**ISSN 1840-4855**
**e-ISSN 2233-0046**

**Review article**
**http://dx.doi.org/10.70102/afts.2025.1834.1363**

# PROPERTIES, SYNTHESIS, AND APPLICATIONS OF NANOMATERIALS: FOCUS ON METAL OXIDE NANOPARTICLES

Dr. Anil Kumar[1], Dr. Swati[2], Niharika[3*]

*[1]Associate Professor, Bharati Vidyapeeth's College of Engineering, New Delhi, India. e-mail: dranilchhikara@gmail.com, orcid: https://orcid.org/0009-0000-8333-4337*
*[2]Assistant Professor, Department of Chemistry, Baba Mastnath University, Rohtak, Haryana, India. e-mail: shswati2@gmail.com, orcid: https://orcid.org/0000-0002-6422-5183*
*[3*]Research Scholar, Department of Chemistry, Baba Mastnath University, Rohtak, Haryana, India. e-mail: niharikaniharika985@gmail.com, orcid: https://orcid.org/0009-0007-8075-1785*

***Received: October 17, 2025; Revised: November 22, 2025; Accepted: December 18, 2025; Published: December 30, 2025***

SUMMARY

Nanoscience and nanotechnology transformed material science with the introduction of nanomaterials that have special physical, chemical, optical, and mechanical characteristics because of their tiny size on the nanoscale. The materials have superior surface areas, quantum imagery, and unique electrical properties when compared to bulk materials, which are indispensable in different industrial uses. The paper provides an overview of the synthesis, properties, and various applications of nanomaterials, with particular reference being given to metal oxide nanoparticles. The metal oxides, including copper oxide (CuO), tin oxide (SnO2), titanium dioxide (TiO2), and zirconium oxide (ZrO2), have received a lot of interest because of their electronic structures and versatile applications in the areas of energy storage, environmental monitoring, medicine, and construction. These synthesis methods, such as top-down and bottom-up methods, including sol-gel, co-precipitation, and chemical vapor deposition, are discussed in detail, and their effects on the material properties of these nanoparticles are highlighted. In addition, the paper provides an exploration of the general uses of metal oxide nanoparticles in solar cells, sensors, fuel cells, photocatalysis, and optoelectronic devices. Associated with the booming innovations in the nanotechnology sector, the metal oxide nanoparticles will spearhead renewable energy, healthcare, and environmental sustainability. However, this has to be combated with issues like scalability, cost-effectiveness, and regulatory issues before they can be fully utilized. The paper also concludes with a future perspective of nanomaterials research, which has seen new trends and the search for green and sustainable ways of producing nanomaterials.

Key words: *nanoscience, nanomaterials, nanoscale, nanotechnology, metal oxide nanoparticles, quantum effects, surface area, applications of nanomaterials.*

## INTRODUCTION

The development, analysis, exploration, and use of materials at the nanoscale are the primary focuses of nanoscience and nanotechnology, which are related fields of study that are considered to be specialist. In order to facilitate communication between individual molecules and massive bulk systems, nanostructures are used. Clusters, quantum dots, nanocrystals, nanowires, and nanotubes are the components that make up single nanostructures [21]. On the other hand, a grouping of these nanostructures includes arrays, assemblies, and superlattices that are constructed from the individual nanostructures. Nanoscale materials are a collection of materials which have one or more dimensions under approximately 100 nanometres. One nanometre is equal to one millionth of a millimetre, which means that it is about 100,000 times smaller than the width of a human hair.

The field of nanoscience and its associated technologies is an expanding domain of research that is evolving swiftly. For the past five decades, nanomaterials have captivated researchers due to their fascinating characteristics. In the realm of nanotechnology and nanoscience, there exists a dual focus: the initial aspect revolves around the exploration of novel materials exhibiting diverse properties, while the subsequent aspect pertains to the modelling and manipulation of substances at the nanometre scale, catering to a broad spectrum of applications. It is well known that nanomaterials (materials or substances whose dimensions are at least 100 nm long; 1 to 100 nm long) exhibit very different physical, chemical, mechanical, optical, and electrical properties in comparison to their bulk analogs [1][2]. The interactions between the nanoparticles and the surrounding environment are increased, and the size and shape parameters have an impact on the characteristics at the nanoscale since both influences increase the surface area and the quantum size effect. Nanomaterials have been utilised across a multitude of fields, including but not limited to solar cells [3][4], white pigments in paints [5], cosmetics [6][7], fuel cells [8][9], an array of sensors [10][11][12], catalysts [14][15], and optoelectronic devices [16][17].

As new growth technologies emerge, a diverse array of nanomaterials with various morphologies has become available, including spherical nanoparticles, nanorods, nanowires, nanotubes, nanobelts, nanorings, and tetrapods, each contingent upon the specific synthetic method employed [18]. Based on the properties of the substance, there are a couple of distinct types of nanoparticles, such as metallic, polymeric, metal oxide, and carbon nanostructures [20]. Among them, metal oxide nanoparticles exhibit unique structural, chemical, electrical, and optical properties due to their extraordinary electronic configuration and surface energy, which vary according to their sizes and shapes [19].

1. The review of the different syntheses of metal oxide nanoparticles (CuO, SnO2, TiO2, ZrO2) and their effects on properties are also discussed in the paper, which sheds some light into the methods of characterisation such as XRD, SEM and UV-Vis spectroscopy.

2. It encompasses the broad-based uses of such nanoparticles in energy, environmental clean-up, and biomedicine with emphasis laid on photocatalysis, solar cells, sensors, and water purification.

3. Future research directions are also presented in the paper, including a necessity of sustainable synthesis methods, overcoming the issues of scalability, and the safety and biocompatibility of metal oxide nanoparticles used in medicine.

The paper begins as follows: Section 1 gives an introduction to nanoscience and nanotechnology, giving an overview of nanomaterials and their peculiarities at the nanoscale. Section 2 outlines a literature review, which reveals the current developments in the synthesis and the application of metal oxide nanoparticles. Section 3 is a categorization of nanomaterials in terms of zero-dimensional, one-dimensional, and two-dimensional, and outlines the structural and functional properties. Section 4 discusses the significance of nanomaterials and their possible use in different applications. In section 5, attention is paid to metal oxide nanoparticles, their synthesis mechanisms, properties, applications, and the comparison of various metal oxides. Section 6 is a summary of the paper, where the main results are summarized, and the research directions are suggested.

LITERATURE SURVEY

In the recent past, metal oxide nanomaterials have undergone a lot of improvement in their synthesis as well as their use. There has been a growing interest among researchers in coming up with green and environmentally friendly synthesis processes that involve the use of biological agents, such as plant extracts or waste materials, to synthesize nanoparticles. Such processes are becoming popular because they are less toxic, less expensive, and have minimal environmental effects as compared to the old chemical processes [22]. Besides the conventional methods of synthesis, alternative methods like microwave-induced solution combustion and polymer coating have been considered to enhance the stability of nanoparticles, uniformity, and their performance. The developments have increased the range of possible applications of metal oxide nanoparticles in other areas of the world, such as energy, water remediation, biomedical equipment, and environmental monitoring.

