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Nanomaterials in Chemistry Emerging Applications in Catalysis, Energy Storage (Including Lithium-Ion Batteries), and Biomedicine

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Abstract **Review Article**

Nanomaterials have gained remarkable attention in modern chemistry due to their unique size-dependent properties, large surface area, and enhanced reactivity, making them highly suitable for a wide range of advanced applications. This article presents a comprehensive review of the recent developments and applications of nanomaterials in the fields of catalysis, energy storage (with a special focus on lithium-ion batteries), and biomedicine. In catalysis, nanomaterials such as metal nanoparticles, nanostructured oxides, and carbon-based materials have shown exceptional activity and selectivity, offering improved performance in processes like photocatalysis, environmental cleanup, and industrial reactions. In energy storage, nanomaterials have significantly advanced the efficiency and capacity of lithium-ion batteries by improving electrode conductivity, increasing charge-discharge rates, and enhancing cycle life. Materials like graphene, carbon nanotubes, silicon nanostructures, and transition metal compounds are discussed for their roles in next-generation battery technologies. In the biomedical field, nanomaterials offer innovative solutions in drug delivery, bioimaging, diagnostics, and cancer treatment, owing to their ability to target specific sites, carry therapeutic agents, and respond to biological stimuli. The article also summarizes experimental findings, synthesis methods, material characterizations, and comparative performance analyses to provide a clear understanding of structure property relationships. Challenges such as toxicity, long-term stability, Environmental effects and scalability are also addressed, with suggestions for future research directions. Overall, the review highlights how nanomaterials are shaping the future of sustainable chemistry and advanced technologies across multiple sectors.

Keywords: Nanomaterials, catalysis, lithium-ion batteries, energy storage, biomedicine, drug delivery, photocatalysis, carbon-based nanostructures, transition metal oxides, nanotechnology.

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1. INTRODUCTION

Nanomaterials are materials that have at least one external dimension in the nanoscale range of 1 to 100 nanometres. Their extremely small size gives rise to exceptional physical, chemical, optical, and mechanical properties. Due to these unique attributes, nanomaterials have attracted significant attention in recent years, particularly in the fields of chemistry, materials science, and biomedical engineering. Traditional materials often lack the tunability and enhanced performance that nanomaterials can provide.

In chemistry, nanomaterials offer new opportunities in catalysis, energy storage, and biomedicine. Their high surface-area-to-volume ratio increases the number of active sites available for chemical reactions, which can lead to improved catalytic performance and reaction kinetics. For energy storage, nanomaterials help enhance the capacity, efficiency, and lifespan of batteries and supercapacitors by providing faster ion transport and greater structural stability. In the biomedical field, nanomaterials enable innovative approaches in drug delivery, diagnostics, and therapeutic applications by improving bioavailability and enabling targeted treatments.

The development of nanomaterials is driven by advances in synthesis methods, such as sol-gel processing, hydrothermal methods, chemical vapor deposition (CVD), and green synthesis. These methods allow precise control over the size, shape, composition, and surface functionalization of nanoparticles, thereby enabling their design for specific applications.

This review aims to provide a comprehensive overview of the current and emerging applications of nanomaterials in three major areas: catalysis, energy storage (including lithium-ion batteries), and biomedicine. Each section of this paper will examine how nanomaterials have improved the performance and efficiency of systems in these fields and will highlight the future trends and challenges associated with their use. The review also discusses the environmental and health implications of nanomaterials, emphasizing the importance of green synthesis and safe handling practices.

