American Journal of Botany and Bioengineering
https://biojournals.us/index.php/AJBP
ISSN: 2997-9331

Applications of Nanotechnology in Material Science

Walid Khaled Hmoud
University of Babylon College of Science Department of physics

Jaafar Adnan Gharkan
University of Kufa College of Science, Department of Physics

Weldan Saad Hamed
Almustansria University College of science Department of Physics

Miami Hameed Jader, Aya Jassim Mohammed
Al_Muthanna University college of science Department of Physics

Received: 2024 19, Oct
Accepted: 2024 28, Oct
Published: 2024 14, Nov

Annotation: Nanotechnology has opened new avenues in the field of material science. The introduction of a small amount of nanomaterials often leads to beneficial modification of the physical, mechanical, thermal, electrical, and optical properties of bulk materials. It leads to the development of new classes of materials termed nanocomposites and multifunctional materials. Nanotechnology has promising applications in both structural materials used in packaging, transportation, housing, and communication, and functional materials used in coatings, healthcare, electronics, electromechanical systems, functional fluids, and as catalysts. Some of the applications are multifunctional windows and seals, neutron-absorbing hexagonal boron nitride coating to limit radiation, microprocessor application of yttrium-barium-copper-oxide superconductor, sinter-resistant dispersible nanocatalysts, nanocatalyst blocks for hydrogen generation, and minimal radiation fibula screws and implants.

Applications of nanotechnology can be seen under the following heads: 1.1. Structural Materials:

Primary applications of nanotechnology can be viewed in our day-to-day life in terms of materials used in structural applications. Nanotechnologically modified materials can show an improvement in the properties and lead to a disproportionate improvement in the lifetime compared to bulk materials. 1.2. Functional Materials: These materials can be used either in the form of bulk or as films or coatings. Functional materials refer to the materials that have very high functionality and work at the nanoscale. A major concern in the preparation of the materials is the sustainability of the process and the life of coated materials in service.

1. Introduction to Nanotechnology

Nanotechnology is the science and technology of systems that span the molecular and mirror scales. This interdisciplinary field includes the study of chemistry, physics, materials science, as well as cell biology, molecular computer science, information sensors, photonic and electronic systems, mechanical systems, quantum bots, chemical devices, and fluids. At the length scale, materials smaller than visible light may behave differently as a result of fluctuations in thermal and electronic motion and as a result of atomic and supramolecular interactions. The performance degradation of information and technology enhances the mechanical, chemical, optical, electrical, thermal, and magnetic properties due to dimensional changes.

Some information on nanotechnology products and materials under the above approach is included in this section. Another metric that typifies nanotechnology is that bodies can be controlled by vacuum systems and supramolecular, atomic-style methods. The ultimate in soft matter in proteomes is from atoms that are thousands of nanometers in size from organic self-assembly in atoms. Nanotechnology is defined as the engineering of chemical and biological systems at spatial dimensions at atomic and molecular levels and the design and creation of functional systems, materials, and devices through controlled design, production, and devices, including neural memory at molecular scales, guided by different time-ordered needs. New capabilities have been opened. [1][2][3]

1.1. Definition and Scope

Nanotechnology overview: Definition and scope

Nanotechnology, sometimes described as molecular manufacturing, refers to the use of technology to create new materials and devices at the level of atoms and molecules. A nanometer is simply one billionth of a meter, and nanotechnology defines a nanomaterial as one whose smallest functional entity at least partially extends into the nanometer-length scale. In other words, a nanomaterial possesses dependent properties, e.g., electromagnetic, mechanical, thermal, and chemical, based on surface and interface effects that emerge around 100 nm up to 1,000 nm or larger. In many fields of research, the range of this phenomenon covers one or two decades below and above about 100 nm. Just a single nanoscale size, therefore, usually is considered to emerge as a material's property, for example, differences in surface area, diffusion rate, and porosity for particles and films.