Moreover, recent studies have extended the limits of metal oxide nanoparticles in the environment and energy fields, especially in the degradation of pollutants, energy storage, and sensor devices [13]. Multifunctional devices and smart materials have become a possibility with the creation of hybrid nanomaterials, e.g., polymer-coated nanoparticles. There is an increasing trend in the integration of these nanoparticles in areas of application such as catalysis, sensing, and antimicrobial therapy, and a greater emphasis on the optimization of the nanoparticles' performance in any application. But with these materials struggling to live up to expected hype, there is a growing concern over the need to look at issues that are associated with the environmental effects and sustainability of these materials, and therefore, the future of metal oxide nanomaterials is both technologically and environmentally sustainable.

Besides their increasing uses, exploration of metal oxide nanomaterials has also increased in the biomedical sector, where their special qualities allow to provide opportunities in drug delivery, diagnostics, and targeted therapy. The researchers are also putting the metal oxide nanoparticles to use due to their capacity to interact with the biological systems at the cellular level to allow therapeutics to be delivered precisely to the tissues or organs. This can be of great consequence to cancer therapy, tissue engineering, and imaging technologies. What is more, the progress of nanomaterials safety has taken center stage, and current research on the subject has been directed towards their biocompatibility, toxicity, and the possible long-term effects on the organisms. The interface between these nanomaterials and the biological systems will be essential as the demand for functional and sustainable nanomaterials persists in increasing to ensure they are safely integrated into the medical and health uses. The current rate of such developments places metal oxide nanoparticles as the major players in the future of technological and healthcare innovations.

Metal oxide nanoparticles have great potential in a number of areas, such as energy, environmental remediation, and biomedicine. Although the current developments in the sustainable synthesis and material versatility are very promising, future studies should aim at scalability, biocompatibility, and reducing the environmental impact. It will be important to maintain a balance between performance and safety so that they can be successfully implemented in practice.

“CLASSIFICATION OF NANOMATERIALS

Nanomaterials are divided into three distinct categories (illustrated in Figure 1). Here is the list.

1. Zero-dimensional, e.g., nanoparticles and clusters of particles
2. One-dimensional, e.g., nanofibers, nanowires, and nanorods
3. Two-dimensional, e.g., nanofilms, nanolayers, and nano coatings.

Nanomaterials may manifest in various configurations, including singular, fused, aggregated, or agglomerated forms, exhibiting shapes that are spherical, tubular, or irregular. Typical varieties of nanomaterials encompass nanotubes, quantum dots, and fullerenes. Nanomaterials exhibit distinct physical and chemical properties compared to conventional bulk materials.

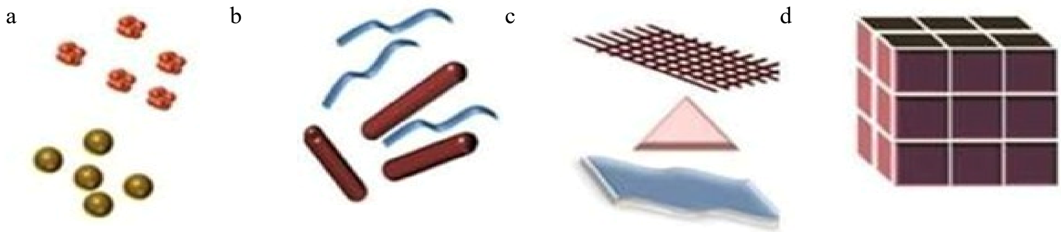


Figure 1. Classification of Nanomaterials (a) 0D spheres and clusters, (b) 1D nanofibers, wires, and rods, (c) 2D films, plates, and networks, (d) 3D nanomaterials [1]

**Zero-dimensional (0-D) Nanomaterials**

When the three dimensions are assessed at the nanoscale, specifically where no dimension exceeds 100 nm, the materials are referred to as Zero-Dimensional Nanomaterials (illustrated in Figure 2). For instance: nanoscopic particles. Nanoparticles may exist in either an amorphous state or a crystalline form, which can be categorised as single crystalline or polycrystalline. It could consist of either individual or multiple chemical components. Nanoparticles can display a multitude of shapes and configurations. It may be composed of metal, ceramic materials, or polymers.

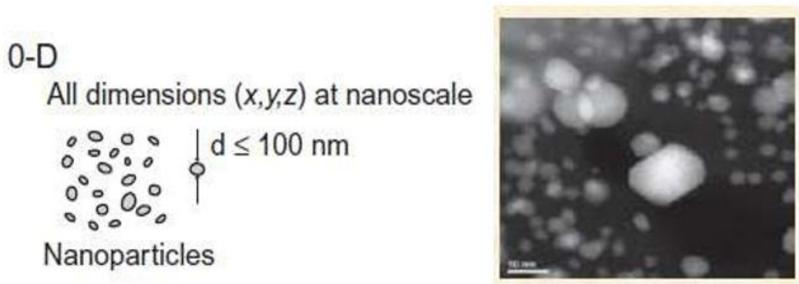


Figure 2. Zero-dimensional nanomaterials [1]

**One-Dimensional Nanomaterials**

One-dimensional nanomaterials are characterised by having only a single dimension that extends beyond the nanoscale, resulting in nanomaterials that resemble needle-like structures (illustrated in Figure 3), such as nanoscale tubes, nanostructured rods, and nanostructured wires. One-dimensional nanomaterials may exhibit characteristics of metals, ceramics, or polymers. They may exist in an amorphous form or as crystalline structures, as single crystals or polycrystalline aggregates, and can be either chemically pure or contain impurities.

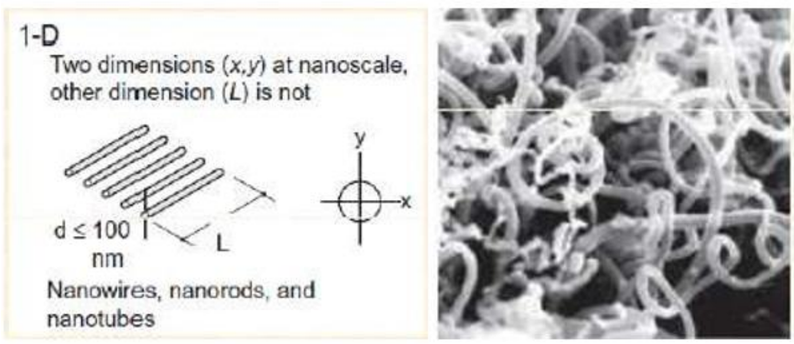


Figure 3. Dimensional nanomaterials [1]

**Two-Dimensional Nanomaterials**

Within this course, two of the dimensions extend beyond the nanoscale spectrum and display flat, plate-like forms. For instance: nanostructured films, nanoscale layers, and nano-coatings. Two-dimensional nanomaterials may exist in either an amorphous or crystalline state, and they can consist of a diverse range of chemical compositions. Two-dimensional nanomaterials (illustrated in Figure 4). These can exist as either single-layer or multilayer configurations applied onto a substrate.

