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# Nanomaterials at the Forefront of Technology: A Comprehensive Review of Classification, Properties, Synthesis and Characterization Techniques, and Multifunctional Applications.

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## Abstract

This paper provides a comprehensive overview of the classification, properties, synthesis, characterization, and applications of nanomaterials. Nanomaterials are defined as materials that have one or more external dimensions in the nanoscale, which range from 1 nanometer (nm) to 100 nm. They can be classified based on their origin, dimensionality, morphology, and composition. Common forms of nanomaterials include nanoparticles, nanowires, nanorods, and nanotubes, each possessing different dimensions within the nanoscale. The unique physical and chemical properties of nanomaterials arise from their small size and high surface area-to-volume ratio. Additionally, the optical properties of these materials are heavily influenced by their size. Because of these remarkable characteristics, nanomaterials are suited for a diverse array of applications, particularly in the fields of catalysis, imaging, medical advancements, energy research, and environmental solutions.

**Keywords:** Nanomaterials, nanometer, quantum effect

## 1. Introduction

Nanostructure science and technology is a multidisciplinary field that has recently gained significant attention and experienced rapid development [1]. Nanoscience focuses on the fundamental principles of molecules and structures at the nanoscale, which ranges from 0.2 to 100 nanometers (nm). In contrast, nanotechnology involves the design, characterization, production, and application of structures, devices, and systems by controlling their shape and size at the nanometer scale. A nanometer is defined as 10^−9 meters in length according to the International System of Units (SI). Nanomaterials serve as the foundation for both nanoscience and nanotechnology [2].

Nanomaterials are substances that exist within the nano-size range, specifically those with dimensions that are smaller than macroscopic (bulk) materials but larger than individual atoms and molecules [3].. The unique properties of nanomaterials arise from several factors: their relatively large surface area compared to the same mass of bulk materials, the quantum effects that dominate the behavior of matter at the nanoscale, and their small size, which brings them into a realm where these quantum effects are significant[4].

Nanomaterials can vary widely in dimensions, shapes, and sizes, in addition to their material composition. They can be classified as zero-dimensional (where length, breadth, and height converge at a single point), one-dimensional (possessing only one dimension), two-dimensional (having length and breadth), or three-dimensional (incorporating length, breadth, and height) (Ealia & Saravanakumar, 2017).

Additionally, nanomaterials come in various shapes, including spherical, cylindrical, tubular, conical, hollow core, spiral, flat, or irregular. Their sizes can range from 1 nm to 100 nm, with surfaces that may be uniform or irregular and exhibit surface variations. Some nanomaterials are crystalline or amorphous and can be found as single or multi-crystal solids, either loose or agglomerated[6].

Due to their unique properties, nanomaterials have found applications across numerous fields, including energy, biomedicine, catalysis, and electronics –– [7]. Although research interest in this area has intensified recently, much remains to be understood about the fundamental behaviors of nanomaterials. Additionally, the global challenges underscore the need for thorough investigations into this subject, exploring potential applications. This review will discuss the classification, properties, synthesis, characterization, and applications of nanomaterials.