The fundamental operating principles used in current electronic and optoelectronic technologies depend critically on the properties of materials and architecture built at the nanoscale. The technology offers the potential to revolutionize electronics, including faster and more efficient circuits and devices, smaller and more portable computers, and devices such as cell phones with longer battery life. Nanotechnology represents advances in a variety of sectors—medicine, electronics, energy, robotics, biotechnology, and materials—each of which has applications in interconnected economic sectors. By developing methods for producing materials in the nanoscale regime, engineers can make the materials more functional, efficient, and economical. In particular, the properties of materials can be engineered so that they are different from their bulk counterparts, i.e., if the microstructure or material is manipulated so that it behaves differently than the same material on a larger scale. This pinpoints the importance of conducting interdisciplinary research, involving collaboration between people with different backgrounds, to maximize the success of research projects. [4][5][6]

1.2. Historical Background

Nanotechnology is actually a modern resurgence of basic sciences initiated at the turn of the 20th century. Nearly a hundred years ago, scientists were exploring the unusual properties of metals as well as the colors of glass changing with a reduction in particle sizes. This awareness and further studies during the 1940s, along with novel scientific detective work, led to a hypothesis in America on "there is plenty of room at the bottom," and thus the concept of nanotechnology emerged as a result of the exploitation of these peculiar material properties for modern scientific and engineering marvels.

In the year 1776, pigments as ground paints that were used in the lingerie trade at that time can be considered as the point of initiation in the history of research on the properties of small particles of materials. Nanoscience and technology are as old as human civilization and date back to the first colloids prepared by early blacksmiths and potters in ancient Rome and Babylon, and the method of coloring glasses with gold colloid via the Roman era sculptor. At that time, the plasmonic effect in nanostructures was revealed and experimented with to get different colors. In the synthesis of colored glass, the study of cereology has been performed, which has proposed various formulations of glass that consist of metal nanoparticles. The stepwise development of nanotechnology was witnessed by various discoveries in the evolution of science. [7][8][9]

2. Fundamentals of Nanomaterials

Nanomaterials possess interesting and fascinating atoms, molecules, and bulk systems dependent characteristics. The shape, size, chemical composition, and structure are some of their special characteristics. Depending on their shapes, sizes, or surface properties, they behave differently from their bulk constituents. Several factors, such as the proportion of atoms at the surface or interface, dictate their distinct characteristics and behavior. As a result, nanomaterials are being studied in relation to their construction in real-world applications such as catalysts, sensors, environmental science, and biotechnology. The large area to volume ratio of nanomaterials, 1 to 100 nm or of the order of the wavelength of scrutiny, gives them properties based on materials in capsules, powders, pellets, ground substances, and other more traditional forms. For these kinds of behavior, the essential short development in nanomaterials in all aspects of science and technology was large. Tagged quantum dots, aggregated metal particle clusters, stretched metal, inorganic and organic half-molecules with carbon, carbon nanotubes, semi-fluid jelly-like handles, hollows, and amphipolar liquid filter silver proteins. Apart from the distance between the main particle and the diameter between the surface molecule, nanomaterials have other residual points with a strong deviation in the physical and biological features as well. The bigger main particle has an extremely large ratio to the edge power and the main specific power, which may otherwise result in zero or an initial nanoparticle over smaller ones. [10][11][12]