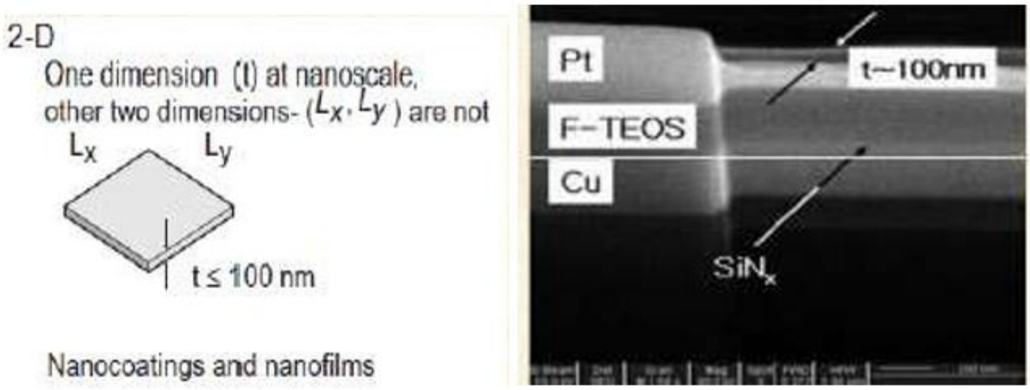


Figure 4. Two-dimensional nanomaterials [1]

Figure 5 illustrates the connections between zero-dimensional, one-dimensional, and two-dimensional nanomaterials within three-dimensional space.

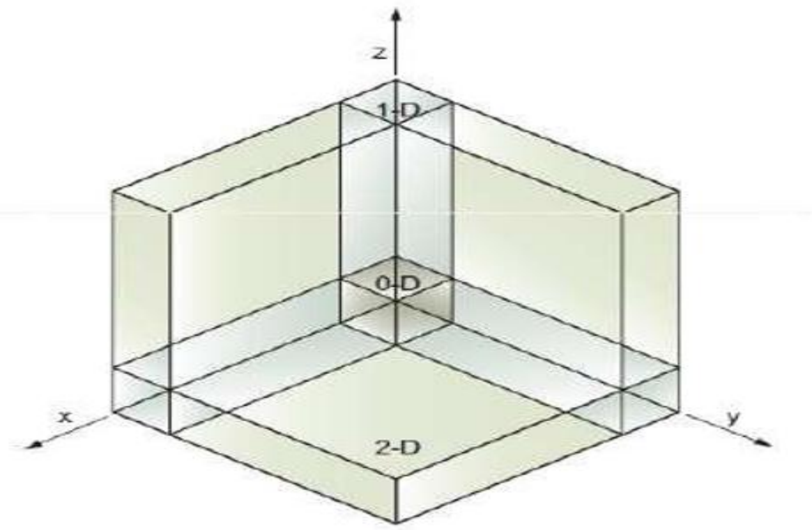


Figure 5. The conceptualization of 3-D space in which the correlation between 0-D, 1-D, and 2-D Nanomaterials [1] is established.

**Importance of Nanomaterials**

Nanostructures exploration is a very large and diverse field of investigation and innovation in the nanotechnology field [1]. This sector has recorded a high growth rate within the past few years across the world, as shown in Fig 6.

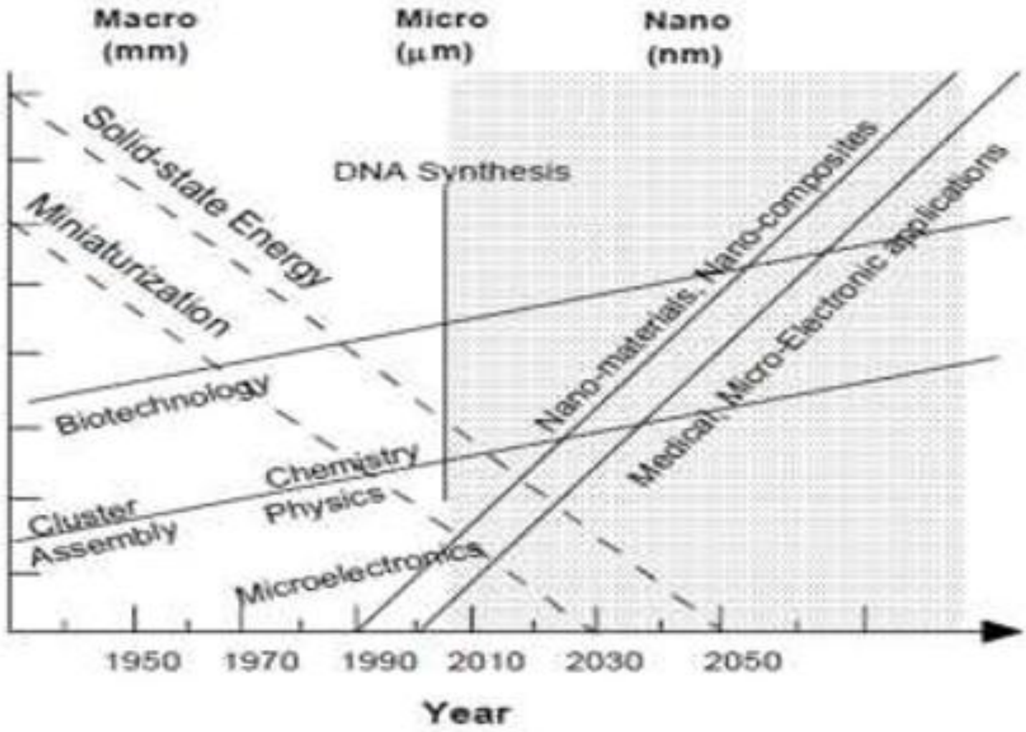


Figure 6. Evolution of science and technology [1]

The use of nanomaterials is the foundation of Nanoscience and nanotechnology. The research of nanostructures is an expansive and multidimensional area of research and development in the field of nanotechnology.

In contemporary times, nanomaterials have sparked significant fascination owing to their remarkable magnetic, optical, mechanical, and electrical characteristics. Several are elaborated upon in the designated nanomaterials:

1. Under elevated temperatures, nanoscale ceramics exhibit greater ductility compared to their conventionally grained counterparts.

2. Nanostructured semiconductor materials have a special importance in the context of semiconductor devices because they have nonlinear optical properties. Furthermore, they exhibit quantum confinement phenomena, resulting in silicon powder displaying luminescent characteristics.

3. Metallic nano powders find diverse uses in the creation of porous coatings, gas-absorbing materials, and more. The characteristics of ductility and cold-welding render them suitable for the bonding of metals, especially within the electronics sector.

4. In the implementations of gas detection devices such as carbon monoxide, carbon dioxide, methane, and aromatic hydrocarbon sensors.

5. Nanostructured metal oxide thin films are very sensitive and selective. The application of nanoscale MnO2 thin films is emerging in the realm of rechargeable batteries, catering to both automotive and consumer product needs. Nanostructured semiconductors serve as transparent layers in photovoltaic cells. Titanium oxide porous films play a crucial role in dye-sensitized solar cells, providing excellent adsorption capabilities thanks to their remarkable transmission properties and extensive surface area.

