value of plants with the distinctive physicochemical properties of nanoparticles, leading to materials that may show enhanced biological activity. In Nigeria, this method has gained attention because plant materials are readily available and the synthesis process is relatively simple and environmentally friendly.

For example, silver nanoparticles synthesized using aqueous extracts of Jatropha tanjorensis have been reported to exhibit several biological activities, including antidiabetic, antioxidant, antiglycation, and anti-inflammatory effects. These nanoparticles demonstrated strong free radical scavenging ability and showed inhibitory activity against enzymes associated with glucose metabolism. Such findings suggest that plant-mediated nanoparticles may contribute to the development of alternative therapeutic strategies for metabolic disorders such as diabetes mellitus (Awote et al., 2023).

Similarly, green-synthesized silver nanoparticles derived from Telfairia occidentalis, a commonly consumed vegetable in Nigeria, have also demonstrated significant antioxidant and anti-inflammatory properties. The nanoparticles were found to inhibit glycation processes linked to chronic metabolic diseases, further highlighting the potential biomedical relevance of plant-mediated nanoparticles. These findings support the growing interest among Nigerian researchers in using locally available plant resources for the development of bioactive nanomaterials (Awote et al., 2024).

3.2 Agricultural Applications

Nanotechnology presents promising innovations for transforming agriculture in Nigeria, offering tools and materials that can improve crop productivity, enhance soil properties, support pest management, and contribute to food security. While the field is still emerging within the Nigerian context, recent research and regional studies indicate a growing interest in nanoparticles for agricultural uses--from soil enhancement and crop growth to precision farming technologies.

Improving Soil Properties and Crop Performance

One notable area of research in Nigeria involves the use of biochar-based nanoparticles to influence soil hydrological properties. A Nigerian study found that adding biochar nanoparticles to agricultural soil significantly improved soil moisture retention, clay flocculation, and structural stability at moderate application levels. These improvements can help crops endure drought and improve water availability in soils prone to moisture loss. However, the authors also noted that excessive nanoparticle levels may impair soil structure, indicating the need for careful dosage control in agricultural applications (Dayo-Olagbende *et al.,* 2025). Research at the Federal University of Lafia explored the effects of iron oxide nanoparticles on maize (Zea mays). Early findings from this work show that different concentrations of iron oxide nanoparticles applied as a foliar spray influenced yield variability and proximate composition in maize. This suggests that nanoparticles may help influence crop growth, nutritional content, and yield metrics, pointing to potential applications in enhancing staple crop performance (Sirajo *et al.,* 2024). Additional research in Nigeria demonstrated that green-synthesized metal nanoparticles like zinc, copper, and manganese (derived from local plant extracts such as Carica papaya, Azadirachta indica, and Hibiscus sabdariffa) can affect crop growth and productivity. In this work, nanoparticle treatments improved the growth performance and physiological condition of rice grown in ferruginous soil, suggesting that biogenic nanoparticles may serve as growth-enhancing soil amendments (Igiebior *et al.,* 2023).

Recent studies have also investigated the use of zinc oxide nanoparticles (ZnO NPs) to enhance plant growth and improve crop tolerance to environmental stress. Zinc plays an essential role in plant metabolism, enzyme activation, and photosynthesis, making it an important micronutrient for plant development. When delivered in nanoparticle form, zinc may become more readily available to plants and may improve nutrient uptake efficiency. For example, research examining the application of zinc oxide nanoparticles on tomato plants demonstrated significant improvements in several growth parameters, including plant height, leaf area, and biomass accumulation. The nanoparticles were also found to influence biochemical processes related to stress tolerance by regulating antioxidant enzyme activity and reducing oxidative stress under water-limited conditions. These findings suggest that ZnO nanoparticles can function as effective nanofertilizers capable of improving crop resilience and productivity (Ojewumi et al., 2025).

Similarly, studies investigating the effects of plant-derived zinc oxide nanoparticles on eggplant plants reported improvements in both morpho-physiological characteristics and biochemical responses associated with plant growth. The nanoparticles enhanced antioxidant activity and influenced metabolic processes that support plant development and stress adaptation. Such findings indicate that nanoparticle-based agricultural inputs may help improve crop productivity while reducing reliance on conventional fertilizers (Ojewumi et al., 2026).

Nanofertilizers and Nutrient Delivery

Globally, nanotechnology is used to develop nanofertilizers--fertilizers formulated at the nanoscale that can enhance nutrient delivery efficiency, reduce nutrient loss, and minimize environmental run-off compared to conventional fertilizers. Nanofertilizers encapsulate nutrients in nanoparticles that release nutrients gradually or in response to plant needs, leading to improved crop uptake and reduced chemical fertilizer usage. This has been shown to increase crop yields and reduce agriculture's ecological footprint (Atanda *et al.,* 2025). This approach is particularly relevant in Nigeria where soil fertility issues and inefficient fertilizer use constrain agricultural productivity. Nanofertilizers could provide a sustainable alternative by increasing nutrient use efficiency while mitigating soil degradation.

Nanopesticides and Pest Management

Another promising agricultural application is the use of nanopesticides and nanobiopesticides for protecting crops and post-harvest produce. Nanopesticides are engineered to carry active ingredients more effectively and target pests at the molecular level, which can reduce overall chemical usage and lower non-target environmental impacts.

A Nigerian review on nanobiopesticides highlights how nanoencapsulated formulations can improve the delivery, stability, and efficacy of pest control agents for insect pests of crops, especially in post-harvest contexts. These nanopesticide systems use polymers, nanoemulsions, and metal nanoparticles to improve control of pests while offering potential environmental and health benefits over conventional pesticides (Adegbola *et al.,* 2024).

Precision Agriculture and Nanosensors

Nanotechnology also supports precision agriculture through nanosensors that monitor soil moisture, nutrient levels, and pest infestations in real time. These nanoscale sensors can help farmers make data-driven decisions, optimizing irrigation, fertilization, and pest management to increase efficiency and reduce resource waste. In

Nigeria, research reviews reveal that nanosensors have the potential to significantly enhance agricultural monitoring and responsiveness, contributing to better crop health and yield outcomes (Atanda *et al.,* 2025).

Addressing Food Security and Sustainability

Nanotechnology's role in agriculture aligns with national food security goals. By improving nutrient delivery, enhancing soil water retention, and enabling precise pest control, nanoparticles can increase crop productivity and resilience against climate stressors--key factors for countries like Nigeria where food production pressures are rising. Innovations like nanofertilizers and nanobiosensors have been projected to improve crop yields by up to ~30% and enhance nutrient uptake efficiency by up to ~50% compared with conventional agricultural inputs (Atanda *et al.,* 2025).

Environmental and Safety Considerations

While the potential benefits are significant, research emphasizes careful management of nanoparticle use in agriculture. Possible impacts on soil microbiomes, plant-associated microorganisms, and long-term ecosystem health remain under exploration. Sustainable application practices must balance crop productivity gains with safeguarding soil functions and environmental integrity (Mgadi *et al.,* 2024).

3.3 Environmental and Water Treatment Uses

Nanotechnology has emerged as a promising tool for addressing environmental pollution and water treatment challenges in Nigeria. Rapid industrialization, urbanization, oil exploration, and agricultural activities have contributed significantly to water contamination and environmental degradation across the country. In response, Nigerian researchers have increasingly explored the application of nanoparticles for pollution remediation, wastewater treatment, and potable water purification due to their high surface area, reactivity, and adsorption efficiency (Friday *et al.,* 2025). One of the most studied applications of nanoparticles in Nigeria is water purification. Metal oxide nanoparticles such as zinc oxide (ZnO), iron oxide ($Fe3O4$), and titanium dioxide ($TiO2$) have demonstrated strong potential in removing heavy metals, organic pollutants, and pathogenic microorganisms from contaminated water sources. Studies conducted in Nigerian laboratories report effective adsorption of toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) using nanoparticle-based adsorbents synthesized from locally sourced materials (Adekola *et al.,* 2022). Silver nanoparticles (AgNPs) have also been widely investigated for their antimicrobial properties in water treatment systems. Nigerian studies have shown that AgNPs synthesized via green methods using plant extracts are effective in inhibiting waterborne pathogens, including Escherichia coli and Staphylococcus aureus, making them suitable for low-cost disinfection technologies in rural and peri-urban communities (Oluwaseun *et al.,* 2023). These findings are particularly relevant given Nigeria's persistent challenges with access to safe drinking water. Nanoparticles have further been applied in environmental remediation, especially in the treatment of oil-polluted soils and industrial effluents. Magnetic nanoparticles have attracted attention due to their ability to be easily separated and recovered after pollutant removal. Nigerian researchers have demonstrated the use of iron oxide nanoparticles in the remediation of hydrocarbon-contaminated soils in oil-producing regions, such as the Niger Delta, where conventional remediation methods are often expensive and inefficient (Nnaji *et al.,* 2024). In addition, nanomaterials such as carbon-based nanoparticles and nanocomposites have been studied for dye removal from textile and industrial wastewater. These materials exhibit high adsorption capacity for synthetic dyes commonly released by local industries, thereby reducing environmental toxicity and improving wastewater quality before discharge into natural water bodies (Muhammad *et al.,* 2023). Despite these promising outcomes, the large-scale application of nanoparticle-based environmental technologies in Nigeria remains limited. Challenges such as inadequate infrastructure, limited funding, concerns about nanoparticle toxicity, and the absence of comprehensive environmental regulations on nanomaterials hinder widespread adoption.