2.1. Properties of Nanomaterials

There are differences in size, surface-to-volume ratio, and quantum mechanical properties between bulk material and nanomaterial. 1 nm = 10^{-9} m. Because it is of the order of the interatomic or molecular distance, the properties of materials are not the same as their bulk counterparts. These unique properties pave the way for advanced nanomaterials in today's cutting-edge research. One of the most important properties is the enhanced mechanical, electrical, thermal, and optical properties of nanomaterials arising from their nanoscale dimensions, surface modifications, and quantum effects. The classic example of this is the golden color of gold nanoparticles produced by the collective excitation of valence electrons inducing an absorption peak in the visible region of electromagnetic radiation through surface plasmon resonance. This is not observed in counterparts made of bulk gold. Reduced melting point: As discussed above, with the reduction in size of particles, the melting point drastically decreases. For example, gold melts at 1,064 °C, whereas nanoparticles of gold melt at around 700 °C. Semiconducting behavior: Nanoparticles of gold will exhibit semiconducting behavior, which is not true for bulk gold. Quantum effect: At nanoscale size, the behavior of the electrons that conduct electricity is no longer governed by the classical laws of physics. They start creeping from one atom to the other, as if they are floating. These undefined behaviors are seen in nanomaterials and never in bulk materials. The term quantum is used because it uses quantum logic. Each particle, whether an electron or photon, has a specific location with a specific energy around its orbit. Taking into account these phenomena, engineers can design and tailor functional materials for specific applications. Besides, the properties of nanomaterials could be utilized in innovative technologies such as sensors, catalysts, optoelectronic devices, and drug delivery systems. Size-dependent behavior allows a higher concentration of solute particles to disperse the crystallites and improve the strength at the nanoscale. This is due to the increasing amount of atoms at the surface. At some point, this becomes the dominant effect. While an outer volume containing atoms allows the particles to move, only the inner particles are interconnected. There is no motion potential for the outer particles. When an object is very small, it allows the particles located at the visible surface to contribute to the supporting load. This eliminates the need for fewer core atoms in the crystal to transfer energy and redistribute stress. Although the fine size of such crystallites can be enough to capitalize on the energy building bonding between the atoms, creating particles in the micrometer often reduces the stress produced in a single crystal shape and orientation at the grain boundary. A material in which the average grain size is less than 100 nm is referred to as ultrafine-grain material, while an average grain size is less than 50 nm. A typical nanocrystalline material contains nanosized grains in the range of 1 to 100 nm. [13][14][15]

2.2. Synthesis and Characterization Techniques

The synthesis of nanomaterials is an important tool in materials science, as their properties strongly depend on the synthesis method used. There are several methods available to synthesize nanomaterials, such as gas condensation, sol-gel synthesis, anodization, and various application-based methods. Nanomaterials have a unique set of properties, such as surface, optical, and electrical properties. They can be obtained by top-down or bottom-up approaches. Bottom-up approaches can produce low-defect and pure materials, whereas top-down approaches can produce nanosized particles in large quantities for industrial applications. Biomolecule-assisted nanoparticles can also be synthesized using E. coli, in which enzymes can act as a reducing agent. Among top-down techniques, chemical vapor deposition is the most promising tool to synthesize various types of vertically aligned nanomaterial arrays for electronic, detection, and catalytic applications.

Besides synthesis techniques, characterization methods such as spectroscopy, microscopy, and diffraction and scattering have been employed to study nanomaterials. Microscopy techniques include atomic force microscopy, scanning electron microscopy, and transmission electron microscopy. The main diffraction techniques involve X-ray and neutron scattering, among others, to interpret the crystal structure and defects in the materials. In characterization techniques, X-ray diffraction is popular for crystallographic analysis and the preparation of nanoparticles. Chemical composition was studied using X-ray diffraction, scanning electron microscopy, energy-dispersive X-ray spectroscopy, and Rutherford backscattering spectrometry. Furthermore, the structural morphology and elemental composition can be characterized by transmission electron microscopy with an electron diffraction pattern. Characterization of the chemical bonding and band gap was studied via X-ray photoelectron spectroscopy and UV-Vis spectroscopy, respectively. Finally, the quality, purity, and reproducibility of sheets can be characterized by employing a SiC EPD substrate and using Raman spectroscopy. In product synthesis methodologies, a characterization study needs to be performed to check the purity and further applications of the synthesized product. [16][17][18]