6. Polynanocomposites based on the polymers have a higher dielectric constant, which is due to the high concentration of inorganic particles, which are key components to photonic band gap structures.

7. Nanoelectronic devices exhibit fascinating characteristics within the radio frequency spectrum and additionally offer the advantage of enhanced integration densities.

8. The characteristics of magnetic nanomaterials exhibit a dependence on their size. Tiny particles possess unique atomic configurations featuring distinct electronic states, leading to remarkable characteristics alongside their superparamagnetic traits. Magnetic nanocomposites have found applications in the transfer of mechanical forces (such as in ferrofluids), as well as in high-density data storage and magnetic cooling technologies.

WHY NANOPARTICLES?

In the current demanding landscape of technology, nanoparticles are assuming a vital position owing to their capacity to deliver remarkable and distinctive magnetic, optical, mechanical, and electrical characteristics across a multitude of applications and investigations. They are evolving into essential elements across a diverse array of applications. The scope of investigation encompasses fields such as nanotechnology, healthcare, pharmaceutical production, biological sciences, molecular engineering, mechanical engineering, chemistry, physics, optical systems, polymer science, toxicology, cosmetics, food technology, energy solutions, as well as environmental and health sciences. Furthermore, nanoparticles hold considerable scientific fascination as they proficiently serve as a link between bulk substances and atomic or molecular configurations. A mass substance is expected to maintain uniform physical characteristics regardless of its dimensions; however, at the nanoscale, these properties become contingent upon size. Examples of size-dependent properties are quantum confinement in semiconductor nanoparticles, surface plasmon resonance in some metallic particles, and superparamagnetism in magnetic materials.

**The Difference Between Bulk and Nanoparticles**

The key factors that result in nanomaterials having significantly different behaviours when compared to bulk materials are:

*Surface effects*

Nanoparticles have an extraordinarily large surface area, in comparison to bulk substances, owing to the large number of particles per unit of mass that are located on the surface. As an example, a carbon microparticle with a single carbon grain of 0.3 μg, which has a surface area of 0.01 mm 2, has a diameter of 60 0 mm. The same amount of nanocarbon, which is 60 nm in diameter, has a surface area of 11.3 mm 2, and it is made up of 1 billion nanoparticles, as depicted by Figure 7a. The correlation between the surface area and the volume (or mass) of a particle with a diameter of 60 nm is a million times more than the surface area and the volume of a particle with a diameter of 60 mm, as shown in Figure 7b. The large surface area in its nanoscale form goes a long way to increase the reactivity of chemical reactions almost a thousand times over. At the nanoscale, atoms exhibit increased binding energy at their surfaces due to having a reduced number of neighbouring atoms compared to those in bulk form. The reduction in particle size results in an increased proportion of atoms located at the surface, leading to a heightened average binding energy for each atom.

A decrease in melting temperature with respect to particle size is noted, attributed to the increased binding energy present at the nanoscale. The melting temperature of gold in relation to particle diameter is illustrated in Figure 7c. Nanomaterials can exhibit notably distinct phase transition temperatures and considerably diminished lattice constants. This results from a significant proportion of surface atoms relative to the overall count of atoms. The improvement in mechanical strength by one or two orders of magnitude can be attributed to the diminished likelihood of defects.

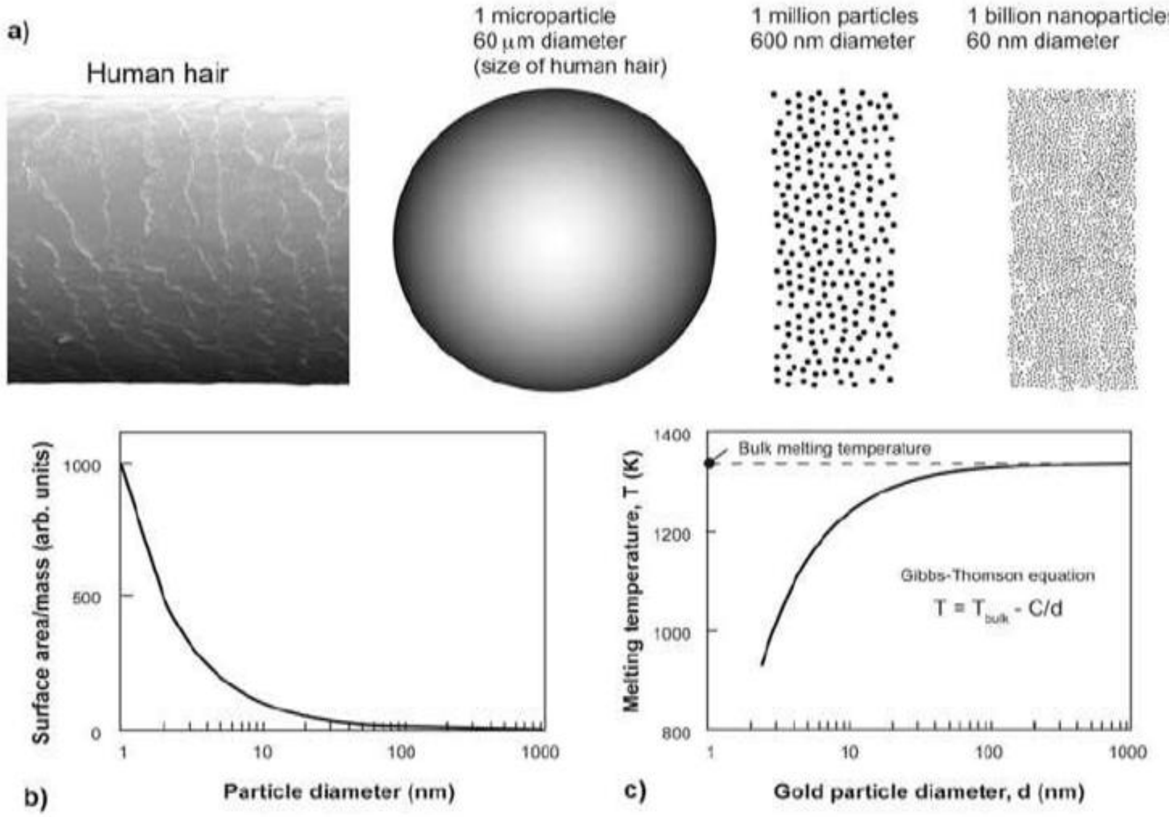


Figure 7. (a) micro particle of 60µm diameter, about the size of a human hair, and number of nanoparticles with diameter 600 nm and 60 nm having the mass as one microparticle of 60µm diameter (nm). (b) Surface area normalized to mass versus particle diameter (c) Gold melting temperature as a function of particle diameter

*Optical Properties*

The optical characteristics of nanomaterials exhibit marked distinctions when compared to those of bulk materials. As an illustration, semiconductor nanoparticles exhibit a movement of the absorption peak towards shorter wavelengths, attributed to the significant band gap present in the nanoparticles. The electrical conductivity and hue of nanoparticles vary according to their dimensions. The hue of metallic nanoparticles varies with their dimensions as a result of surface plasmon resonance, while electrical conductivity diminishes as particle size reduces due to surface scattering effects.