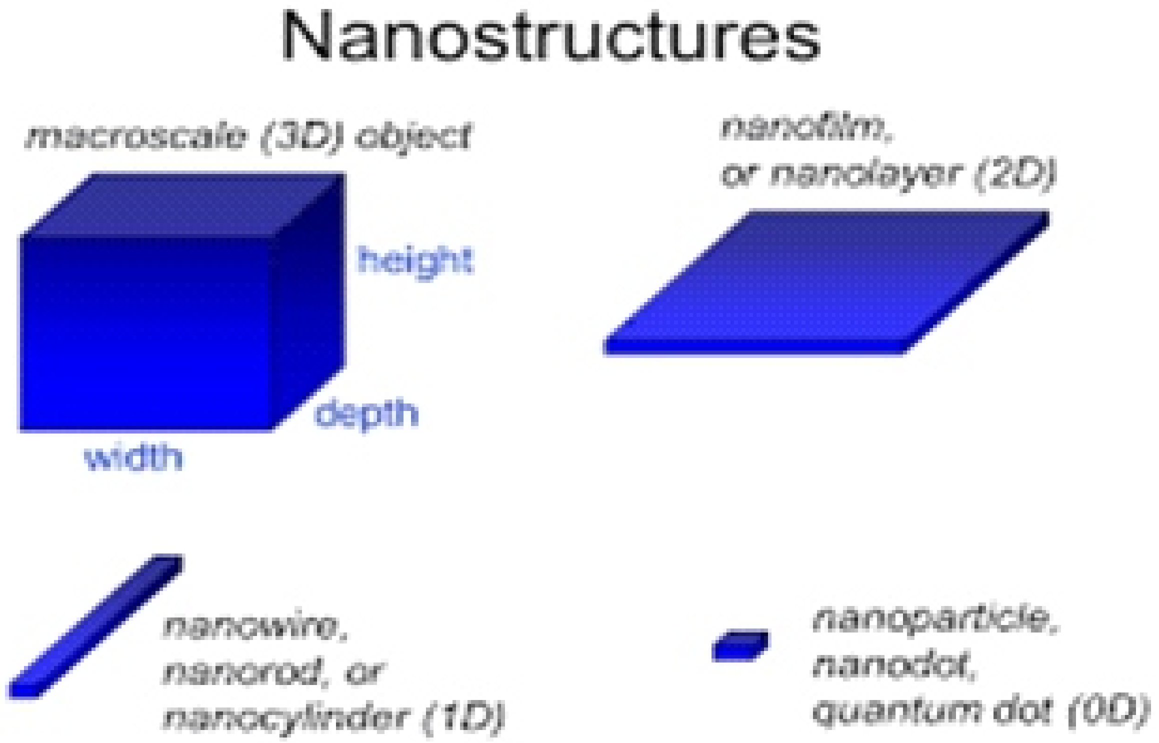
## 2.0 Classification of Nanomaterials

Nanomaterials can be classified based on their origin, dimensionality, morphology, and composition[4,8].

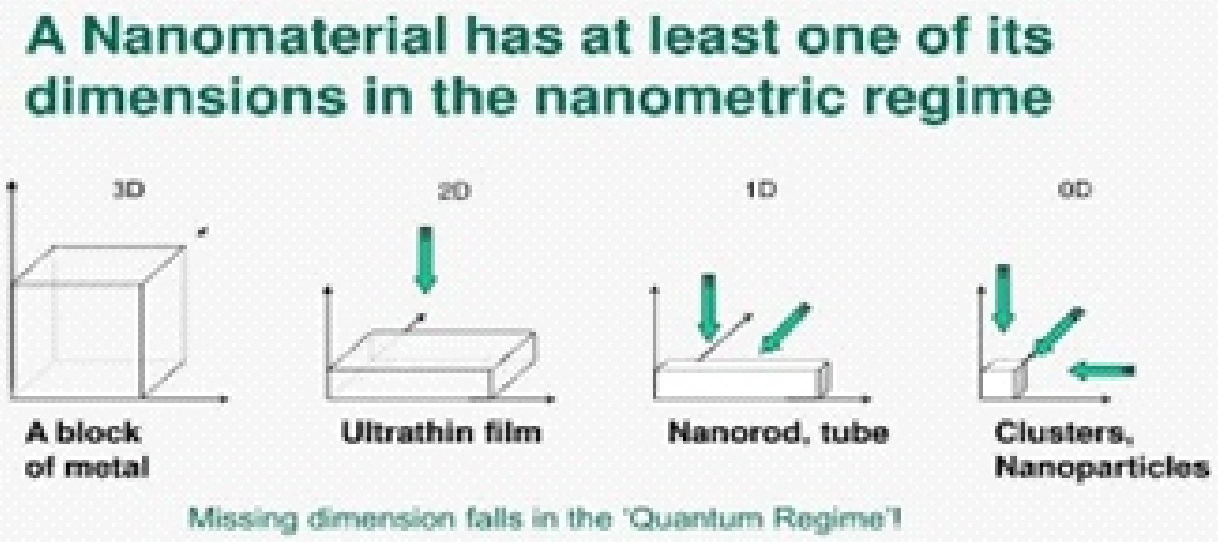
There are two primary categories of nanomaterials based on their source: natural and anthropogenic nanomaterials[9]. Those with a natural and incidental origin are referred to as ultrafine particles. Natural sources of inorganic nanomaterials include erupting volcanoes, crashing sea waves, forest fires, sandstorms, and soil. Anthropogenic nanomaterials, on the other hand, are unintentional by-products of human activities. These include emissions from internal combustion engines, power plants, incinerators, jet engines, metal fumes (from processes like smelting and welding), polymer fumes, heated surfaces, cooking methods (such as baking, frying, broiling, and grilling), and electric motors[8].