3. Nanotechnology in Structural Materials

Many aspects of material behavior have their origin at the nano level. It is well established that materials in which the structural scale is comparable to microstructural features and components, such as the grains in polycrystals, are much stronger and more durable than coarser grained materials. Bulk nanostructured materials and nanocrystalline materials with grain sizes in the nanometer regime, typically 100 nm or less, often show exceptional mechanical strength and wear resistance, improved creep and corrosion properties, in comparison with the coarser grained counterparts. The structural and mechanical properties of a material are in general sensitive to the adopted synthesis and processing route. The advent of nanotechnology has provided the possibility for performing a precise tuning of the properties of existing materials, to achieve unprecedented levels of performance, and the concurrent development of nano-manufacturing techniques for the fabrication of novel structural materials, with unique combinations of properties. The field of nanotechnology already has many areas of application; nanocomposites are very promising materials because the incorporation of a relatively small amount of either nanometer or micrometer-sized material phases, such as ceramics, polymers, or even clay, can lead to a significant improvement in mechanical properties, especially the strength, toughness, hardness, creep-rupture properties, and wear resistance, as well as provide additional functionalities, such as thermal protection or impact resistance for structural components, lightweighting for packaging, automotive, and aerospace industries, and corrosion resistance for parts used in chemical or nuclear plants. New generation automobiles and aircraft are gravitating towards lightweight structures to enhance fuel efficiency, leading to increased global demand for lightweight structural materials such as aluminum-based materials, high strength steel, magnesium alloys, titanium-based materials, and a myriad of polymer matrix composites reinforced with glass fibers, carbon, or ceramics. The emerging generation of civil infrastructure is also being designed with high demands on materials with a high strength-to-weight ratio, corrosion resistance, and high fracture toughness. Innovative design and materials for these structures must meet these goals. Nanotechnology presents a potential solution to these demands. Much of the last century has been marked by many great discoveries in the development of advanced materials and novel manufacturing techniques. A bigger share of infrastructure that America and many parts of the industrialized world will be developing will go into retrofitting existing and aging structures or in building resilient structures that are environmentally friendly and cost-efficient for maintenance. The development of such advanced materials and their subsequent application would contribute to the creation of a sustainable civil infrastructure with the potential to reduce the environmental and economic burden of maintenance implicit in the built infrastructure. A major deterrent to using advanced materials and advanced technologies has been their cost of development and the scaling up implications upon the overall cost of the structure. In this regard, some of the advanced materials such as nanostructured metal systems, lightweight metals, and polymers with dispersed systems are revealing promise of the cost demands. [19][20][21]

3.1. Nanocomposites

Nanocomposites are well-defined, multiphase materials that have been developed to infuse a polymer or matrix with controlled amounts of nanoparticles to significantly enhance various properties of the agricultural material due to close interactions and bonding between the atoms at the interface. In the past thirty years, a large improvement has been evidenced in the enhancement of different properties of materials. Nanocomposites have two main components: the matrix and the dispersed phase. The matrix can be either a polymer, ceramic, a soft, or a hard material, enabling it to be implemented in different application fields. The dispersed phase mainly comprises nanoparticles whose dimensions range from 1 to 100 nm. Size and shape, in addition to the fact that the volume of this phase does not increase proportionally with the dispersion, are some of the factors that distinguish nanocomposites from classical ones.

The benefits that can be realized with the use of nano-sized reinforcements can be quite significant for a range of commercial products such as coatings and packaging materials, in addition to strategic sectors like automotive, construction, and biomedical technologies. The prime interest nowadays in nanocomposites is an outcome of a number of research articles that have been published specifically in the area of mechanical properties, not excluding gas and liquid barriers in polymer nanocomposites. These articles have clearly demonstrated that the reinforcing mechanism due to nanoparticles relies on confined dimensions, besides the high interaction and activation at the interface due to the large surface area of the particles, in addition to better stress transfer from the matrix to the reinforcements. Nanocomposites are composite materials in which the filler has at least one dimension around 10^-9 meters and are currently widespread in a number of industries. Every year, thousands of research papers are published globally to offer enhanced understanding of the subject in addition to better products. There is practically no industry, such as automotive, medical, electronic, etc., that is not making use of it in one manner or another. Owing to their small size and their linked nanoscale effects or phenomena, their incorporation into other host materials gives rise to a whole range of materials with superior or 'tailored' properties. Advances in nanotechnology and the accessible heightened knowledge of the paradigms of nanoscience have, without doubt, opened up fresh divisions into health and biomedical applications of materials with improved properties for current applications. [22][23][24]

3.2. Nanostructured Metals

Nanostructured metals, also termed nanocrystalline metals or bulk nanostructured metals, have drawn widespread interest due to their unique properties that are considerably different from their coarse-grained polycrystalline counterparts. These unique properties arise from two effects: the high density of grain boundaries that affect both thermal and electrical transport, and the small size of the grains. The depletion of dislocations in nanocrystalline metals contributes to the enhancement in strength, often exceeding the Hall-Petch upper limit of coarse-grained counterparts. Additionally, it is well established that the processing of metals to the nanoscale enhances their ductility. The rapid diffusion and high chemical activity of atoms at grain boundaries, which increases as grain size reduces, allow the fabrication of nanostructured metals with enhanced wear resistance and anti-corrosion properties.