3.4 Energy and Industrial Applications

Nanotechnology has increasingly been explored in Nigeria as a strategic tool for improving energy production, energy storage, and industrial efficiency. With persistent challenges such as unreliable power supply, dependence on fossil fuels, and inefficient industrial processes, nanoparticle-based technologies offer innovative solutions for enhancing performance, reducing costs, and promoting sustainability (Muhammad *et al.,* 2023). In the energy sector, nanoparticles have been widely studied for applications in renewable energy systems, particularly solar energy. Nigerian researchers have investigated the use of metal oxide nanoparticles such as titanium dioxide ($TiO2$), zinc oxide (ZnO), and copper oxide (CuO) in solar cells to improve light absorption, charge transport, and overall energy conversion efficiency. These nanoparticles are commonly incorporated into dye-sensitized solar cells (DSSCs) and thin-film solar technologies due to their stability, low cost, and availability of raw materials within the country (Akinwale *et al.,* 2022). Nanomaterials have also shown promising potential in energy storage systems, including batteries and supercapacitors. Carbon-based nanoparticles, graphene derivatives, and metal oxide nanostructures have been studied for electrode fabrication, offering improved conductivity, higher surface area, and enhanced charge-discharge performance. Nigerian studies report that nanoparticle-enhanced electrodes can significantly improve the efficiency and lifespan of lithium-ion batteries and supercapacitors, which are critical for renewable energy integration and backup power solutions (Nnaji *et al.,* 2024).

In industrial applications, nanoparticles are increasingly applied as catalysts to enhance chemical reactions in petroleum refining, fertilizer production, and manufacturing processes. Given Nigeria's oil and gas-dependent economy, nanocatalysts have attracted attention for improving refining efficiency, reducing energy consumption, and minimizing harmful emissions. Research has demonstrated that nano-sized catalysts exhibit higher activity and selectivity compared to conventional catalysts, making them suitable for industrial-scale optimization (Akinsipo, 2025). Nanoparticles are also utilized in materials engineering and manufacturing, where they are incorporated into coatings, composites, and construction materials. Nigerian researchers have explored nanoparticle-reinforced polymers and cement composites to improve mechanical strength, corrosion resistance, and durability. For example, the inclusion of silica and alumina nanoparticles in cement-based materials has been shown to enhance compressive strength and reduce permeability, which is particularly beneficial for infrastructure development in harsh environmental conditions (Olatunji *et al.,* 2021). Despite the promising research outcomes, the translation of nanoparticle-based energy and industrial technologies into large-scale applications in Nigeria remains limited. Key barriers include high production costs, limited industrial infrastructure, lack of skilled manpower, and insufficient collaboration between research institutions and the private sector.

3.5 Consumer and Cosmetic Applications

The application of nanoparticles in consumer and cosmetic products has gained increasing attention in Nigeria due to rising consumer demand for enhanced product performance, durability, and aesthetic appeal. Nanotechnology has been integrated into a wide range of consumer goods, including cosmetics, personal care products, textiles, packaging materials, and household items. Nigerian researchers and manufacturers are exploring nanoparticle-based formulations to improve product quality, safety, and functionality (Muhammad *et al.,* 2023).

In the cosmetic and personal care industry, nanoparticles are primarily used to enhance product stability, penetration, and effectiveness. Commonly studied nanoparticles include titanium dioxide (TiO2), zinc oxide (ZnO), silver nanoparticles (AgNPs), and lipid-based nanoparticles. TiO2 and ZnO nanoparticles are widely applied in sunscreens and skin-care products due to their ability to provide broad-spectrum ultraviolet (UV) protection while maintaining cosmetic transparency on the skin (Ogunleye *et al.,* 2022). Nigerian studies have reported that nano-sized UV filters offer improved sun protection efficiency compared to their conventional counterparts. Silver nanoparticles have also been investigated for their antimicrobial properties in cosmetic formulations such as creams, soaps, and deodorants. Research conducted in Nigeria demonstrates that AgNPs synthesized through green methods using plant extracts exhibit strong antibacterial and antifungal activities, making them suitable for incorporation into hygiene and personal care products aimed at reducing microbial contamination and extending shelf life (Oluwaseun *et al.,* 2023). Nanotechnology has further found applications in cosmetic delivery systems, particularly through nanoemulsions and lipid nanoparticles. These systems enhance the controlled release and bioavailability of active cosmetic ingredients such as vitamins, antioxidants, and herbal extracts. Nigerian researchers have highlighted the potential of nanocarriers to improve skin hydration, reduce irritation, and increase the effectiveness of natural cosmetic formulations derived from locally sourced plants (Akinsipo, 2025).

Beyond cosmetics, nanoparticles are increasingly applied in consumer products and packaging materials. Nanocomposites containing silica, clay, or metal oxide nanoparticles are used to improve the mechanical strength, barrier properties, and durability of plastic packaging. In Nigeria, such materials have been studied for food packaging applications to enhance shelf life, prevent microbial growth, and reduce post-harvest losses, particularly in perishable agricultural products (Adekola *et al.,* 2022). Despite these advantages, concerns remain regarding the safety and regulation of nanoparticles in consumer and cosmetic products. Limited toxicological data, lack of standardized labeling, and weak regulatory frameworks pose challenges to widespread adoption in Nigeria. However, recent studies emphasize the need for comprehensive risk assessment, consumer awareness, and policy development to ensure the safe and responsible use of nanotechnology in consumer markets (Muhammad *et al.,* 2023). Overall, research conducted between 2020 and 2025 indicates growing interest in nanoparticle-based consumer and cosmetic applications in Nigeria, driven by innovation in green synthesis, natural product formulation, and performance-enhancing technologies.

4.0 CHALLENGES FACING NANOTECHNOLOGY IN NIGERIA

4.1 Infrastructural Limitations

A major barrier to the advancement of nanotechnology in Nigeria is the lack of adequate research infrastructure. Nanoscience and nanotechnology research, especially at an advanced level, requires access to high-precision instruments for synthesis, characterization, and application testing. These include scanning electron microscopes (SEM), transmission electron microscopes (TEM), atomic force microscopes (AFM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and other analytical tools essential for measuring size, morphology, crystalline structure, and surface properties of nanoparticles. Such instruments are expensive to acquire, maintain, and operate, and the cost is often beyond the budgets of many Nigerian universities and research institutes (Muhammad *et al.,* 2023). Most Nigerian research institutions rely on basic laboratory equipment or collaborate with external partners to access advanced characterization tools abroad, which slows research progress and limits independent experimentation (Friday *et al.,* 2025). The absence of centralized facilities that are wellequipped for nanoparticle synthesis and testing means that researchers often face delays in project timelines, encounter increased costs, and must compromise on the rigor and scope of their studies (Nnaji *et al.,* 2024). This infrastructural gap discourages experimentation with cutting-edge nanotechnologies and undermines efforts to produce novel materials with industrial or commercial potential. High operating costs and the lack of skilled technical personnel to operate and maintain advanced instruments further compound the infrastructural challenge. Even when advanced equipment is available through collaborations or shared facilities, limited on-site technical support often results in underutilization of expensive tools or misinterpretation of complex data. This not only affects the quality of research outputs but also deters early-career scientists from engaging in nanotechnology research due to perceived complexity and resource barriers (Akinsipo, 2025). Government and institutional funding shortfalls contribute significantly to these limitations. Nigeria's investment in science, technology, and innovation (STI) remains lower than global averages, and priority is frequently directed toward more immediate socioeconomic needs, leaving nanotechnology facilities underfunded or nonexistent in many parts of the country (Muhammad *et al.,* 2023). Attempts by agencies like the National Agency for Science and Engineering Infrastructure (NASENI) to establish centers of excellence and technology platforms are often hampered by inconsistent funding flows, bureaucratic delays, and logistical challenges associated with equipment procurement, installation, and maintenance.

In addition to the challenges associated with acquiring laboratory equipment, the effective use of nanotechnology facilities often depends on the availability of specialised environments where sensitive instruments can be properly operated and maintained. Nanoscale research frequently involves the analysis of materials using highly precise imaging and characterization tools that require stable laboratory conditions and trained technical support staff. Where these conditions are not consistently available, the range of experimental procedures that researchers can perform locally may become limited. This has been noted in discussions of nanotechnology development across several African countries where research interest in nanomaterials continues to grow, but the supporting scientific infrastructure required for advanced nanoscale investigations is still developing (Musee et al., 2012). The availability of infrastructure also affects the ability of research institutions to sustain experimental programmes in nanotechnology over extended periods of time. Many nanoparticle studies require repeated measurements, careful sample preparation, and specialised analytical procedures. In situations where laboratories operate with limited facilities or irregular access to technical equipment, researchers may focus on smaller experimental studies rather than larger collaborative projects. Observations of nanotechnology development in Africa indicate that the growth of the field is often closely linked to the availability of specialised research laboratories and technical facilities that allow scientists to investigate nanoscale materials in greater detail (Musee et al., 2012).