*Large Surface Energy*

When the mass of the material diminishes to the nanoscale, the ferromagnetic properties transition to superparamagnetic characteristics as a result of significant surface energy. The process of heat treatment influences a variety of physical characteristics, such as the enhancement of impurity diffusion, the presence of structural imperfections, and the occurrence of dislocations, among others. On the nanoscale, the effects of gravity and inertia would be negligible.

*Quantum Effects*

Quantum dots, along with single atoms or diminutive molecules, exhibit comparable electronic characteristics and are regarded as akin to synthetic atoms [7]. In quantum dots, electrons are restricted in all three spatial dimensions, resulting in a quantised energy spectrum. The quantum confinement effect allows for the observation of magnetic moments in nanoparticles, even in materials that exhibit non-magnetic properties in their bulk form, such as platinum and gold [5]. The phenomenon of quantum confinement leads to measurable alterations in the capacity to either accept or donate electrical charge, which is similarly reflected in the catalytic efficiency. The aforementioned elements affect the chemical reactivity of substances, as well as their magnetic, optical, mechanical, and electrical characteristics.

**Applications Of Nanoparticles**

The following are several significant uses of Nanomaterials:

*Coatings or Paints*

The efficacy of coatings can be improved through the incorporation of nanoparticles within them. Nanoparticles diminish the mass of coatings. Such a light coating has a useful purpose in aviation, which may prove beneficial to the ecosystem.

*Batteries*

The increase in the use of portable electronic devices such as smartphones, laptops, and remote sensors means that there is a high demand for batteries that have high energy density and lightweight properties. Nanomaterials have a foam-like structure, which demonstrates impressive potential in being able to store significantly more energy than the materials of the past.

Nanocrystalline nickel and metal hydride batteries, composed of nickel and metal hydrides, necessitate recharging less often due to their extensive surface area.

*Cosmetics and Sunscreens*

In contemporary times, nanoparticles are incorporated into sunscreens and cosmetics because of their ability to provide UV protection. Safeguarding the skin against ultraviolet radiation is a crucial element from a health perspective. Titanium oxide nanoparticles possess similar properties for UV protection. Consequently, titanium dioxide and zinc oxide are currently incorporated in various sunscreens due to their ability to absorb and reflect ultraviolet (UV) rays, while remaining transparent to visible light. Certain lipsticks incorporate iron oxide nanoparticles as a colouring agent [24].

*Food Industry*

Numerous uses of nanotechnology exist in the realms of manufacturing, processing, safety, and food packaging. The enhancement of food packaging can be achieved through the application of nanocomposite coatings, which involve the direct incorporation of antimicrobial agents onto the coated film. Nanotechnology possesses remarkable potential to transform the food sector, impacting everything from production to preservation, processing, packaging, transportation, and even the treatment of wastewater.

*Displays in public places*

The advancement of certain nanomaterials fuels a significant market for expansive, high-luminosity, flat-panel displays, utilised in devices such as computer monitors, television screens, and more. Certain nanoparticles, including zinc sulphide, zinc selenide, lead telluride, and cadmium sulphide, hold great potential as materials for the forthcoming generation of light-emitting phosphors.

*Medical Science*

Nanotechnology has emerged as a remarkable advancement in the realm of medical science. Magnetic nanoparticles have the potential to facilitate the identification of cancer. The magnetic nanoparticles are enveloped in antibodies specifically designed to seek out cancer cells or proteins. The magnetic nanoparticles can be retrieved, and the linked cancer-related molecules can be analysed to verify their presence. Nanotechnology holds the potential to aid in the restoration of injured tissue or even in its replication. Therefore, the field of tissue engineering holds great potential as an innovative solution for organ transplantation.

The utilisation of gold nanoparticles proves to be highly beneficial for medical applications. In the realm of Ayurveda, gold finds its application in a variety of formulations. A widely recognised formulation is known as Saraswatharishtam, recommended for boosting memory function.

*Construction*

Nanotechnology has great potential in the construction industry. The use of nanomaterials in construction can make the process efficient, less expensive, and safer. Silica (SiO2) has commonly been added to the normal concrete in the form of part of the normal mixture. Silica nanoparticles can be used to improve the mechanical properties of concrete. The nano silica that is incorporated in the cement can control the degradation of the vital C-S-H (calcium silicate hydrate) reaction of concrete, which is catalyzed by calcium leaching in water. It also has the ability to hinder water penetration, which eventually improves durability. The strength of concrete can also be enhanced by the addition of haematite (2Fe2O3) nanoparticles. The use of steel as a construction tool is important. Nanotechnology may be used to enhance the properties of steel to a considerable extent. The steel cables made using nanomaterials have superior tensile strength, hence they are suitable for the construction of bridges. One of such materials is glass, which has been used in the outer facade of the structure to block light and heat. TiO2 nanoparticles have beneficial properties in glaze coating that include sterilising and antifouling effects.

*Energy*

Energy conservation is the most important thing in times. Nanotechnology is definitely an important solution to energy saving especially in projects that aimed at conversion, reduction of materials, process speed optimisation, storage, placing an emphasis on energy efficiency and exploration of renewable energy sources that are highly advanced. The current efficiency of the solar cells is the most efficient at about 40 %. Nanotechnology is applicable in light conversion to improve the efficiency of the conversion by using nanostructures.

*Catalytic Activity*

The role of catalytic activity is crucial in the synthesis of various chemicals. Nanoparticles exhibit enhanced catalytic performance owing to their substantial surface area. As an example, the platinum nanoparticles can be considered the future of automotive catalytic converters, since due to a large surface area, the quantity of platinum nanoparticles is likely to be reduced.

**Synthesis of Nanoparticles**

Techniques for producing nanomaterials can typically be categorised into two distinct groups: top-down approaches and bottom-up strategies (illustrated in Figure 8). With the top-down method, rationally remove material from the bulk substrate until obtain the desired nanomaterials. Think about the way to make a figure out of a large piece of marble. Different printing techniques are also found in this category. Within the realm of semiconductors, a diverse array of top-down nanotechnological techniques is employed to construct the myriad components of computer chips. The techniques referred to as lithography employ either a light or electron beam to precisely eliminate micron-scale patterns from a substrate known as resist. A different hierarchical method involves attrition processes, such as grinding. Grinding is a mechanical abrasion technique that functions within the solid state.

Bottom-up approaches function in an inverse manner: the nanomaterial, like nanocoating, is derived from atomic or molecular precursors, progressively assembling until the intended structure is achieved. Bottom-up approaches can be categorised into gas-phase techniques and liquid-phase techniques [23]. In each scenario, the nanomaterials are crafted via a meticulously regulated fabrication process that initiates from individual atoms or molecules: gas-phase techniques encompass plasma arcing, inert gas condensation, and chemical vapour deposition; whereas, in liquid-phase approaches, the most recognised technique is sol-gel synthesis. The phenomenon of molecular self-assembly is gaining recognition as an innovative technique.