Based on dimensionality, nanomaterials can be categorized into zero, one, two, and three dimensions within the nanoscale. Nanomaterials with all external dimensions at the nanoscale, specifically between 1 and 100 nm, are classified as zero-dimensional (0D). Examples of 0D nanomaterials include quantum dots, which are semiconductor nanocrystals with sizes less than 10 nm that act as potential wells and are used in electronics to confine electrons and holes. Other 0D nanomaterials encompass various types of nanoparticles, such as full spheres like anatase titanium dioxide, highly symmetrical branched macromolecules known as dendrimers, and hollow spheres made of carbon (such as fullerenes) [10].

One-dimensional (1D) nanomaterials possess two external dimensions at the nanoscale, with the third dimension typically at the microscale. Examples of 1D nanomaterials include nanofibers, nanotubes, nanowires, and nanorods. Two-dimensional (2D) nanomaterials have only one external dimension at the nanoscale; examples include thin films, nanocoatings, and nanoplates. Three-dimensional (3D) nanomaterials have internal nanoscale features but do not have any external dimensions at the nanoscale. This category encompasses nanocomposites and nanostructured materials[11].



Nanostructures



A Nanomaterial has at least one of its dimensions in the nanometric regime

Missing dimension falls in the 'Quantum Regime'!

Fig. 1 Dimensionality of nanomaterials (https://www.slideserve.com/milly/nanomaterials-for-biological-applications).

Nanocomposites are multiphase solid materials, with at least one phase having a nanoscale external dimension. The term "nanocomposite" is typically used to describe nanofillers dispersed within a bulk matrix.

The classification of nanomaterials according to their morphology (shape and size) divides them into low- and high-aspect ratio particles. High-aspect ratio nanomaterials can take various forms, such as nanowires, nanohelices, nanozigzags, nanopillars, nanotubes, or nanobelts. Low-aspect ratio nanomaterials can also have diverse shapes, including spherical, helical, pillar-like, pyramidal, and cubic forms.

According to their composition, nanoparticles can be made of a single material, either compact or hollow. Nanomaterials may also consist of two or more materials, which can be arranged as coatings, encapsulations, barcodes, or mixtures. Based on their uniformity, nanoparticles can be categorized as isometric (uniform) or inhomogeneous (uneven). Regarding their agglomeration status, nanoparticles can be either dispersed or agglomerated. The degree of agglomeration depends on their electromagnetic properties, including surface charge and magnetism. When suspended in a liquid, their agglomeration can also be influenced by their surface morphology and functionalization, which can impart hydrophobic or hydrophilic characteristics[4].

## 3.0 Properties of Nanomaterials

A significant change in nanomaterial properties can be observed when reduced to the nanoscale. As we scale up from the molecular to the nanoscale, the electronic properties of materials change due to the quantum size effect –[12,13]. Mechanical, thermal, and catalytic properties also shift, influenced by the increased surface area to volume ratio at the nanoscale [14]. At nanoscale dimensions, many insulating materials exhibit conductive behavior. Additionally, as we approach nanoscale dimensions, unique quantum and surface phenomena emerge.

Physicochemical properties of nanomaterials include particle size, shape, chemical composition, crystal structure, physicochemical stability, surface area, surface energy, and more. With an increased surface area to volume ratio, nanomaterial surfaces become more reactive to themselves and other systems. Nanomaterial size significantly impacts their pharmacological behavior. When nanomaterials interact with water or other dispersing media, they can alter their crystal structure. Their size, composition, and surface charge also influence aggregation states[15].

## 4.0 Synthesis of Nanomaterials

Figure 2 provides a simplified overview of various nanomaterial (nanoparticle) synthesis methods. These methods are categorized into bottom-up and top-down approaches. The bottom-up, or constructive, method involves assembling materials from atoms to clusters and then to nanoparticles. Common bottom-up techniques include sol-gel, sonochemical methods, spinning, chemical vapor deposition (CVD), pyrolysis, and biosynthesis.