The lack of regional and national nanotechnology hubs forces individual research groups to invest scarce resources into duplicative equipment or travel abroad for advanced characterization. This decentralization reinforces inequalities in research capacity across institutions and regions and limits multidisciplinary collaborations that are crucial for high-impact nanoscience research (Friday *et al.,* 2025). Furthermore, limited access to high-speed internet, stable electricity, and computational resources hampers data analysis, modeling, and simulation studies that are integral to modern nanotechnology research.

Addressing infrastructural limitations is essential for Nigeria to transition from basic laboratory research toward applied and translational nanotechnology, where innovations move from bench to industrial prototypes and commercial products. Investments in shared nanotechnology facilities, training programs for instrument operation, and public-private partnerships could help bridge gaps. Without such infrastructural improvements, Nigeria risks lagging behind countries that are rapidly commercializing nanoparticle technologies across medicine, environment, agriculture, energy, and consumer markets.

4.2 Funding and Technical Expertise

One of the most significant challenges facing nanotechnology development in Nigeria is the inadequacy of sustained funding and the limited availability of technical expertise, both of which are essential for high-quality research, innovation, and commercialization. Nanotechnology research, especially involving nanoparticles requires not only financial resources for laboratory equipment and materials but also investment in human capital capable of carrying out sophisticated experimental designs, advanced characterization, and interdisciplinary problem solving. However, both funding and technical expertise remain constrained within the Nigerian context, limiting the country's capacity to fully harness the benefits of nanotechnology (Muhammad *et al.,* 2023).

Funding Constraints

In Nigeria, research funding is predominantly channeled toward immediate socioeconomic priorities such as healthcare infrastructure, education, and basic services, leaving comparatively little for advanced technological research such as nanoscience and nanotechnology. Federal and state research grants are limited in size and frequency, making sustained research efforts difficult. Nanotechnology projects often require multi-year commitments to cover expensive inputs such as precursor chemicals, nanoparticle synthesis reagents, maintenance of specialized equipment, and publication or patenting fees. Without continuous funding, research teams are frequently forced to abandon long-term projects, scale down experimental designs, or rely on external collaborations that may divert research away from locally relevant problems (Muhammad *et al.,* 2023). While agencies like the National Agency for Science and Engineering Infrastructure (NASENI) and the Ministry of

Innovation, Science and Technology have supported select nanotechnology initiatives, these efforts are often project-specific rather than part of a strategic, long-term national funding framework.

The level of financial support allocated to emerging scientific fields can significantly influence the pace at which research develops. Nanotechnology has been identified globally as a technology capable of contributing to solutions in areas such as water treatment, energy production, environmental remediation, and medicine. Despite these potential benefits, Nigeria has not fully integrated nanotechnology development into long term national science and technology strategies aimed at addressing socio economic challenges. Earlier reviews of nanotechnology development in Nigeria have pointed out that although awareness of the technology is increasing among researchers and academic institutions, national investment in the field remains limited compared with other countries that have prioritised nanotechnology research as part of their technological advancement programmes (Bankole et al., 2014). Limited funding also affects the development of specialised expertise required for nanoscale research. Nanotechnology is an interdisciplinary field that requires knowledge drawn from chemistry, physics, materials science, engineering, and biotechnology. Without consistent financial support for advanced training programmes, postgraduate research, and collaborative research projects, the number of scientists with strong expertise in nanotechnology may remain relatively small. Discussions of nanotechnology development in Nigeria have suggested that although the country possesses significant human resources and research potential, the absence of sustained policy implementation and structured investment has influenced the pace at which nanotechnology research expands within the national scientific system (Lateef, 2022). In addition to financial resources, access to training opportunities and specialised knowledge is essential for the effective use of nanotechnology facilities. Research involving nanoparticles often requires familiarity with advanced characterization techniques and laboratory procedures. Where opportunities for training and technical development are limited, researchers may rely on collaborations with external laboratories or international partners in order to access specialised knowledge and equipment. Such collaborations are common in emerging nanotechnology research environments where the field is still developing.

Consequently, funding remains patchy, unpredictable, and insufficient to sustain high-impact research programs that could lead to technological breakthroughs or commercial applications (Friday *et al.,* 2025). Private sector investment in nanotechnology R&D is also minimal, partly because of market uncertainty, concerns about regulatory frameworks, and lack of clear pathways for return on investment.

Limited Technical Expertise

In addition to funding gaps, Nigeria faces a shortage of highly trained technical personnel with expertise in nanotechnology. Nanoscience is inherently interdisciplinary, requiring competencies in chemistry, physics, materials science, engineering, and computational modelling. However, many Nigerian universities and research institutions lack faculty and postgraduate researchers who are sufficiently trained in advanced nanotechnology techniques, particularly those involving nanoparticle synthesis, characterization, and application testing. Although some Nigerian researchers have pursued advanced degrees abroad and returned with valuable skills, their numbers are relatively few compared with demand. Moreover, there is often a "brain drain" effect, where skilled researchers emigrate for better funding, research environments, and professional opportunities, further depleting local technical capacity (Muhammad *et al.,* 2023). Without sustained efforts to train and retain nanotechnology specialists, Nigeria's research ecosystem risks stagnation in basic nanoparticle studies rather than progression to applied research, product development, or commercialization. The lack of local access to specialized training programs, workshops, and certification courses in nanotechnology also contributes to the expertise gap. While some collaborative workshop programs and nanotechnology conferences have been organized by groups such as the Nanotechnology Research Group (NANO+) at Ladoke Akintola University of Technology (LAUTECH), these efforts are ad hoc and often dependent on external participation or sponsorship rather than part of a coordinated national human capital strategy (Salau, 2025).

Interlinked Challenges and Consequences

The interplay between limited funding and scarce expertise creates a vicious cycle: weak funding discourages investment in advanced training programs, while the lack of skilled researchers makes it harder to secure competitive grants and attract industry partners. This cycle constrains the development of locally relevant nanoparticle technologies, reduces opportunities for cutting-edge research, and restricts Nigeria's ability to influence emerging global standards in nanoscience. Addressing these challenges requires a multi-pronged approach. Increased public and private investment in nanotechnology research, coupled with incentives for industry participation, can broaden the resource base. Equally important is the development of structured educational programs, such as specialized postgraduate degrees, industry-linked internships, and continuous professional development courses, to build a critical mass of nanotechnology-trained scientists and engineers. Establishing research chairs and centers of excellence with long-term funding commitments could provide stability that encourages both talent retention and impactful research.

4.3 Regulatory and Safety Concerns

As nanotechnology research and applications expand globally and within Nigeria, concerns related to regulatory frameworks, safety standards, and risk assessment of nanoparticles have become increasingly important. Nanomaterials, due to their extremely small size and high surface reactivity, can interact with biological systems and the environment in ways that differ from conventional materials. This introduces complexities for regulation, safety evaluation, and public health protection, especially in countries where governance structures for emerging technologies are still developing (Abubakar *et al.,* 2025).

Limited Regulatory Frameworks

Nigeria currently lacks a comprehensive, nanoparticle-specific regulatory framework that adequately addresses the unique properties and risks of nanomaterials in consumer products, environmental applications, industrial uses, and medical technologies. Existing regulations governing chemicals, pharmaceuticals, and environmental health often do not explicitly account for nanoparticles or provide criteria for assessing nano-specific hazards such as increased bioavailability, cellular penetration, and potential ecological persistence. Although some regulatory agencies such as the National Agency for Food and Drug Administration and Control (NAFDAC) and the Federal Ministry of Environment oversee general safety standards for chemicals and marketed products, there are no clearly articulated guidelines that differentiate nanomaterials from bulk counterparts. This regulatory gap creates uncertainty for researchers, manufacturers, and consumers, as there are no clear pathways for registration, safety testing, labeling, or post-market surveillance specifically tailored to nanoparticle-based products (Okafor *et al.,* 2024).

Safety and Toxicological Uncertainties

Nanoparticles can interact with biological systems at the cellular and molecular levels, potentially causing oxidative stress, inflammation, and cytotoxicity depending on their composition, size, shape, surface chemistry, and dose. These interactions can vary significantly from those of larger particles of the same material, making traditional toxicology methods less predictive for nanomaterials (Abubakar *et al.,* 2025). For example, certain metal oxide nanoparticles such as zinc oxide (ZnO) and silver (Ag) have shown promising antimicrobial properties but can also induce toxicity in non-target cells if used at high concentrations or without proper formulation (Okorie *et al.,* 2025). In Nigeria, studies examining nanotoxicology are limited in number and scope. Although some work has explored antimicrobial effects and efficacy (Okorie *et al.,* 2025), comprehensive safety assessments evaluating long-term exposure, dose-response relationships, and impacts on human health and ecosystems remain scarce. Without robust toxicological data, it is difficult for regulatory agencies to establish safety thresholds, exposure limits, or risk management guidelines for nanoparticle applications in food, water, cosmetics, pharmaceuticals, agriculture, and industrial products.