Both approaches necessitate two essential prerequisites: regulation of the synthesis parameters (such as the energy of the electron beam) and regulation of the environmental conditions (including the presence of dust, contaminants, and so forth). Consequently, the realm of nanotechnologies necessitates the use of exceptionally advanced fabrication instruments that operate under ultra-high vacuum environments and pristine clean-room facilities.

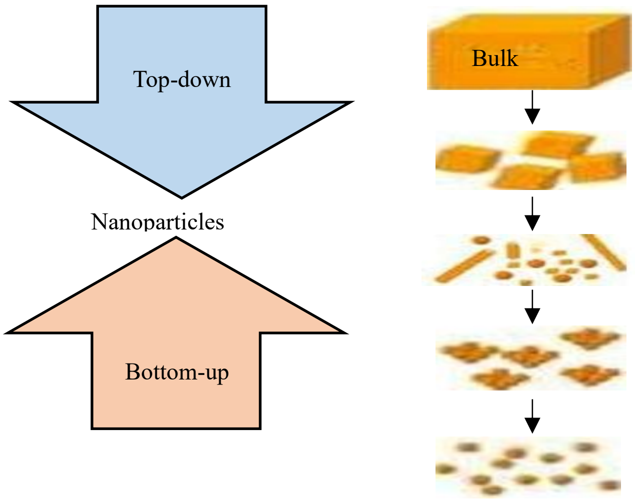


Figure 8. Top-down and bottom-up approach to nanoparticles [1]

## METAL OXIDE NANOPARTICLES

Metal oxide nanoparticles hold a crucial position in numerous domains of physics, chemistry, and materials science [9]. The array of structural geometries exhibited by these metal oxide nanoparticles can be extensive, accompanied by a diverse electronic structure. They may display properties that are metallic, semiconducting, or insulating in nature. Oxides play a significant role in the creation of microelectronic circuits, sensors, piezoelectric devices, fuel cells, protective coatings for surfaces against corrosion, and more. In the emerging realm of nanotechnology, a significant hurdle lies in the creation of nanostructures that exhibit unique characteristics compared to their bulk counterparts or individual particle forms. Owing to their diminutive dimensions and elevated density of edge surface sites, they display distinctive chemical and physical characteristics. The dimensions of particles play a crucial role in determining the structural attributes and electronic characteristics. Regarding the structural characteristics, the size of particles will impact the symmetry of the lattice between the parameters of the cell, and so on. However, in the case of bulk oxides, such features are quite consistent. Much attention should be paid to the growing importance of the surface free energy and stress at diminutive particle sizes. In the study of the electronic properties of the oxides in different materials, a nanostructure produces so-called quantum size or confinement effects, which are essentially a result of the presence of discrete, atom-like, electronic states [10]. The large ratio of the surface area to the volume is very important in the introduction of unique properties to nanoparticles, such as the optical, structural, and magnetic properties. The metal oxides of such elements as iron, nickel, cobalt, copper, and zinc have a number of important applications, including magnetic storage devices, conversion of solar energy, electronics, semiconductors, and catalytic reactions [11]. In the periodic table, metallic (M) elements interact to create a diverse array of oxides characterised by the chemical formula $MO_x$, where x can be either 1 or 2. The characteristics of these metal oxides, influenced by their structural geometry and electronic configuration, display properties of metallic, semiconducting, and insulating nature. Lately, a new range of semiconductor nanostructures, namely $MO_x$, has attracted serious research focus because of their various structural, chemical, mechanical, and physical properties. The MOX compounds are made up of positively charged metallic ions and negatively charged oxygen ions, which have varied properties. Among the great number of metal oxide nanoparticles, MgO, CuO, $SnO_2$, $TiO_2$, $CeO_2$, $SiO_2$, and ZrO2 are the ones that have received much attention and examination over the past decade. Moreover, metal oxide nanoparticles exhibit exceptional mechanical stability attributed to their reduced surface energy when compared to their bulk counterparts [12]. Metallic oxides that have distinct crystalline structures are very durable and stable. They display some peculiar structural and optical properties that can be manipulated by quantum size effects and structural changes. Additionally, the availability of oxygen vacancies is supposed to have a specific effect on the optical properties [14].

The metal oxide nanoparticles with unique shapes and sizes can greatly modify the fluorescence properties of organic dyes at an optimal distance. Metal oxides actively find use as energy donors or acceptors in FRET systems as substitutes for organic dyes due to their limited excitation spectrum and wide emission bands. More so, nanoparticles with a higher percentage of corner states and high surface area, which are associated with excellent electrical and optical properties, may be a valuable asset towards FRET. In recent years, some MOx have been used as FRET system contributors, with a wide range of different applications (including cancer therapy, pharmaceutical delivery, biosensors, and the dynamics and structure of many biomolecules).

Nowadays, it is well known that metal oxides, due to their unique properties, which depend on size, including such exceptional optical transparency, high mobility, broad bandgap, large refractive indices, and enormous dielectric constants, among others, can be considered as promising candidates to a variety of applications. These are solar cells, fuel cells, a collection of sensors, catalysts, photovoltaic systems, and optoelectronic devices. Among the large variety of metal oxides and choose to prepare CuO, SnO2, TiO2, and ZrO2 through the co-precipitation method, and examine the effect of various solvents and the temperature of the calcinations on their optical properties. In the following section, a brief summary of the synthesised MOx will be given.

**Copper Oxide (CuO)**

There are two varieties of copper oxide, namely Cu2O and CuO. CuO is a p-type semiconductor with a band gap ranging between 1.2 and 1.55 eV, although Cu2O has a band gap of 2.1 eV. The small band gap makes it a suitable one to be used in solar cells and optoelectronic devices. CuO is more thermally stable than Cu2O, and thus, oxidation of Cu2O leads to the formation of CuO. They are both known to have different crystalline structures, chemical and physical properties.

Among these two variations, it is observed that CuO has exceptional optical features due to the presence of a variety of surface defects. It has been determined that oxygen vacancies play a crucial role in fluorescence (FL) emission, leading to the creation of distinct energy states compared to those associated with Cu vacancies. The green luminescence of CuO is attributed to the presence of oxygen vacancies. The emissions of yellow and red hues are associated with the existence of interstitial copper ions. The emission of oxygen vacancies in CuO is another advantage to the use of this material in optoelectronics device manufacture.

**Tin Oxide ($SnO_2$)**

One notable transition-metal oxide is tin oxide because it is highly optically transparent and is also chemically and thermally stable. It comes in two forms, namely stannous (SnO) and stannic oxide (SnO2), which both have a tetragonal crystalline structure. Among the two, SnO2 is an n-type semiconductor with a direct band-gap (Eg) of 3.6 eV, whereas SnO is a p-type semiconductor that has a band-gap of between 2.5 and 3.4 eV. SnO is observed to be in a metastable form at ambient temperature. Whether or not SnO and SnO2 co-exist depends on the oxidation of SnO or the reduction of SnO2. Among such compounds, SnO2 is more stable than SnO, which is attributed to the existence of induced oxygen vacancies. A notable characteristic of SnO2 is its significantly larger electronic binding energy, approximately 130 meV, when contrasted with other metal oxides. Moreover, SnO2 exhibits remarkable electrical conductivity alongside outstanding optical transparency within the visible spectrum.