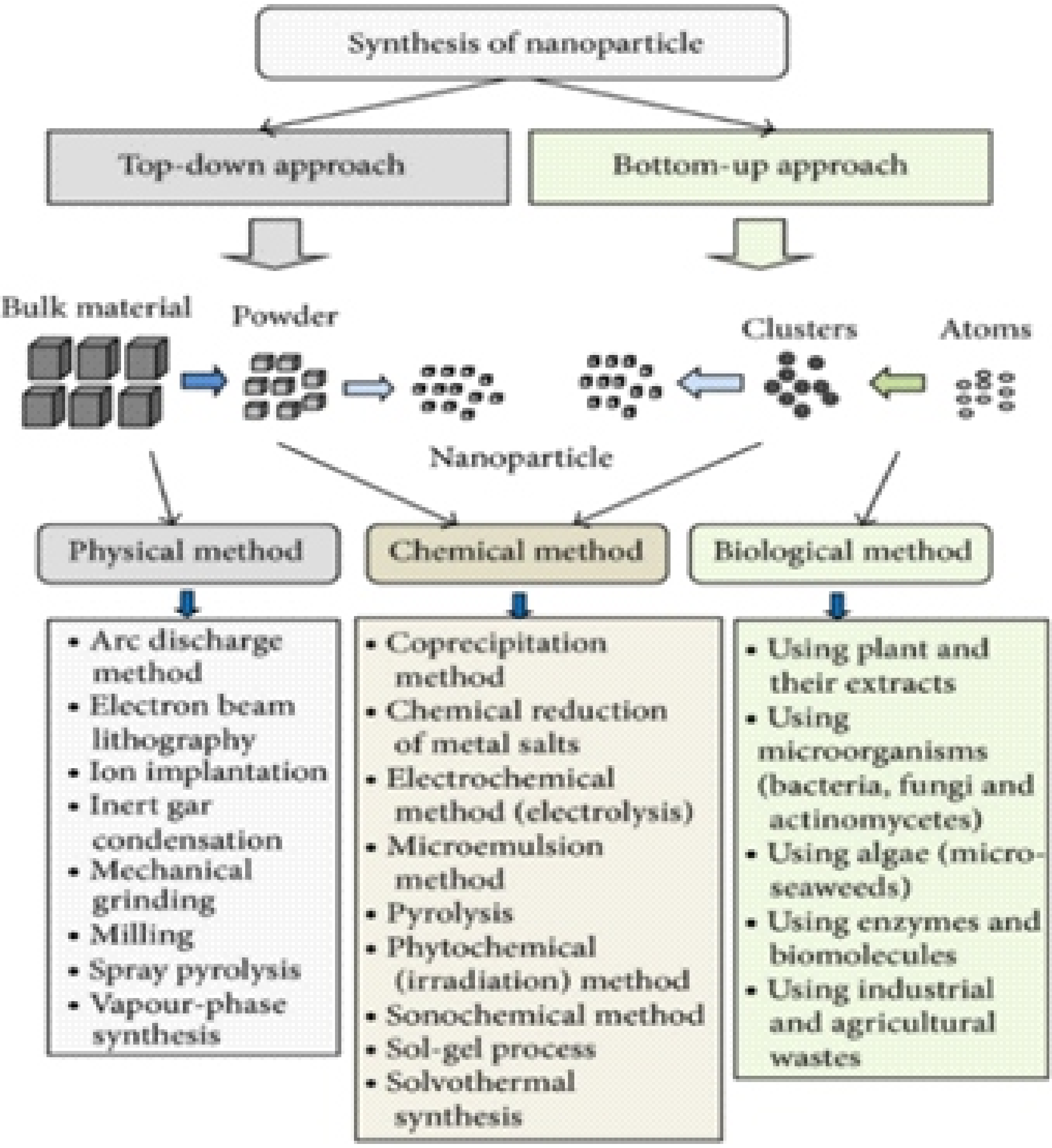


Fig. 2 Synthesis methods of nanomaterials

The top-down, or destructive, method reduces bulk materials to nanoscale particles. Widely used top-down techniques for synthesizing nanomaterials include mechanical milling, mechanical grinding, arc discharge, electron beam lithography, sputtering, and thermal decomposition[16,17].