Nanoparticles possess unique physicochemical properties that may influence how they interact with biological systems and environmental processes. Because of their extremely small size and large surface area, nanoparticles may behave differently from conventional materials when introduced into living organisms or ecological systems. These characteristics have led researchers to examine the possible health and environmental implications associated with the growing use of nanomaterials in different scientific and industrial applications. Within the Nigerian context, the expansion of nanotechnology research has also raised questions about how existing regulatory systems can address the emerging challenges associated with nanoscale technologies. Studies examining nanotechnology and human health in Nigeria have observed that while scientific interest in nanoscience is increasing, regulatory and legislative frameworks related to the technology are still developing (Etim, 2024)

Risk Assessment and Monitoring Challenges

Effective regulation of nanomaterials requires systematic risk assessment, including hazard identification, exposure assessment, dose-response evaluation, and risk characterization. However, Nigeria currently lacks institutional capacity, standardized testing protocols, and laboratory facilities dedicated to nano-specific safety evaluation. Many Nigerian research laboratories do not possess the instrumentation or expertise needed to measure nanoparticle behavior in biological and environmental matrices, such as determining biodistribution, persistence, and bioaccumulation patterns. This limitation makes it difficult to develop evidence-based safety policies or guidelines that can protect workers, consumers, and vulnerable ecosystems. Furthermore, there is no centralized system for monitoring the life cycle of nanomaterial products, from production to disposal, which could help identify potential points of exposure or environmental release. Without surveillance mechanisms and reporting standards, risks associated with nanoparticle use may go undetected or poorly understood until adverse effects emerge.

Public Awareness and Consumer Confidence

Another regulatory challenge is the low level of public awareness about nanotechnology and its potential risks and benefits among Nigerian consumers, industry stakeholders, and policymakers. Without clear communication strategies and labeling requirements, consumers may be unaware of whether products contain nanomaterials, how they function, or what precautions are recommended. This lack of transparency can undermine consumer trust, discourage responsible adoption of nanotechnologies, and increase vulnerability to unregulated or unsafe products. Enhancing public understanding of nanotechnology safety requires collaboration between regulators, researchers, industry groups, and civil society organizations to develop educational campaigns, safety guidelines, and risk communication tools. These efforts can help bridge the gap between scientific advancements and public perceptions of technology, ensuring that nanotechnology's benefits are realized without compromising health and environmental safety.

The Need for Comprehensive Regulation

To address regulatory and safety concerns, Nigeria would benefit from the development of nano-specific regulations and safety frameworks that:

i. Define nanomaterials and establish classification criteria for regulatory purposes.
ii. Create risk assessment protocols tailored to the unique behaviors of nanoparticles. iii. Mandate pre-market safety testing, labeling, and post-market surveillance.
iv. Strengthen institutional capacity and laboratory infrastructure for toxicological evaluation.
v. Promote industry compliance, transparency, and data sharing.
vi. Integrate public education and stakeholder engagement on safe nanotechnology use.

Such policies would help align Nigeria with international standards and best practices in nanotechnology governance while protecting public health and the environment.

4.4 Environmental and Ethical Issues

The rapid development and application of nanoparticles in Nigeria bring both environmental and ethical considerations that require careful evaluation. While nanoparticles offer significant advantages in medicine, agriculture, energy, and consumer products, their unique physicochemical properties, such as nanoscale size, high surface area, and enhanced reactivity--pose potential risks to ecosystems, human health, and societal norms (Abubakar *et al.,* 2025).

Environmental Concerns

Nanoparticles can enter soil, water, and air through industrial effluents, agricultural runoff, wastewater, and improper disposal of consumer products. Due to their high reactivity and small size, nanoparticles can interact with biological organisms in unpredictable ways, potentially leading to bioaccumulation, toxicity, and disruption of ecological balance (Mgadi *et al.,* 2024).

Discussions surrounding nanotechnology development have also drawn attention to the importance of considering environmental and societal implications alongside technological advancement. Studies examining nanotechnology development in Africa have noted that although the technology offers promising opportunities in areas such as water purification, disease control, and energy production, questions relating to environmental safety and responsible management of nanomaterials remain important areas of ongoing discussion (Musee et al., 2012). In Nigeria, the lack of comprehensive monitoring systems for nanoparticle release means that the long-term environmental impacts remain largely unknown. Research in Nigerian agricultural and water treatment contexts has shown that while nanoparticles improve soil fertility or remove pollutants from water, excessive or uncontrolled use may negatively affect soil microbial communities and aquatic ecosystems (Dayo-Olagbende *et al.,* 2025). For example, metal oxide nanoparticles, such as zinc oxide or iron oxide, can persist in soils and water bodies, potentially causing oxidative stress in non-target organisms, inhibiting microbial processes, and altering nutrient cycling. Without proper environmental risk assessment and management strategies, these applications may inadvertently compromise ecosystem sustainability.

Ethical Considerations

Ethical issues related to nanotechnology in Nigeria encompass human health, social justice, transparency, and informed consent. The incorporation of nanoparticles into food, medicine, cosmetics, and consumer products raises concerns about exposure to materials whose long-term effects are not fully understood (Okafor *et al.,* 2024). Nigerian researchers and policymakers face the ethical challenge of balancing innovation and societal benefit with precautionary principles to protect vulnerable populations from unintended harm. Access and equity also represent ethical concerns. The high cost and technical complexity of nanotechnology may limit participation and benefit to certain regions or socioeconomic groups, exacerbating technological inequities (Muhammad *et al.,* 2023). Ensuring that nanotechnology applications are developed inclusively, with considerations for rural communities, smallholder farmers, and marginalized populations, is essential to prevent unequal distribution of both benefits and risks. Another ethical dimension involves consumer awareness and labeling. Many Nigerian consumers may not be fully informed about the presence of nanoparticles in products or their potential effects, undermining informed decision-making. Transparency in labeling and public education are therefore crucial ethical obligations to ensure autonomy and safety in consumer choices (Abubakar *et al.,* 2025).

Mitigation and Governance Strategies

To address environmental and ethical challenges, Nigerian policymakers and researchers must adopt a holistic governance approach that integrates science, ethics, and policy. Key strategies include:

i. Developing environmental monitoring and risk assessment frameworks for nanoparticles in soil, water, and air.
ii. Implementing regulatory standards for safe production, use, and disposal of nanomaterials.
iii. Promoting public engagement, stakeholder consultations, and education campaigns to enhance awareness and informed decision-making.
iv. Encouraging ethical research practices, including human and ecological risk assessments, before commercialization of nanotechnology products.

v. Strengthening collaborations between industry, research institutions, and civil society to ensure responsible innovation aligned with national sustainability goals (Mgadi *et al.,* 2024; Friday *et al.,* 2025).

4.5 Public Awareness and Human Capacity Gaps

The successful adoption and sustainable development of nanotechnology in Nigeria are heavily influenced by the level of public awareness and the availability of a skilled workforce capable of conducting advanced research, implementing applications, and managing associated risks. Both factors are currently limiting the widespread utilization and societal acceptance of nanoparticles across healthcare, agriculture, environmental, industrial, and consumer sectors.

Public Awareness Challenges

Despite increasing research activity, the general Nigerian public remains largely unaware of nanotechnology and its potential applications. Limited media coverage, lack of educational outreach, and minimal integration of nanoscience into school and university curricula contribute to low understanding of both the benefits and risks associated with nanoparticles (Muhammad et al., 2023). As a result, consumers often make choices without full knowledge of whether products contain nanomaterials, how they function, or potential safety considerations. Low public awareness also affects acceptance of innovative technologies in sectors like healthcare and agriculture. For instance, nanoparticle-based water treatment systems or nano-formulated agrochemicals may be underutilized in rural and urban communities due to skepticism or limited understanding of their efficacy and safety (DayoOlagbende *et al.,* 2025). This knowledge gap not only impedes technology uptake but also increases vulnerability to misinformation, which can undermine trust in regulatory bodies, researchers, and commercial innovators.

Human Capacity Gaps

Nigeria's research and technical workforce in nanotechnology is relatively small compared to global standards. Nanotechnology is inherently multidisciplinary, requiring expertise in chemistry, physics, materials science, biology, engineering, and computational modeling. However, the number of Nigerian professionals trained in these areas--particularly in nanoparticle synthesis, characterization, application development, and toxicological evaluation, remains limited (Nnaji *et al.,* 2024). This shortage is exacerbated by the brain drain phenomenon, where skilled researchers migrate to countries with better infrastructure, funding, and professional opportunities, leaving local institutions under-resourced.

The limited human capacity also extends to technical support staff who are essential for operating and maintaining specialized instruments such as SEM, TEM, AFM, XRD, and FTIR, which are critical for nanoparticle research. Without sufficient skilled personnel, even available high-end equipment remains underutilized, slowing research progress and reducing the quality of outputs (Friday *et al.,* 2025).

Implications for Innovation and National Development

The combination of low public awareness and limited human capacity has direct implications for Nigeria's ability to translate nanotechnology research into practical innovations. Projects may stall at the experimental stage, and opportunities for commercialization, industrial collaboration, and societal benefit may be missed. Moreover, inadequate understanding of nanotechnology risks among the public and industry stakeholders increases the likelihood of improper handling, misuse, or exposure to potentially harmful nanoparticles, posing ethical and safety challenges (Abubakar *et al.,* 2025).

Strategies for Addressing Gaps

Addressing public awareness and human capacity gaps in Nigeria requires a multi-faceted approach:

i. Educational Integration: Introduce nanoscience and nanotechnology topics into secondary and tertiary curricula to build foundational knowledge and stimulate interest among students (Muhammad *et al.,* 2023).
ii. Training and Capacity Building: Establish postgraduate programs, workshops, and specialized certification courses to train researchers, engineers, and technical staff in nanoparticle synthesis, characterization, and application (Nnaji *et al.,* 2024).
iii. Public Engagement and Outreach: Conduct awareness campaigns, community workshops, and media initiatives to educate consumers about the benefits, risks, and safe use of nanotechnology-based products (Dayo-Olagbende *et al.,* 2025).
iv. Incentivizing Retention: Develop policies to retain skilled researchers in Nigeria through competitive salaries, research grants, and access to well-equipped laboratories (Friday *et al.,* 2025).
v. Collaboration and Partnerships: Encourage international and industry partnerships to provide exposure, technical training, and mentorship for Nigerian researchers while promoting knowledge transfer and local capacity development (Abubakar *et al.,* 2025).