The optical characteristics of SnO2 exhibit a notable sensitivity to the concentration of oxygen vacancies, and they fluctuate based on the dimensions and morphology of the particles. The presence of oxygen vacancies engages with the interfacial tin atom, resulting in the creation of intermediate defect-related energy states within the band gap, thereby showcasing a pronounced FL emission in the visible spectrum. The high UV absorbance and defects related photoluminescence in the visible spectrum make SnO2 a strong candidate for use in photosensitive and optoelectronic applications.

**Titanium Oxide (TiO2)**

Titanium oxide is an n-type semiconductor with a broad band gap and has a high refractive index. TiO2 is unique in the sense that it occurs in three different polymorphic forms, which include brookite, an orthorhombic crystal, anatase, and rutile, with its tetragonal structure. The three different phases have different band gaps. Titanium dioxide (TiO2) can be used at temperatures below 450 °C in the anatase form, and conversion between anatase and the rutile form occurs between 450 °C and 800 °C. The TiO2 has three different phases, rutile is more thermally stable than the brookite and anatase phases because of its low oxygen vacancy and the availability of titanium ions (Ti2+). Anatase TiO2 has high surface energy and a large band gap, and therefore, it has better photocatalytic and photovoltaic action compared to other phases.

The photophysical properties of TiO 2 are very sensitive to its phase and the number of oxygen vacancies available. Deficiency of oxygen in the rutile TiO2 phase leads to minimum FL intensity compared to that of the anatase phase because of the presence of a non-radiative recombination process. The photoluminescence properties of TiO2 depend on the size of the particles, the shape of the particles as well, and can also respond to many external factors, including solvents, temperature of calcinations, among other factors. TiO2 has good prospects to be used in photovoltaic systems and optical technologies as it is an excellent photostable and light-sensitive material.

**Zirconium Oxide (ZrO2)**

Another example of a semiconductor with a wide band gap is zirconium oxide, with a refractive index of 2.13. Also, it is in three different crystalline forms, namely cubic, monoclinic, and tetragonal, with different optical band gaps of 5.42 eV, 5.55 eV, and 6.4 eV, respectively. Each of these three crystalline formations exhibits stability at varying temperature conditions. The monoclinic configuration of ZrO2 is present at ambient temperature and remains thermodynamically stable until reaching 1100°C. The transition from monoclinic to tetragonal phases occurs within a temperature spectrum of 1100 to 2370 degrees Celsius, while temperatures exceeding 2370 degrees Celsius favour the stability of the cubic phase. When heated above 2680 °C, it is totally converted into a liquid. The uniformity of zirconia depends on the mode of production, the starting materials used, and the environment under which the materials are produced. The material demonstrates phase-dependent mechanical, electrical, and optical properties, which make it applicable for use as an insulator in metal oxide semiconductor devices. Among the three forms, the tetragonal phase is of high importance in the optoelectronic devices due to its durability and other kinds of imperfections on the surface.

The change of phase and the presence of various imperfections on the surfaces are what make ZrO2 interesting in regard to optical properties. The m-ZrO2 (monoclinic) exhibits the lowest photoluminescence intensity when contrasted with the t-ZrO2 (tetragonal) due to a lack of oxygen vacancies. The absorption edge and emission wavelength of ZrO2 are influenced not only by the formation and transition of phases but also fluctuate with the dimensions and morphology of the particles. The phase-dependent shorter emission wavelength positions ZrO2 as an optimal choice for a range of photonic applications. Here is the comparison table for different metal oxide nanoparticles (CuO, SnO2, TiO2, ZrO2) based on their synthesis methods, properties, and applications.

A comparative study of the four metal oxide nanoparticles CuO, SnO2, TiO2, and ZrO2 has been done in Table 1 based on their synthesis, physical characteristics, photocatalytic behavior, and application to various applications. The table compares the band gaps, crystal structure, and the common sizes of the particle in detail, which gives us an understanding of their application in energy, environmental, as well as biomedical uses. It also describes their explicit functions in photocatalysis, water purification, the delivery of drugs, and sensor technologies. The table shows that metal oxide nanoparticles are versatile and their peculiarities and possible uses in various industries and research are underlined. This comparison is a basis on which a person can learn about the functioning ability and limitations of these nanoparticles in different situations.

Table 1. Comparison of different metal oxide nanoparticles

| **Properties/Applications** | **CuO (Copper Oxide)** | **SnO2 (Tin Oxide)** | **TiO2 (Titanium Oxide)** | **ZrO2 (Zirconium Oxide)** |
|---|---|---|---|---|
| Synthesis Methods | Co-precipitation, Sol-gel, Chemical Vapor Deposition | Sol-gel, Hydrothermal, Co-precipitation | Sol-gel, Hydrothermal, Co-precipitation | Sol-gel, Chemical Vapor Deposition |
| Particle Size | 20-40 nm | 30-50 nm | 25-40 nm | 30-45 nm |
| Shape | Spherical, Cubic | Spherical, Rod-like | Spherical, Nanotubes | Cubic, Tetragonal |
| Band Gap | 1.2 - 1.55 eV | 3.6 eV | 3.0 - 3.2 eV | 5.4 - 6.4 eV |
| Crystal Structure | Monoclinic | Tetragonal | Anatase, Rutile, Brookite | Monoclinic, Tetragonal, Cubic |
| Photocatalytic Activity | High in the UV-visible range | High in the UV range | Highest among metal oxides | Moderate to High in UV range |
| Applications | Solar cells, Sensors, Photocatalysis | Transparent Conductors, Gas Sensors, Photocatalysis | Photocatalysis, Solar cells, Water Purification | Catalysis, Photocatalysis, Sensors |
| Biomedical Applications | Limited due to toxicity | Non-toxic, drug delivery, biosensors | Non-toxic, Drug delivery, Cancer therapy | Biocompatible, Drug delivery |
| Environmental Applications | Water purification, Pollution control | Water purification, Environmental monitoring | Pollution control, Photodegradation | Pollution control, Sensors |
| Stability | High thermal stability | High chemical stability | Excellent photostability | High thermal and chemical stability |

## CONCLUSION

To sum up, metal oxide nanoparticles, due to their exceptional characteristics under the nanoscale, have been very promising in a number of industries, such as energy, environmental clean-up, and biomedicine. They have the potential to be used in solar cells, sensors, photocatalysis, and drug delivery systems because they have a high surface area, tunable optical and electrical properties, and can undergo quantum effects. Their size, shape, and functionality are also dependent on the synthesis techniques, such as sol-gel, co-precipitation, and chemical vapor deposition, leading to more applications. The metal oxide nanoparticles also include CuO, TiO2, SnO2, and ZrO2, which are especially interesting due to their versatility, where they have particular benefits in energy storage, environmental monitoring, and health-related benefits. Although this is highly developed, there are still issues associated with scalability, cost-effectiveness, and environmental impact. These nanoparticles cannot be used in large-scale processes because of the challenges that are found in the uniform production processes, regulatory issues, and the possibility of toxicity. Consequently, future studies need to work on constructing sustainable and green methods of synthesis that can increase the production of metal oxide nanoparticles on a large scale; while lowering the negative impacts they have on the environment.