## 5.0 Characterization of Nanomaterials

Various characterization techniques are employed to analyze nanomaterials' physicochemical properties. These include methods like X-ray diffraction (XRD), Scanning electron microscopy (SEM), Transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), Fourier transform infrared (FTIR) spectroscopy, Raman spectroscopy, Brunauer–Emmett–Teller (BET), and particle size analysis. The optical properties of nanomaterials can be examined through UV-Vis spectroscopy and luminescence spectroscopy ––[7].

### 5.1 Morphological and Chemical Composition Characterizations

The morphological characteristics, such as structure, shape, size, and particle distribution, can be analyzed using SEM and TEM (Mbakaan et al., 2020). SEM and TEM remain the most widely used microscopy techniques. SEM and TEM images of nanomaterials are shown in Fig. 3. Energy-dispersive X-ray (EDX) spectroscopy, often attached to a field-emission scanning electron microscope (FESEM) or TEM, is used to assess the chemical composition of nanomaterials.

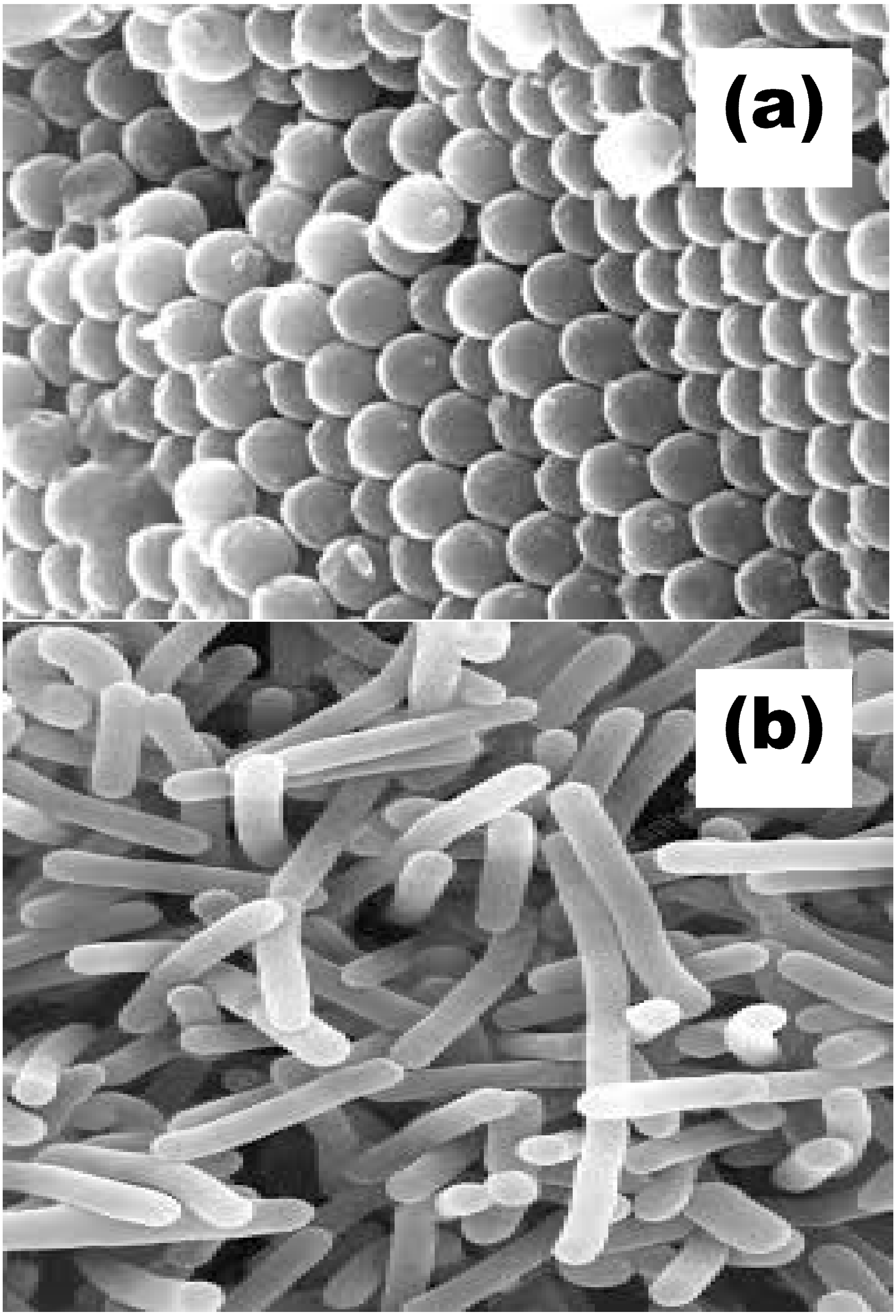


Fig.3 Images of nanomaterials (nanoparticles and nanorods) produced by (a) SEM and (b) TEM respectively (https://www.google.com/search?q=TEM).