5.0 FUTURE PROSPECTS AND CONCLUSION

5.1 Opportunities for Nanotechnology Development

Nanotechnology presents Nigeria with significant opportunities to accelerate economic growth, enhance scientific innovation, and address critical societal challenges. Despite the existing infrastructural, financial, and regulatory challenges highlighted in previous sections, the country's abundant natural resources, growing research community, and increasing interest in technological advancement provide a favorable environment for developing nanotechnology-based solutions across multiple sectors (Muhammad *et al.,* 2023).

Industrial and Economic Opportunities

Nanotechnology offers the potential to modernize Nigerian industries and enhance competitiveness in both domestic and international markets. For example, the integration of nanoparticles into manufacturing, construction, and materials engineering can produce stronger, lighter, and more durable materials, reducing production costs and energy consumption (Olatunji *et al.,* 2021). Nanocatalysts in oil refining and chemical production can increase efficiency, reduce waste, and improve environmental compliance, positioning Nigeria to derive greater value from its industrial and petrochemical sectors (Akinsipo, 2025). Moreover, nanoparticle-based innovations in energy and renewable technologies provide avenues to mitigate Nigeria's energy challenges. The development of nanostructured solar cells, supercapacitors, and batteries can improve energy storage, efficiency, and reliability, helping to address persistent power shortages while fostering sustainable industrial growth (Akinwale *et al.,* 2022). These innovations can stimulate entrepreneurship, create high-tech jobs, and promote local industries capable of producing advanced energy solutions.

Healthcare and Pharmaceutical Advancements

The medical and pharmaceutical sectors represent one of the most promising areas for nanotechnology in Nigeria. Nanoparticle formulations can improve drug delivery, enhance bioavailability, and reduce side effects, particularly in treating chronic diseases, infections, and cancer (Okorie *et al.,* 2025). Additionally, nanosensors and diagnostic tools can enable early disease detection, monitor health parameters in real time, and support personalized medicine initiatives. With growing public health demands and a need to strengthen Nigeria's healthcare system, these technologies offer substantial benefits for both patients and the broader healthcare infrastructure.

Agriculture and Food Security

Nigeria's large agricultural sector can benefit significantly from nano-enabled technologies. Nanoparticles can enhance the efficiency of fertilizers, pesticides, and soil amendments, improving crop yield and reducing environmental impact (Dayo-Olagbende *et al.,* 2025). Nano formulations can also help manage pests, control diseases, and extend the shelf life of perishable food products through advanced packaging and antimicrobial coatings. These applications present opportunities to enhance food security, increase farmer income, and support sustainable agricultural practices.

Environmental and Water Management

Nanotechnology provides innovative solutions for environmental protection and water treatment, key challenges in Nigeria. Nanomaterials such as titanium dioxide, iron oxide, and carbon-based nanoparticles have demonstrated effectiveness in removing heavy metals, organic pollutants, and pathogens from contaminated water sources (Friday *et al.,* 2025). The development of localized, nanoparticle-based water purification systems can improve access to clean drinking water, particularly in rural and underserved communities, thereby promoting public health and environmental sustainability.

Educational and Research Development

Nanotechnology also presents opportunities for capacity building and scientific advancement in Nigeria. The growing number of universities, research institutions, and collaborative initiatives provides a foundation for developing highly skilled researchers, technicians, and entrepreneurs (Nnaji *et al.,* 2024). With strategic investment in human capital, laboratory infrastructure, and international partnerships, Nigeria can become a regional leader in nanoscience research, fostering innovation ecosystems that generate intellectual property, patents, and commercialization opportunities.

Entrepreneurship and Technology Transfer

Finally, nanotechnology opens avenues for entrepreneurship and local innovation, allowing Nigerian startups and small enterprises to develop nano-enabled products and services across healthcare, agriculture, consumer goods, energy, and industrial applications. With appropriate support from government, academia, and industry, these enterprises can stimulate job creation, knowledge transfer, and technological self-reliance, reducing dependency on imported solutions and enhancing national competitiveness (Muhammad *et al.,* 2023).

While challenges in infrastructure, funding, regulation, and public awareness remain, Nigeria's abundant natural resources, human capital potential, and increasing research activity provide a solid foundation to harness nanotechnology's transformative potential. Strategic investment, capacity building, and policy support can convert these opportunities into tangible economic, societal, and environmental benefits, positioning Nigeria as a regional leader in nanotechnology innovation.

5.2 Policy and Research Recommendations

To fully harness the potential of nanoparticles in Nigeria, while mitigating associated risks and challenges, it is critical to implement strategic policies and research initiatives. Addressing gaps in infrastructure, funding, human capacity, public awareness, regulation, and environmental safety will provide a solid foundation for sustainable development in nanotechnology. The following recommendations are proposed based on recent research and national needs.

Strengthening Regulatory Frameworks

Nigeria should develop nano-specific regulations that govern the production, importation, use, labeling, and disposal of nanomaterials. Current chemical and pharmaceutical regulations often do not differentiate nanoparticles from their bulk counterparts, creating uncertainties in safety assessment and compliance (Okafor *et al.,* 2024). Key regulatory recommendations include:

i. Establishing a National Nanotechnology Safety and Standards Board to oversee all aspects of nanotechnology governance.
ii. Mandating pre-market toxicity testing and post-market monitoring of nanoparticle-containing products. iii. Requiring transparent labeling for consumer and pharmaceutical products containing nanoparticles.
iv. Developing environmental risk assessment protocols for the release of nanomaterials in industrial, agricultural, and consumer applications (Abubakar & Ishola, 2025).
v.

Increasing Funding and Investment in Nanotechnology

Sustainable development of nanoparticles in Nigeria requires long-term and dedicated funding. Both public and private sector investments are essential to support research infrastructure, equipment acquisition, human capital development, and technology commercialization. Policy recommendations include:

i. Allocating special grants for nanotechnology research through the Ministry of Science and Technology and research agencies such as NASENI.
ii. Encouraging public-private partnerships to co-fund research projects with industrial application potential. Creating innovation funds and incentives for startups developing nanoparticle-based products in healthcare, agriculture, energy, and consumer goods (Muhammad *et al.,* 2023).

Such initiatives will provide continuity for multi-year research projects and foster local innovation in nanoparticle technologies.

Enhancing Human Capacity and Technical Expertise

Nigeria's ability to conduct advanced nanotechnology research depends on skilled personnel and technical expertise. Recommendations to build human capacity include:

i. Expanding graduate and postgraduate nanotechnology programs in universities and research institutions.
ii. Organizing workshops, training, and certification programs for researchers, laboratory technicians, and industrial personnel.
iii. Establishing mentorship programs and international collaborations to facilitate knowledge transfer, skill development, and retention of trained researchers (Nnaji *et al.,* 2024).

Strengthening human capital will allow Nigerian researchers to conduct high-quality research, innovate responsibly, and bridge the gap between academic discoveries and industrial application.

Promoting Public Awareness and Education

Raising public awareness about nanoparticles and their potential benefits and risks is essential to encourage responsible adoption. Policy and research recommendations include:

i. Incorporating nanotechnology education into secondary and tertiary curricula to build foundational knowledge.
ii. Conducting public outreach campaigns via media, workshops, and seminars to explain nanoparticle applications, safety, and ethical considerations.
iii. Engaging civil society, industry stakeholders, and communities in discussions about nanotechnology to ensure societal acceptance and participatory decision-making (Dayo-Olagbende *et al.,* 2025).

Enhanced public understanding will reduce misinformation, build trust, and increase the adoption of safe nanotechnology innovations.

Encouraging Multidisciplinary and Applied Research

Nigeria should prioritize applied and multidisciplinary research that addresses local challenges while contributing to global nanotechnology advancement. Recommendations include:

i. Establishing centers of excellence for nanotechnology in strategic regions, equipped with advanced instrumentation for nanoparticle synthesis, characterization, and testing.
ii. Fostering collaboration between universities, research institutions, and industry to translate laboratory research into commercial products and sustainable technologies. iii. Supporting research on nanotoxicology, environmental impact assessment, and ethical implications to guide safe and responsible innovation (Friday et al., 2025).

A focus on applied research ensures that Nigeria can leverage nanoparticles for economic growth, environmental sustainability, and societal well-being.

Encouraging International Collaboration and Knowledge Transfer

Global collaboration can accelerate nanotechnology development in Nigeria by providing access to expertise, funding, and cutting-edge techniques. Recommended strategies include:

i. Partnering with international research institutes, universities, and development agencies for joint research projects.
ii. Facilitating researcher exchange programs and internships to build local capacity.
iii. Participating in global standardization and regulatory initiatives to align Nigerian nanotechnology policies with international best practices (Abubakar *et al.,* 2025).