The methods for processing HNSMs are conventionally divided into bottom-up methods and top-down methods. For the bottom-up methods, it is notable that the concept of accumulating smaller grains is rarely applied. Coating methods using plastics and grain growth inhibitors are employed here to restrict grain growth during long-term isothermal heat treatment. For the top-down methods, accumulated severe plastic deformation techniques are widely accepted. SPD allows the processing of hard-to-deform materials into nanostructured materials. Many SPD techniques, such as high-pressure torsion, equal channel angular pressing, repetitive corrugation and straightening, friction stir processing, and accumulative roll bonding, to obtain ultrafine and nanostructured materials have been developed over the past three decades. HNSMs have drawn considerable attention from researchers around the globe, owing to their increasing number of promising applications as next-generation materials in a variety of fields such as aerospace, automotive, and biomedical applications.

In recent years, a great deal of research has been carried out in this field, and a number of reviews have been published. The findings predominantly introduce nanostructured metals and materials in general rather than focusing on materials science and crystal characteristics. Many studies on mono and gradient structured nanostructured materials, as an imitation of the natural bone structure, have also been performed, and the significant improvement in the mechanical properties was verified by the findings. Natural bone is a nanocomposite material with a hierarchical structure. Many studies on the nanostructure of materials, including single filaments, have been diligently conducted. Furthermore, HNSMs have attracted substantial attention as an alternative due to their unique properties and potential applications. It is expected that these HNSMs show superior load-bearing capacity due to the suppression of early micro-damage. Despite a great deal of effort, considerable challenges still remain, including the fabrication of this large quantity of applicable materials at acceptable dimensions. The PM technique is not practical for industrial applications for producing functional and structural parts that must meet precise specifications. Severe challenges can be associated with the manufacturing of component parts by additive manufacturing due to part size limitations. [25][26][27]

4. Nanotechnology in Functional Materials

Nanotechnology cuts across almost all sciences and presents itself as an emerging field for the development of functional materials. The property of a nanomaterial to serve a specific function is known as functional materials. In terms of applications, the nanostructured materials are versatile and can find potential in diverse areas of applications. In the area of catalysis and surface science, the metal or metal oxides at the nanoscale dimensions in the form of sols or clusters are found to possess good catalytic activity as well as enhanced selectivity. The nanomaterials are also used in sensors and biosensors mainly to increase the sensitivity of the device. The nanoparticles of size in the range of 100 nm to 50 µm are also electrochemically active and used for the development of higher performance electrodes or to increase the capacity of various batteries or the charge rate performance of supercapacitors. The three different examples of the functional materials for the mentioned range of applications are summarized. The increase in the number of publications on the functional properties of the nanomaterials indicates more advanced research in this area.

It is mainly the design of materials that explores the structure-property relationship at the nanoscale. The nanostructure exhibits different properties as compared to its extended solid counterpart, such as melting point, diffusivity, thermal conductivity, coefficient of thermal linear expansion, surface energy, surface tension, free energy, and density. In general, nanostructured materials demonstrate significantly modified electrical, optical, magnetic, mechanical, and thermal properties compared to their bulk counterparts. Nanoparticles possess greater surface area as compared to bulk or fine particles, which is beneficial in the case of nanoparticles because it will increase their interaction with the volume of the medium and can efficiently utilize their reactivity. The following are some catalytic processes and the nanomaterials involved and summarized. In the current scenario, a new version of the energy storage system has attracted considerable attention. Recent innovation using nanomaterials, like nanoparticles, to be utilized in energy storage devices is as follows. [28][29][30]

4.1. Nanoparticles for Catalysis

Nanoparticles play a crucial role in catalysis. This is because they have a high surface area, components on their surface are typically more reactive than in the bulk, and there is a finite size effect. Their small size gives them an extremely high surface area-to-volume ratio, which can range from 5 to 10 times more than the maximum surface area available per unit mass in macro-sized materials. This large characteristic surface area, which is exposed, makes them more reactive than larger-sized materials. Nanoparticles can be made from a number of different materials, such as metals, oxides, and carbon-based materials like carbon nanotubes.