Also, further research on optimization of the use of such nanoparticles in practical uses, especially in the delivery of drugs and in the cleanup of the environment, is a vital topic of great future research. It may also be the research in the future that would look into the integration of metal oxide nanoparticles with other nanomaterials to enable the development of hybrid systems that would tackle a number of challenges at once. The next avenue that has potential is further research on their stability, biocompatibility, and toxicity over the long run, especially in the field of medicine. With the ever-changing nanotechnology, it is only through these advancements that renewable energy, healthcare, and environmental sustainability will be innovated with the metal oxide nanoparticles at the center stage in defining the future of technology.

## REFERENCES


[1] Ryu HW, Choi GP, Lee WS, Park JS. Preferred orientations of NiO thin films prepared by RF magnetron sputtering. Journal of materials science. 2004 Jul 1;39(13):4375-7. 10.1023/B: JMSC.0000033431.52659.e5

[2] Rao CN, Cheetham AK. Science and technology of nanomaterials: current status and future prospects. Journal of Materials Chemistry. 2001;11(12):2887-94. https://doi.org/10.1039/B105058N

[3] Ramesh KT. Nanomaterials. In Nanomaterials: Mechanics and Mechanisms 2009 Mar 20 (pp. 1-20). Boston, MA: Springer US. https://doi.org/10.1007/978-0-387-09783-1_1

[4] Roduner E. Size matters: why nanomaterials are different. Chemical society reviews. 2006;35(7):583-92. https://doi.org/10.1039/B502142C

[5] Saadeddin A, Rodrigo-Navarro A, Monedero V, Rico P, Moratal D, González-Martín ML, Navarro D, García AJ, Salmerón-Sánchez M. Functional living biointerphases. Advanced healthcare materials. 2013 Sep;2(9):1213-8. https://doi.org/10.1002/adhm.201200473

[6] Kouwenhoven LP, Austing DG, Tarucha S. Few-electron quantum dots. Reports on progress in physics. 2001 Jun 1;64(6):701-36. 10.1088/0034-4885/64/6/201

[7] Larcher D, Masquelier C, Bonnin D, Chabre Y, Masson V, Leriche JB, Tarascon JM. Effect of particle size on lithium intercalation into α Fe2 O 3. Journal of the Electrochemical Society. 2003 Jan 1;150(1):A133-9. https://doi.org/10.1149/1.1528941

[8] Noguera C. Physics and chemistry at oxide surfaces. Cambridge University Press; 1996 Sep 28.

[9] Dghoughi L, Elidrissi B, Bernede C, Addou M, Lamrani MA, Regragui M, Erguig H. Physico-chemical, optical and electrochemical properties of iron oxide thin films prepared by spray pyrolysis. Applied Surface Science. 2006 Dec 15;253(4):1823-9. https://doi.org/10.1016/j.apsusc.2006.03.021

[10] Kumar RV, Diamant Y, Gedanken A. Sonochemical synthesis and characterization of nanometer-size transition metal oxides from metal acetates. Chemistry of Materials. 2000 Aug 21;12(8):2301-5. https://doi.org/10.1021/cm000166z

[11] Jeong JR, Lee SJ, Kim JD, Shin SC. Magnetic properties of γ-Fe2O3 nanoparticles made by coprecipitation method. physica status solidi (b). 2004 Jun;241(7):1593-6. https://doi.org/10.1002/pssb.200304549

[12] Hasany SF, Ahmed I, Rajan J, Rehman A. Systematic review of the preparation techniques of iron oxide magnetic nanoparticles. Nanosci. Nanotechnol. 2012;2(6):148-58.

[13] Chen DH, Huang SH. Fast separation of bromelain by polyacrylic acid-bound iron oxide magnetic nanoparticles. Process Biochemistry. 2004 Oct 29;39(12):2207-11. https://doi.org/10.1016/j.procbio.2003.11.014

[14] Dräger G, Czolbe W, Leiro JA. High-energy-spectroscopy studies of a charge-transfer insulator: X-ray spectra of α-Fe 2 O 3. Physical Review B. 1992 Apr 15;45(15):8283. https://doi.org/10.1103/PhysRevB.45.8283

[15] Whitesides GM, Boncheva M. Beyond molecules: Self-assembly of mesoscopic and macroscopic components. Proceedings of the National Academy of Sciences. 2002 Apr 16;99(8):4769-74. https://doi.org/10.1073/pnas.082065899

[16] Guo X, Zhong S, Zhang J, Wang W, Mao J, Xie G. Synthesis, phase transition, and magnetic property of iron oxide materials: effect of sodium hydroxide concentrations. Journal of materials science. 2010 Dec;45(23):6467-73. https://doi.org/10.1007/s10853-010-4733-8

[17] Daou TJ, Greneche JM, Lee SJ, Lee S, Lefevre C, Bégin-Colin S, Pourroy G. Spin canting of maghemite studied by NMR and In-Field Mossbauer spectrometry. The Journal of Physical Chemistry C. 2010 May 20;114(19):8794-9. https://doi.org/10.1021/jp100726c

[18] Sahoo SK, Agarwal K, Singh AK, Polke BG, Raha KC. Characterization of γ-and α-Fe2O3 nano powders synthesized by emulsion precipitation-calcination route and rheological behaviour of α-Fe2O3. International Journal of Engineering, Science and Technology. 2010;2(8). https://doi.org/10.4314/ijest.v2i8.63841

[19] Leslie-Pelecky DL, Rieke RD. Magnetic properties of nanostructured materials. Chemistry of materials. 1996 Aug 14;8(8):1770-83. https://doi.org/10.1021/cm960077f

[20] Chen P, Zhang HB, Lin GD, Hong Q, Tsai KR. Growth of carbon nanotubes by catalytic decomposition of CH4 or CO on a Ni MgO catalyst. Carbon. 1997 Jan 1;35(10-11):1495-501. https://doi.org/10.1016/S0008-6223(97)00100-0

[21] Tang J, Myers M, Bosnick KA, Brus LE. Magnetite $Fe_3O_4$ nanocrystals: spectroscopic observation of aqueous oxidation kinetics. The Journal of Physical Chemistry B. 2003 Jul 31;107(30):7501-6. https://doi.org/10.1021/jp027048e

[22] Maruyama T, Kanagawa T. Electrochromic properties of iron oxide thin films prepared by chemical vapor deposition. Journal of the Electrochemical Society. 1996 May 1;143(5):1675. https://doi.org/10.1149/1.1836697

[23] Balela MDL. Synthesis and characterization of cobalt nanoparticles by liquid-phase reduction [master's thesis]. Penang (MY): Universiti Sains Malaysia; 2008. p. 1–4, 8–32.

[24] Al-Kuhaili MF, Saleem M, Durrani SM. Optical properties of iron oxide ($\alpha$-$Fe_2O_3$) thin films deposited by the reactive evaporation of iron. Journal of alloys and compounds. 2012 Apr 25; 521:178-82.