Implementing these policy and research recommendations will create a robust ecosystem for nanoparticle development in Nigeria. By addressing regulatory gaps, funding limitations, human capacity shortages, public awareness deficits, and ethical and environmental concerns, Nigeria can maximize the benefits of nanotechnology while mitigating potential risks. Strategic interventions in these areas will enhance research outputs, drive innovation, and ensure that nanoparticle technologies contribute meaningfully to national development and societal welfare.

5.3 Potential Socioeconomic Impact

Nanotechnology has the potential to significantly influence Nigeria's socioeconomic landscape by driving innovation, creating employment, improving healthcare, enhancing agricultural productivity, and promoting sustainable development. Strategic development and responsible implementation of nanoparticles can address pressing national challenges, while also positioning Nigeria as a regional hub for advanced technology.

Economic Growth and Industrial Development

Nanotechnology can enhance industrial efficiency, product quality, and competitiveness, contributing to economic growth. Applications in manufacturing, construction, and materials engineering allow for lighter, stronger, and more durable products, reducing production costs and energy consumption (Olatunji *et al.,* 2021). Industries adopting nanoparticle-based solutions, such as nano catalysts in chemical production, nano-enhanced coatings, and advanced materials can increase productivity, reduce waste, and gain a competitive advantage in global markets (Akinsipo, 2025). In the energy sector, nanoparticles in solar cells, batteries, and supercapacitors can improve energy efficiency and storage capabilities. Enhanced access to energy supports industrial activities, attracts investment, and stimulates entrepreneurship, leading to job creation and revenue generation (Akinwale *et al.,* 2022). These innovations can also reduce Nigeria's dependence on imported technology and energy solutions.

Healthcare and Public Health Benefits

Nanotechnology has significant implications for healthcare and public health, which in turn impacts socioeconomic development. Nanoparticle-based drug delivery systems can improve therapeutic efficacy, reduce side effects, and enable targeted treatment for chronic diseases, infections, and cancer (Okorie *et al.,* 2025). Early detection and diagnostic tools based on nano sensors can reduce healthcare costs and improve patient outcomes. Improved healthcare efficiency supports workforce productivity, reduces disease-related economic losses, and strengthens Nigeria's human capital.

Agriculture and Food Security

Nanotechnology can enhance agricultural productivity and food security, a key socioeconomic concern in Nigeria. Nanoparticles can improve the efficiency of fertilizers, pesticides, and soil amendments, reducing crop losses and environmental impact (Dayo-Olagbende *et al.,* 2025). Advanced nanoparticle-based packaging can extend the shelf life of perishable foods, reduce post-harvest losses, and improve market access for farmers. These applications increase rural incomes, support economic diversification, and strengthen the resilience of the agricultural sector.

Environmental and Sustainability Impacts

Nanotechnology contributes to environmental protection and sustainable development, which indirectly influences socioeconomic progress. Nano-enabled water treatment systems, air purification technologies, and pollution remediation techniques help provide access to clean water, reduce disease incidence, and protect ecosystems (Friday *et al.,* 2025). Sustainable management of environmental resources reduces healthcare costs, supports community well-being, and fosters long-term economic stability.

Human Capacity and Employment Opportunities

The development of nanotechnology generates highly skilled employment opportunities in research, manufacturing, quality control, and regulatory compliance. Universities, research institutions, and startups focused on nanoparticle applications provide training and professional growth, creating a pool of skilled human capital (Nnaji *et al.,* 2024). This strengthens Nigeria's knowledge economy, promotes innovation-driven entrepreneurship, and reduces dependence on foreign expertise.

Equity and Inclusive Development

Nanotechnology has the potential to support inclusive socioeconomic development if policies ensure equitable access to its benefits. Applications in healthcare, agriculture, water treatment, and consumer products can improve living standards across rural and urban populations (Muhammad *et al.,* 2023). However, careful consideration of affordability, distribution, and public engagement is necessary to prevent disparities and ensure that marginalized communities also benefit from nanotechnology advancements.

The socioeconomic impact of nanoparticles in Nigeria is potentially transformative. By driving industrial growth, enhancing healthcare, improving agriculture, supporting environmental sustainability, and creating employment, nanotechnology can contribute to broad-based national development. To realize these benefits, strategic investment, regulatory oversight, human capacity development, and public engagement are essential to ensure that nanotechnology is applied safely, equitably, and effectively.

Conclusions

Nanotechnology, particularly the study and application of nanoparticles, presents immense potential for scientific, technological, and socioeconomic advancement in Nigeria. This review has highlighted the development of nanotechnology in the country, the types of nanoparticles studied, notable research findings, and the emerging applications across medical, agricultural, environmental, energy, industrial, and consumer sectors. At the same time, it has underscored the challenges and limitations that may hinder the sustainable adoption and impact of nanoparticles, including infrastructural gaps, funding and technical expertise shortages, regulatory and safety concerns, environmental and ethical considerations, and low public awareness (Muhammad *et al.,* 2023; Abubakar *et al.,* 2025).

Key Findings

Nigeria has made progressive strides in nanotechnology research, with increasing interest from universities, research institutions, and government agencies. Studies on metal oxide nanoparticles, carbon-based nanomaterials, and phytochemical-mediated nanoparticles demonstrate promising applications in healthcare, agriculture, water treatment, energy, and consumer goods (Okorie *et al.,* 2025; Dayo-Olagbende *et al.,* 2025). Government initiatives, such as support from NASENI and strategic research collaborations, indicate recognition of the potential economic and societal benefits of nanotechnology. Despite these advancements, the sustainability and impact of nanotechnology in Nigeria are constrained by several challenges. Limited research infrastructure and laboratory facilities hinder high-quality experimental work, while funding constraints and scarcity of skilled personnel restrict both the scope and continuity of research projects (Friday *et al.,* 2025; Nnaji *et al.,* 2024).

Regulatory and safety frameworks are currently insufficient to govern nanoparticle production, application, and disposal, raising concerns about public health, environmental safety, and ethical responsibility (Okafor *et al.,* 2024; Abubakar *et al.,* 2025).

Opportunities and Socioeconomic Potential

Despite these challenges, opportunities abound. Nanotechnology can drive industrial growth, improve healthcare outcomes, enhance agricultural productivity, and promote environmental sustainability (Muhammad et al., 2023; Akinwale et al., 2022). Strategic investments in research, human capital, regulatory frameworks, and public awareness can help Nigeria leverage its natural resources, growing research capacity, and entrepreneurial potential to become a regional leader in nanotechnology innovation. Socioeconomic impacts, such as job creation, technological self-reliance, and equitable access to advanced solutions, can substantially contribute to national development (Okorie et al., 2025; Dayo-Olagbende et al., 2025).

Recommendations for Sustainable Development

To maximize benefits and mitigate risks, Nigeria should focus on:

i. Strengthening regulatory frameworks tailored to nanomaterials and their unique properties.
ii. Increasing research funding and promoting public-private partnerships to support innovation and commercialization.
iii. Enhancing human capacity through targeted education, training, and retention strategies.
iv. Promoting public awareness and stakeholder engagement to encourage safe adoption and responsible use of nanoparticles.
v. Fostering applied and interdisciplinary research to address local challenges and global competitiveness (Abubakar & Ishola, 2025; Friday *et al.,* 2025; Nnaji *et al.,* 2024).

By adopting these measures, Nigeria can ensure that its nanotechnology sector develops sustainably, safely, and inclusively, transforming scientific potential into tangible economic and social benefits.

Finally, while challenges remain, nanotechnology offers Nigeria a transformative opportunity. With coordinated efforts from government, academia, industry, and civil society, nanoparticles can play a pivotal role in advancing healthcare, agriculture, industry, energy, and environmental sustainability. Strategic policy implementation, research investment, capacity building, and public engagement are crucial to realize the full potential of nanotechnology, positioning Nigeria as a forward-looking nation capable of leveraging cutting-edge science for inclusive and sustainable national development (Muhammad *et al.,* 2023; Abubakar *et al.,* 2025).

References

Adegbola, R. Q., Atanda, S. A., Jimoh, M. O., Okparavero, N. F., Aremu, M. B., Ajayi, O. A., Onyegbula, A. F., Okunlade, A. F., & Adegbola, J. A. (2024). Nanobiopesticides in post-harvest management of insect pests of crops: Present status, challenges and prospects – A review. FUDMA Journal of Sciences, 8(4), 40–54.

Adekola, F. A., Hodonou, D. S. S., & Adegoke, H. I. (2022). Removal of heavy metals from aqueous solutions using nanoparticle-based adsorbents: Implications for water treatment in developing countries. Journal of Environmental Chemical Engineering, 10(4), 107789.

Abubakar, S. J., & Ishola, I. O. (2025). Nanotoxicology: Balancing risks and opportunities in nanotechnology. The Nigerian Journal of Pharmacy.

Agbaje, A., Moyosore Muhammed, M., Bello, S. A., et al. (2023). Synthesis of silver nanoparticles and antimicrobial activities of methanolic extract of Azadirachta indica leaf against clinical isolates. FUDMA Journal of Sciences.