Metal nanoparticles can be used for catalyzing reactions, which is the science of increasing the rate at which chemical reactions occur. They have even been integrated with other catalysts to form bimetallic nanoparticles, which exhibit other catalytic properties. Also, they can be used in heterogeneous catalysis. Heterogeneous catalysis is the type of catalysis where the phases of the catalysis and the reactants they are acting upon are distinct, usually gaseous or liquid phases with solid catalysts. These types of catalytic reactions are used in the petrochemical, automotive, and fuel industries. As such, the greatest body of work has been performed on the catalytic capabilities of metal nanoparticles. There is also wide commercial interest in these types of catalysts, for example, in the area of air purification, where nanoparticulate photocatalysts are being used to degrade volatile organic compounds. These types of catalysts can also be used to produce energy or for environmental remediation. [31][32]

4.2. Nanomaterials for Energy Storage

Nanotechnology has facilitated the development of new systems in the field of energy storage. Advancements in the synthesis of nanomaterials have become a popular trend in the field of battery and supercapacitor technology. It has been shown that materials with nanosized particulates are able to exhibit enhanced electrochemical performance due to increased capacity, high rate capability, and life cycle. The major driving force for developing improved energy storage technologies is to reduce the cost and increase the energy density of the systems. This trend is rapidly expanding, and corporations and established research and development laboratories are engaging in the energy sector to push technology towards globalization. The advancements presented in this subsection in nanostructured materials for energy storage demonstrate the field of nanotechnology and focus on several aspects of using nanomaterials in energy storage systems. As background, applications of electronic, thermal, and structural aspects of nanomaterials are reviewed.

The energy storage materials can store excess electric power, for example, renewable energy resources. The increase in global electricity demand is also being driven by environmental concerns. This makes it important to generate power from alternative sources to avoid harmful effects on the environment. Sustainable sources of energy, such as sunlight, provide diffuse and intermittent energy, which cannot be utilized directly to fulfill our needs. The storage of energy is indispensable in order to operate electrical appliances at a time delayed from the energy supply. Technological advancements in the field of materials, as well as nanotechnology, have also impacted the development of energy storage systems. More nanomaterials and nanotechnology are in the research and development stage. [33][34]

5. Future Prospects and Challenges

Even though nanotechnology has come a long way in addressing significant mechanical and biological problems and more than 1,800 products have been integrated into the market, many nanotechnology-based products are in their submission phase to reduce the prices of their applications. In the near future, other major areas of nanotechnology such as food technology, cosmetics, and microelectronics are also likely to adopt nanotechnology in a big way. However, this field of science is facing several challenges. The initiation and participation of a computational model like artificial intelligence and machine learning would be highly promising to support researchers in nanotechnology characterization, analysis, and prediction.

The potential nascentness of synthetic nanomaterials and its impact on environmental health facilities the potential factuality of minimizing the maximum potential welfare and bundle of random facts which potentially encompass activated and wide interventions down. The high cost of production of nanotechnology-related instruments and their equipment is also a major concern. International agreements and industry interest in the standardization and regulation of different commercial nanomaterials have not yet stopped. Many possible products related to commercial, industrial, and home applications are available and will be available in the future in the field of nanotechnology. Possible future revenues from nanotechnology products depend in large part on the successful movement of these various applications from the current state of innovation and development to the established industrial health value chain. The nanotechnology character of these applications was investigated during the development of the technology roadmap in quantitative and qualitative scenarios, predecessor sequencing indistinctively to nanomaterial invention and production, through R&D to market launch ultimately to recycling and disposal. The current economic potential of these nanotechnology products is at the early stages of the trajectory. To overcome these challenges and derive maximum benefit, interdisciplinary collaboration and continuous effort are necessary. It could provide opportunities for policymakers and scientists to protect society from barriers and possible negative risks. It is also important to continually drive a wide debate covering the public, the market, and the relevant laws and regulations.