### 5.2 Structural Characterizations

X-ray diffraction (XRD) is a crucial technique for determining nanomaterials' structural properties, providing information about crystallinity and phase. XRD also estimates particle size using the Debye-Scherrer formula [14,18], making it effective for identifying both single and multiphase nanomaterials.

### 5.3 FTIR, Raman, and X-ray Photoelectron Spectroscopy (XPS)

FTIR, Raman, and XPS are key methods for examining the structural properties of nanomaterials. These techniques reveal bonding elements and atomic vibrations within the nanomaterials ––––[1921].

### 5.4 Optical Characterization

Optical characterization provides insights into nanomaterials' absorption, reflectance, and luminescence properties [18,22,23]. Metallic and semiconductor nanoparticles exhibit diverse colors, which align well with photo-related applications. Understanding these materials' absorption and reflectance values helps clarify the mechanisms for various applications. A UV/vis-diffuse reflectance spectrometer (DRS) measures optical absorption, transmittance, and reflectance, and is ideal for determining the bandgaps of nanoparticles and other nanomaterials, essential for assessing photoactivity and conductivity.

## 6.0 Applications of Nanomaterials

Due to the distinctive properties of nanomaterials, they are applied across diverse fields, including aerospace, automobiles, chemicals, construction, cosmetics, nanoengineering, electronics, energy, environment, food, medicine, military, and textiles.

### 6.1 Applications in Medicine

Inorganic nanomaterials (nanoparticles), whether simple or complex, exhibit unique physical and chemical properties and are increasingly significant in developing new nanodevices for physical, biological, biomedical, and pharmaceutical applications [24,25]. Nanomaterials have gained traction in medicine due to their ability to deliver drugs at optimal doses, often enhancing therapeutic efficacy, reducing side effects, and improving patient compliance [24,25].

### 6.2 Applications in Electronics

Printed electronics has gained attention for its use of traditional silicon techniques and potential for low-cost, large-area electronics for flexible displays and sensors. Functional inks containing nanoparticles such as metallic, organic electronic molecules, carbon nanotubes, and ceramic nanoparticles are expected to enable mass production of new electronic devices [26]. The unique properties of one-dimensional semiconductors and metals position them as key elements for a new generation of electronics, sensors, and photonic materials [27]. New semiconductor discoveries have spurred innovation from vacuum tubes to transistors and ultimately to microchips. Nanoparticles are especially valuable due to their ease of manipulation and reversible assembly, which facilitate their integration into electronic, optical, and electrical devices.

### 6.3 Application of Nanomaterials in Energy Harvesting

Fossil fuel depletion has led scientists to explore renewable energy from accessible, low-cost resources. Nanomaterials, with their large surface area, optical behavior, and catalytic properties, are ideal for this purpose. They are extensively used for energy generation through photoelectrochemical (PEC) and electrochemical water splitting [28]. Besides water splitting, electrochemical $CO_2$ reduction, solar cells, and piezoelectric generators provide advanced energy generation methods [29,30]. Nanomaterials are also integral to energy storage, allowing energy to be stored at the nanoscale. The development of nanogenerators, which convert mechanical energy into electricity using piezoelectric materials, is a remarkable achievement [31].

## 7.0 Conclusion

This paper presents a comprehensive review of nanomaterials. The classification of nanomaterials into 0D, 1D, 2D, and 3D structures has been thoroughly examined, highlighting the spatial confinement of nanoparticles within distinct nanoscale dimensions. The properties of nanomaterials, such as reduced size and increased surface area, place them in a domain where quantum effects dominate, significantly influencing their magnetic, optical, and electrical properties. These unique characteristics of nanomaterials have led to their broad application across fields such as medicine, energy, electronics, and aerospace, among others.

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