Ali Assim Adul-Rasool, D. M. A., Haider Kamil Zaidan, Ahmed Mahdi Rheima, Zainab T. Al-Sharify, Srwa Hashim Mohammed, Ehsan kianfar,. (2024). 0,1,2,3D nanostructures, types of bulk nanostructured materials, and drug nanocrystals: An overview. Cancer Treatment and Research Communications, 40. doi: https://doi.org/10.1016/j.ctarc.2024.100834

Ali, S. B., Mahmoud, A. A., Ajiya, D. A., Chindo, I. Y., & Musa, B. (2025). Eco-friendly fabrication and characterization of ZnO nanoparticles, PANI, and ZnO-PANI nanocomposites. UMYU Scientifica. 4(3), 448–457.

Ali, S. B., Mahmoud, A. A., Ajiya, D. A., Chindo, I. Y., & Musa, B. (2025). Eco-friendly fabrication and characterization of ZnO nanoparticles, PANI, and ZnO-PANI nanocomposites. UMYU Scientifica, 4(3), 448–457.

Atanda, S. A., Shaibu, R. O., & Agunbiade, F. O. (2025). Nanoparticles in agriculture: Balancing food security and environmental sustainability. Discover Agriculture, 3(1)

Akinsipo, O. B. (2025). Recent advances in the synthesis of metal nanoparticles: A comparative review of physical, chemical and biological methods. Journal of Science and Information Technology, 19(1), 304–319.

Bawoke Mekuye, B. A. (2023). Nanomaterials: An overview of synthesis, classification, characterization, and applications. Nano Select, 4(8). doi: https://doi.org/10.1002/nano.202300038

Billik, O., et al. (2025). Evaluation of the mechanochemical synthesis of ZnO nanoparticles as a potential treatment technology for restaurant wastewater discharge within Awka Capital City, Nigeria. International Journal of Research and Innovation in Applied Science (IJRIAS).

Dayo-Olagbende, O. G., Babadele, D. O., Sanni, K. O., Adetimehin, K. M., & Ewulo, B. S. (2025). Hydrological properties of agricultural soil under treatment with different levels of biochar-based nanoparticle. Nigerian Journal of Technology.

Ejeta, K. (2017). Impact of nanotechnology in nigeria: a short survey. International Journal of Biosensors & Bioelectronics, 2(5). doi: https://doi.org/10.15406/IJBSBE.2017.02.00035

Ekwumemgbo, P. A., Shallangwa, G. A., Okon, I. E., & Awodi, I. (2025). Green synthesis and characterization of iron oxide nanoparticles using Prosopis africana leaf extract. Communication in Physical Sciences.

Esfandiar, F. R. a. N. (2021). Liposomal Nanomedicine: Applications for Drug Delivery in Cancer Therapy. Nanoscale Research Letters. doi: https://doi.org/10.1186/s11671-021-03553-8

Freitas de Freitas, L., Varca, G. H. C., Dos Santos Batista, J. G., & Benevolo Lugao, A. (2018). An Overview of the Synthesis of Gold Nanoparticles Using Radiation Technologies. Nanomaterials, 8(11). doi: https://doi.org/10.3390/nano8110939

Friday, C., Igwe, O. U., & Nnaji, J. C. (2025). Nanoremediation research in Nigeria: A review. Communication in Physical Sciences.

ICEESR Materials and Nanoscience Group. (n.d.). Materials and nanoscience research focus. Institute for Continuous and Emerging Scientific Research. Retrieved from https://iceesr.org.ng/research/materials-andnanoscience/.

Idris, N. U., Faruk, A. U., & Yerima, M. I. (2025). Recent advances in the delivery, mechanism of action and antibacterial activity of silver nanoparticles. UMYU Journal of Microbiology Research.

Igiebor, F. A., Ikhajiagbe, B., & Asia, M. (2023). Green nanotechnology: A modern tool for sustainable agriculture in Nigeria-A review. International Journal of Horticultural Science and Technology, 10(3), 269-286.

Igiebior, F. A., & Ikhajiagbe, B. (2023). Assessment of Zn, Cu and Mn nanoparticle usage on the growth and yield of rice. Studia Universitatis "Vasile Goldiş", Seria Ştiinţele Vieţii.

Jani, M., Arcos-Pareja, J. A., & Ni, M. (2020). Engineered Zero-Dimensional Fullerene/Carbon Dots-Polymer Based Nanocomposite Membranes for Wastewater Treatment. Molecules, 25(21). doi: https://doi.org/10.3390/molecules25214934

Khairul Basyar Baharudin, N. A. a. D. D. (2021). Synthesis of raspberry-like structure zinc oxide nanoparticles via glycol-solvothermal, low-temperature solvothermal and coprecipitation methods. Comptes Rendus Chimie, 24(1). doi: https://doi.org/10.5802/crchim.53

Khan, Y., Sadia, H., Ali Shah, S. Z., Khan, M. N., Shah, A. A., Ullah, N., Ullah, M. F., Bibi, H., Bafakeeh, O. T., Khedher, N. B., Eldin, S. M., Fadhl, B. M., & Khan, M. I. (2022). Classification, Synthetic, and Characterization Approaches to Nanoparticles, and Their Applications in Various Fields of Nanotechnology: A Review. Catalysts, 12(11). doi: https://doi.org/10.3390/catal12111386

Ladoke Akintola University of Technology Nanotechnology Research Group. (2025). Nanotechnology in the 4IR: Conference and policy advocacy. Guardian Nigeria.

LAUTECH Nanotechnology Research Group (NANO$^+$). (n.d.). Who we are. Ladoke Akintola University of Technology Nanotechnology. Retrieved from https://lautechnanotech.com/

Mgadi, H., Ndaba, B., Roopnarain, A., Rama, N., & Adeleke, S. (2024). Nanoparticles in agriculture: Plantassociated microorganisms and sustainable practices. Frontiers in Sustainable Food Systems.

Ministry of Innovation, Science and Technology. (2024). Stakeholders meeting to develop SOPs for chemical and nanotechnology policies. Science Nigeria Report.

Moses, E., Thliza, B. A., & Khan, I. Z. (2025). Biotechnical synthesis and characterization of silver nanoparticles (AgNPs) from Moringa oleifera leaves in Biu, Borno State, Nigeria. BJSTR.

Muhammad, S., Arudi, T., & Arogundade, O. (2023). Emerging trends in nanotechnology research and innovation in Nigeria. Nigerian Journal of Technological Development, 20(2), 45–56.

Nanotechnology Experts in Nigeria. (n.d.). Profiles of researchers and affiliations. Nanotechnology Blog. Retrieved from https://nanotechnology.blog/experts/nigeria/nanotechnology-experts

NASENI Centre of Excellence in Nanotechnology and Advanced Materials. (n.d.). Nanotechnology programme overview. National Agency for Science and Engineering Infrastructure. Retrieved from https://naseni.dhagun.com.ng/institutes/center_details/1/co_ex_na/

National Information Technology Development Agency. (2023). 3 Million Technical Talent Programme (3MTT).

National Board for Technology Incubation. (2025). Innovation challenges and incubation frameworks. Technext Report.

National Agency for Science and Engineering Infrastructure. (n.d.). About NASENI's mission and mandate. NASENI Official Website.

National Agency for Science and Engineering Infrastructure. (2025). NASENI secures investment commitments and market-ready products under federal policy direction. Guardian Nigeria.

Negrescu, A. M., Killian, M. S., Raghu, S. N. V., Schmuki, P., Mazare, A., & Cimpean, A. (2022). Metal Oxide Nanoparticles: Review of Synthesis, Characterization and Biological Effects. Journal of Functional Biomaterials, 13(4). doi: https://doi.org/10.3390/jfb13040274

Nnaji, P. C., Nnaji, J. N., Zakari, S., Amuji, D. N., & Ogunlana, O. O. (2024). Review of magnetic nanoparticles: From synthesis and design to applications. UMYU Scientifica, 3(4), 67–83.

Nnamdi Azikiwe University researchers. (2025). Evaluation of the mechanochemical synthesis of ZnO nanoparticles as a potential treatment technology for restaurant wastewater discharge within Awka Capital City, Nigeria. International Journal of Research and Innovation in Applied Science (IJRIAS).

Ogbeide, O. K., Ndip, L. O., Udezi, O. C., Onaiwu, G. E., & Ifijen, I. H. (2025). Antimicrobial activity of synthesized zinc oxide-carbonized Moringa oleifera leaf nanocomposite. Tropical Journal of Chemistry.

Okafor, C. G. (2025). Emerging frontiers of nanotechnology in biomedical engineering: Innovations and clinical applications. Advance Journal of Science, Engineering and Technology.

Okonkwo, C. C., Edoziuno, F., & Orakwe, L. C. (2020). Environmental Nano-remediation in Nigeria: A Review of its potentials. Algerian Journal of Engineering and Technology, 3, 043-057.

Okorie, H. N., Okorie, C. P., & Ikeh, G. O. (2025). Phytochemical-mediated ZnO nanoparticles from Chromolaena odorata: Structural characterization and antimicrobial efficacy against multidrug-resistant clinical isolates, Nigeria. Journal of Pharmaceutical Research International, 37(10), 86–105.

Oluwaseun, A. O., Adeyemi, O. G., & Lawal, A. A. (2023). Green synthesis of silver nanoparticles and their antimicrobial applications in water treatment. Nigerian Journal of Science, 57(1), 112–121.

Onu, O. (2025). Federal Government must embrace new and emerging technologies. Federal Ministry of Information and National Orientation.

Onu, O. (2020). FG to domesticate nanotechnology to enhance socioeconomic growth. Independent Newspaper Nigeria.