6. Conclusion

Nanomaterials have become increasingly attractive in the field of material science due to their structural and functional applications such as sanitization, sensing, energy storage, renewable energy devices, water and wastewater treatment, and electronic and magnetic applications, among other material properties. This text has reviewed and summarized the synthesis process and detailed applications of a series of nanomaterials, including photocatalyst TiO_2–SnO_2, polyvinyl alcohol-grafted nanobiocellulose, gold nanoparticle-graphene oxide, strontium titanate, silver nanoparticle, and graphene-based nanomaterials. It has also outlined some of the challenges encountered and the discussions associated with previous development and systems of the materials, including the cost, investment, and efforts associated with the large-scale production of different nanomaterials. Interestingly, research in these areas of nanoscience and nanotechnology is ongoing for new and more feasible materials having more than one functional approach to the materials being synthesized. The progression and research prospects of this sophisticated new field of materials engineering are upon us, and as established, researchers across the globe must act interdisciplinary to both address and overcome the numerous challenges encountered with this science and technology. Recurrent needs and concerns of environmentalism include factors of sustainability, green synthesis, and the dynamic role of chemistry in the development of defined government infrastructure, policy, and legal interpretations. Subject to critique and opinion, it is commonly agreed that this nanotechnology can lead to the conviction that these areas of evolution are possible. In conclusion, this text reinforces the reasons behind the potential immensity of this field and provides some insight into the present endeavors and aspirations of the scientists operating therein.

References:

1. D. Suhag, P. Thakur, and A. Thakur, "Introduction to nanotechnology," in *Integrated Nanomaterials and their …*, Springer, 2023. springer.com
2. C. Binns, "Introduction to nanoscience and nanotechnology," 2021. [HTML]
3. F. Findik, "Nanomaterials and their applications," Period. Eng. Nat. Sci, 2021. academia.edu
4. C. F. Guimarães, L. Gasperini, and A. P. Marques, "The stiffness of living tissues and its implications for tissue engineering," Reviews Materials, 2020. uminho.pt
5. J. Gigault, H. El Hadri, B. Nguyen, and B. Grassl, "Nanoplastics are neither microplastics nor engineered nanoparticles," Nature, 2021. mcgill.ca
6. S. Khan and M. K. Hossain, "Classification and properties of nanoparticles," Nanoparticle-based polymer composites, 2022. [HTML]
7. A. Mandal and E. Ray Banerjee, "Introduction to nanoscience, nanotechnology and nanoparticles," in *Nanomaterials and Biomedicine: Therapeutic …*, Springer, 2020. [HTML]
8. T. Kumar, R. K. Pandey, R. Kumar, and C. V. Sudheep, "Historical perspective of nanotechnology and functionalized nanomaterials," in *Functionalized*, Springer, 2023. [HTML]
9. C. Binns, "Introduction to nanoscience and nanotechnology," 2021. [HTML]

10. N. Alizadeh and A. Salimi, "Multienzymes activity of metals and metal oxide nanomaterials: applications from biotechnology to medicine and environmental engineering," Journal of Nanobiotechnology, 2021. springer.com

11. M. Ramya, P. S. Kumar, G. Rangasamy, and G. Rajesh, "A recent advancement on the applications of nanomaterials in electrochemical sensors and biosensors," Chemosphere, 2022. [HTML]

12. L. Fritea, F. Banica, T. O. Costea, and L. Moldovan, "Metal nanoparticles and carbon-based nanomaterials for improved performances of electrochemical (Bio) sensors with biomedical applications," Materials, 2021. mdpi.com

13. N. Hossain, M. H. Mobarak, M. A. Mimona, and M. A. Islam, "Advances and significances of nanoparticles in semiconductor applications–A review," Results in ..., 2023. sciencedirect.com

14. S. Kim and S. Yoon, "On the origin of the plasmonic properties of gold nanoparticles," Bulletin of the Korean Chemical Society, 2021. [HTML]

15. M. Sun, X. Fu, K. Chen, and H. Wang, "Dual-plasmonic Gold@ Copper sulfide core–shell nanoparticles: Phase-selective synthesis and multimodal photothermal and photocatalytic behaviors," ACS Applied Materials & Interfaces, 2020. google.com