Ovenseri, A. C., & Johnbull, O. A. (2023). Formulation of silver nanoparticles from the leaves extract of Vernonia amygdalina: Antibacterial and antioxidant effects. The Nigerian Journal of Pharmacy.

Ovonramwen, O. B., Nwaogu, N., Okunzuwa, I. G., & Omoruyi, U. (2025). Green synthesis and characterization of zinc oxide nanoparticles using Jatropha curcas for enhanced antibacterial potential.
Walisongo Journal of Chemistry.

Oyelaja-Akinsipo, O. B., Dare, E. O., Oladoyinbo, F. O., et al. (2025). Nanoemulsion: A promising and novel nanotherapeutic vehicle for transdermal drug delivery application. Journal of Chemical Society of Nigeria.

Patani, B. O., Jackson, T. C., Otafu, C. O., et al. (2024). Characterisation and surface plasmon resonance of omeprazole loaded silver nanoparticles. Nigerian Journal of Pharmaceutical and Applied Science Research, 13(2).

Rajiv Gandhi, B. V., Pune, Maharashtra. (2021). Nanoparticles: Properties, Applications and Toxicities. IJISET - International Journal of Innovative Science, Engineering & Technology, 8(5).

Salau, S. J. (2025, October 21). NANO+ advocates strategies to move research findings from lab to market. BusinessDay Nigeria.

Saravanakumar, S. A. M. E. a. M. P. (2017). A review on the classification, characterisation, synthesis of nanoparticles and their application. IOP Conference Series: Materials Science and Engineering, 263(3). doi:10.1088/1757-899X/263/3/032019

Shehu, A., Oluwole, O. J., & Uduma, A. (2025). Green synthesis, optimization, and characterization of copper nanoparticles using selected plant seed extracts. UMYU Journal of Microbiology Research.

Sirajo, S. A., Kwon-Ndung, E. H., Mshelmbula, B. P., Mustafa, Y. S., Ilyas, S. D., Hudu, M. A., Zakari, S. A., & Ekpo, U. E. (2024). Yield variability studies and proximate analysis of two varieties of maize (Zea mays L.) exposed to iron oxide nanoparticles. Proceedings of the Faculty of Science Conferences.

Toumey, C. (2008). Reading Feynman Into Nanotechnology: A Text for a New Science. Techne: Research in Philosophy & Technology, 12(3).

University of Nigeria, Nsukka. (n.d.). Drug Delivery and Nanotechnology Research Unit (RUNDD). Retrieved from https://www.unn.edu.ng/drug-delivery-and-nanotechnology-research-unit-rundd/

Woo Yeup Jeong, M. S. K., Haeni Lee, Jong Hun Lee, Jeesu Kim ,Dong-Wook Han and Ki Su Kim (2021). Recent Trends in Photoacoustic Imaging Techniques for 2D Nanomaterial-Based Phototherapy. Biomedicines. doi: https://doi.org/10.3390/biomedicines9010080

Bayda, S., Adeel, M., Tuccinardi, T., Cordani, M., & Rizzolio, F. (2019). The history of nanoscience and nanotechnology: From chemical–physical applications to nanomedicine. *Molecules, 24*(1), 112. https://doi.org/10.3390/molecules24010112

Binnig, G., Quate, C. F., & Gerber, C. (1986). Atomic force microscope. *Physical Review Letters, 56*(9), 930–933 https://doi.org/10.1103/PhysRevLett.56.930

Feynman, R. P. (1959). *There's plenty of room at the bottom.* California Institute of Technology. https://calteches.library.caltech.edu/47/2/1960Bottom.pdf

Iijima, S. (1991). Helical microtubules of graphitic carbon. *Nature, 354*, 56–58. https://doi.org/10.1038/354056a0

Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F., & Smalley, R. E. (1985). C60: Buckminsterfullerene. *Nature, 318*, 162–163. https://doi.org/10.1038/318162a0

Malik, S., Muhammad, K., & Waheed, Y. (2023). Emerging applications of nanotechnology in healthcare. *Frontiers in Pharmacology, 14*. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10536529/

National Nanotechnology Initiative. (2000). *National nanotechnology initiative: Leading to the next industrial revolution.* https://www.nano.gov/sites/default/files/pub_resource/nni_implementation_plan_2000.pdf

National Nanotechnology Initiative. (n.d.). *Applications of nanotechnology.* https://www.nano.gov/about-nanotechnology/applications-nanotechnology/

Cuenya, B. R. (2010). Synthesis and catalytic properties of metal nanoparticles: Size, shape, support, composition, and oxidation state effects. *Thin Solid Films, 518*(12), 3127–3150. https://doi.org/10.1016/j.tsf.2009.11.075

Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *Journal of Nanobiotechnology, 20*, 262. https://doi.org/10.1186/s12951-022-01477-8

Kelly, K. L., Coronado, E., Zhao, L., & Schatz, G. C. (2003). The optical properties of metal nanoparticles: The influence of size, shape, and dielectric environment. *Journal of Physical Chemistry B, 107*(3), 668–677. https://doi.org/10.1021/jp026731y

Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry, 12*(7), 908–931. https://doi.org/10.1016/j.arabjc.2017.05.011

Kolhatkar, A. G., Jamison, A. C., Litvinov, D., Willson, R. C., & Lee, T. R. (2013). Tuning the magnetic properties of nanoparticles. *International Journal of Molecular Sciences, 14*(8), 15977–16009. https://doi.org/10.3390/ijms140815977

Wu, Q., et al. (2020). Mechanical properties of nanomaterials. *Nanotechnology Reviews, 9*, 259–273. https://doi.org/10.1515/ntrev-2020-0021

Abuzeid, H. M., Julien, C. M., Zhu, L., & Hashem, A. M. (2023). Green synthesis of nanoparticles and their energy storage, environmental, and biomedical applications. *Crystals, 13*(11), 1576. https://doi.org/10.3390/cryst13111576

Ealias, A. M., & Saravanakumar, M. P. (2017). A review on the classification, characterisation, synthesis of nanoparticles and their application. *IOP Conference Series: Materials Science and Engineering, 263*, 032019. https://doi.org/10.1088/1757-899X/263/3/032019

Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. *Journal of Nanobiotechnology, 20*, 262. https://doi.org/10.1186/s12951-022-01477-8

Osman, A. I., Zhang, Y., Farghali, M., Rashwan, A. K., Eltaweil, A. S., Abd El-Monaem, E. M., Mohamed, I. M. A., Badr, M. M., Ihara, I., Rooney, D. W., & Yap, P.-S. (2024). Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review. *Environmental Chemistry Letters, 22*, 841–887. https://doi.org/10.1007/s10311-023-01682-3

Patil, N., Bhaskar, R., Vyavhare, V., Dhadge, R., Khaire, V., & Patil, Y. (2021). Overview on methods of synthesis of nanoparticles. *International Journal of Current Pharmaceutical Research, 13*(2), 11–16. https://doi.org/10.22159/ijcpr.2021v13i2.41556

Awote, O. K., Ojekale, A. B., & Kazeem, M. I. (2023).
Green synthesis of silver nanoparticles using *Jatropha tanjorensis* extracts and evaluation of their antidiabetic, antiglycation, antioxidant, and anti-inflammatory activities. *Journal of Research and Review in Science, 10*(1), 180–193. https://doi.org/10.36108/jrrslasu/3202.01.0180

Awote, O. K., Ojekale, A. B., & Kazeem, M. I. (2024).

Antidiabetic, antioxidant, antiglycation and anti-inflammatory potentials of green-synthesized silver nanoparticles using *Telfairia occidentalis*. *Letters in Applied NanoBioScience, 13*(1), 041. https://doi.org/10.33263/LIANBS131.041

Ojewumi, A. W., Ojediran, J. O., Omodara, M. A., & Adewumi, A. W. (2025). Growth and production of water stress indicators modified by zinc oxide nanoparticles as nanofertilizers under water-regulated conditions on tomatoes (*Solanum lycopersicum*). *Plant Nano Biology, 3*, 100168. https://doi.org/10.1016/j.plana.2025.100168

Ojewumi, A. W., Ojediran, J. O., Omodara, M. A., & Adewumi, A. W. (2026). Characterization and modulatory influence of flora-based zinc oxide nanoparticles on morpho-physiological and biochemical changes in eggplant. *BMC Agriculture*. https://doi.org/10.1186/s44399-025-00028-4

Bankole, M. T., Tijani, J. O., Mohammed, I. A., & Abdulkareem, A. S. (2014). A review on nanotechnology as a tool of change in Nigeria. *Scientific Research and Essays, 9*(8), 213–223. https://doi.org/10.5897/SRE2013.5704

Etim, M. (2024). Nanotechnology and human health: Bioethical challenges within the Nigerian context. *European Journal of Public Health Studies, 7*(2), 39–52. https://doi.org/10.46827/ejphs.v7i2.178

Lateef, A. (2022). Rusty gold in Nigeria: Untapped advances in nanotechnology. *South African Journal of Science, 118*(3/4). https://doi.org/10.17159/sajs.2022/11870

Musee, N., Foladori, G., & Azoulay, D. (2012). *Social and environmental implications of nanotechnology development in Africa*. CSIR / IPEN / ReLANS.

By checking the following box, the senior author acknowledges that they and the other authors have read, understood, and complied with the Instructions to Authors (ItA).

☐