16. SS Salem, EN Hammad, AA Mohamed, "A comprehensive review of nanomaterials: Types, synthesis, characterization, and applications," Biointerface Res. Appl, 2022. academia.edu

17. Y. Khan, H. Sadia, S. Z. A. Shah, M. N. Khan, and A. A. Shah, "Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review," Catalysts, 2022. mdpi.com

18. T. A. Saleh, "Trends in the sample preparation and analysis of nanomaterials as environmental contaminants," Trends in Environmental Analytical Chemistry, 2020. [HTML]

19. H. Wu, W. P. Fahy, S. Kim, H. Kim, N. Zhao, L. Pilato, "Recent developments in polymers/polymer nanocomposites for additive manufacturing," Progress in Materials, Elsevier, 2020. [HTML]

20. A. Al Rashid, S. A. Khan, S. G. Al-Ghamdi, and M. Koç, "Additive manufacturing of polymer nanocomposites: Needs and challenges in materials, processes, and applications," Journal of Materials, 2021. sciencedirect.com

21. G. Huang, W. Chen, T. Wu, H. Guo, C. Fu, Y. Xue, "… -based nano-additives toward high-performance polymer nanocomposites with enhanced mechanical, thermal, flame retardancy and smoke suppressive properties," Chemical Engineering, Elsevier, 2021. [HTML]

22. N. H. Al-Mutairi, A. H. Mehdi, "Nanocomposites materials definitions, types and some of their applications: A review," European Journal of…, 2022. uobabylon.edu.iq

23. T. Hassan, A. Salam, A. Khan, and S. U. Khan, "Functional nanocomposites and their potential applications: A review," *Journal of Polymer*, 2021. researchgate.net

24. J. Njuguna, F. Ansari, S. Sachse, and V. M. Rodriguez, "Nanomaterials, nanofillers, and nanocomposites: types and properties," in Environmental Safety of..., Elsevier, 2021. [HTML]

25. C. Deepa, L. Rajeshkumar, and M. Ramesh, "Preparation, synthesis, properties and characterization of graphene-based 2D nano-materials for biosensors and bioelectronics," Journal of Materials Research and …, 2022. sciencedirect.com

26. S. Noreen, M. B. Tahir, A. Hussain, and T. Nawaz, "Emerging 2D-Nanostructured materials for electrochemical and sensing Application-A review," International Journal of ..., 2022. [HTML]

27. G. Korotcenkov, "Current trends in nanomaterials for metal oxide-based conductometric gas sensors: Advantages and limitations. part 1: 1D and 2D nanostructures," Nanomaterials, 2020. mdpi.com
28. Q. Ma, G. Ren, K. Xu, and J. Z. Ou, "Tunable optical properties of 2D materials and their applications," Advanced Optical Materials, 2021. [HTML]
29. P. A. Vinosha, A. Manikandan, R. Ragu, and A. Dinesh, "Impact of nickel substitution on structure, magneto-optical, electrical and acoustical properties of cobalt ferrite nanoparticles," Journal of Alloys and Compounds, 2021. [HTML]
30. Y. Qi, M. A. Sadi, D. Hu, M. Zheng, and Z. Wu, "Recent progress in strain engineering on van der Waals 2D materials: Tunable electrical, electrochemical, magnetic, and optical properties," Materials, 2023. wiley.com
31. M. J. Ndolomingo, N. Bingwa, and R. Meijboom, "Review of supported metal nanoparticles: synthesis methodologies, advantages and application as catalysts," Journal of Materials Science, 2020. academia.edu
32. C. Gao, F. Lyu, and Y. Yin, "Encapsulated metal nanoparticles for catalysis," Chemical Reviews, 2020. [HTML]
33. J. O. Gidiagba, C. Daraojimba, and K. A. Ofonagoro, "Economic impacts and innovations in materials science: a holistic exploration of nanotechnology and advanced materials," Science & Technology, 2023. fepbl.com
34. R. R. Kumar, M. Samykano, A. K. Pandey, "… change materials and nano-enhanced phase change materials for thermal energy storage in photovoltaic thermal systems: A futuristic approach and its technical …," … and Sustainable Energy …, Elsevier, 2020. [HTML]