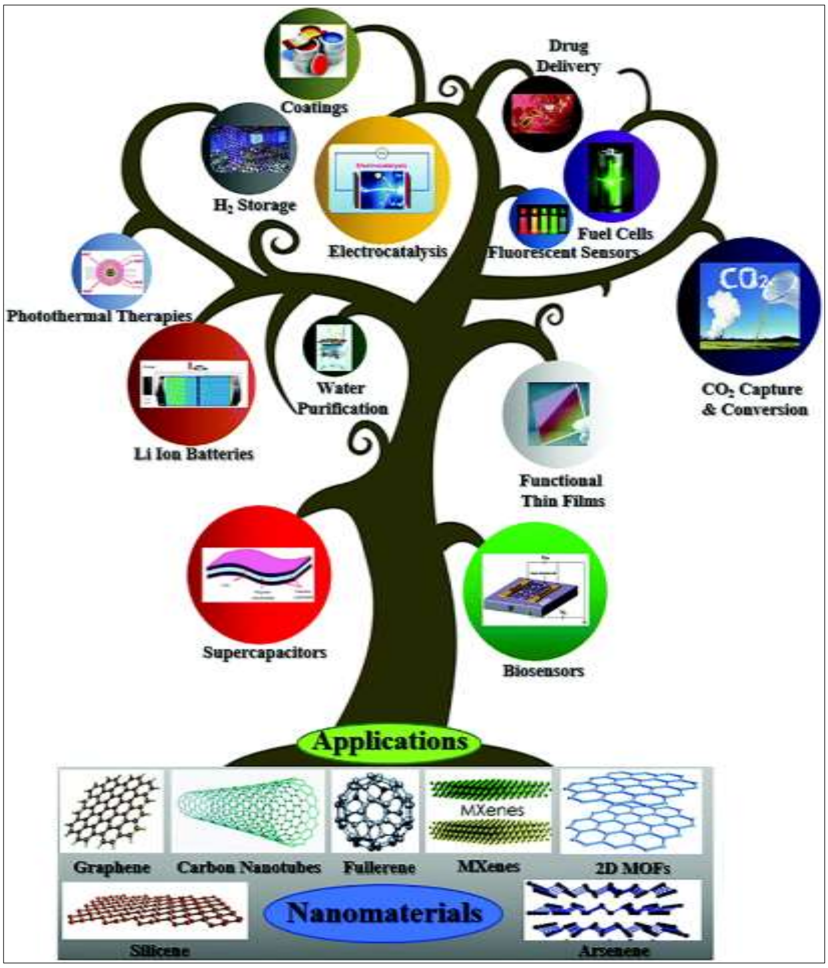

Fig 1: Nano materials in chemistry as an introduction

2. Types and Properties of Nanomaterial

Nanomaterials are broadly categorized based on their dimensions and composition. By dimension, nanomaterials are classified into zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) structures:

0D Nanomaterials: All dimensions are in the nanoscale. Examples include quantum dots and nanoparticles. They are often used in bioimaging and electronics due to their quantum confinement effects.

1D Nanomaterials: These include nanotubes and nanowires. Their elongated shape provides directional conductivity and is beneficial for use in nanoelectronics and sensors.

2D Nanomaterials: Materials such as graphene and MoS_2 sheets fall in this category. They have large surface areas and are promising for energy storage and catalysis.

3D Nanomaterials: These include dendrimers and nanoflowers, often used in drug delivery and catalysis due to their hierarchical structures. In terms of composition, nanomaterials can be carbon-based (e.g., graphene, carbon nanotubes), metal-based (e.g., gold, silver, copper), metal oxide (e.g., TiO_2, ZnO), or polymer-based. Each type possesses distinct characteristics that determine its application potential. Nanomaterials exhibit a wide range of enhanced properties, such as:

Mechanical Strength: Carbon nanotubes are known for their tensile strength, surpassing steel by orders of magnitude.

Thermal Conductivity: Graphene and CNTs have excellent thermal conductivity, beneficial for electronic cooling systems.

Electrical Conductivity: Metal nanoparticles and carbon-based nanomaterials improve electrical conductivity in sensors and batteries.

Chemical Reactivity: The increased surface area leads to more active sites for catalysis.

Optical Properties: Quantum dots and noble metal nanoparticles exhibit surface plasmon resonance and fluorescence, making them useful for imaging and sensing.

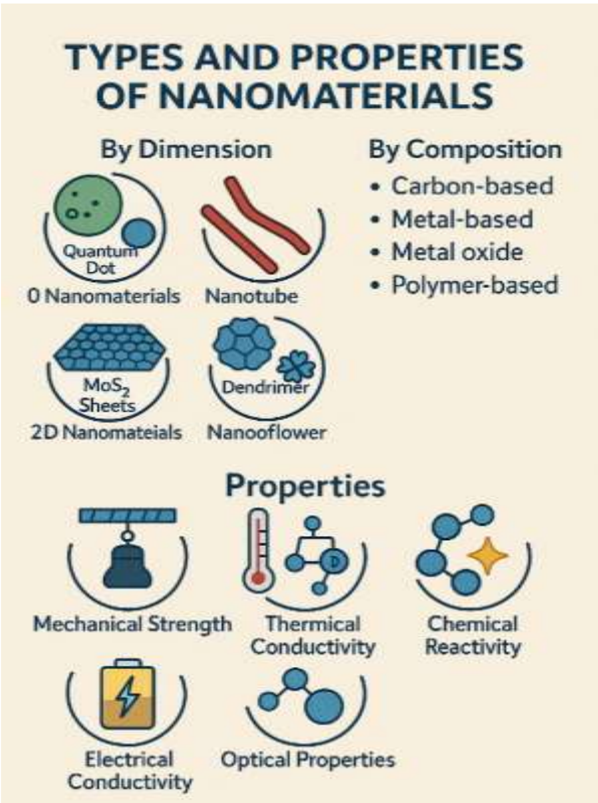

Fig 2: Types and properties of Nanomaterials

3. Applications in Catalysis

Catalysis is one of the most significant areas where nanomaterials have revolutionized traditional chemical processes. Nano catalysts exhibit superior performance due to their high surface-area-to-volume ratio, increased number of active sites, and unique surface energy properties. These features enable nanomaterials to enhance catalytic activity, selectivity, and stability while reducing the required amount of catalyst material. Nano catalysts are used in various chemical reactions, including hydrogenation, oxidation, CO_2 reduction, and environmental pollutant degradation. Based on their function, nanomaterials in catalysis can be divided into heterogeneous catalysts, photocatalysts, and electrocatalysts.

3.1 Heterogeneous Catalysis

In heterogeneous catalysis, the catalyst exists in a different phase than the reactants, usually as a solid with gaseous or liquid reactants. Nanoparticles of metals like platinum (Pt), palladium (Pd), gold (Au), and silver (Ag) are widely used due to their excellent surface reactivity. For instance, platinum nanoparticles supported on carbon or metal oxides are extensively used in fuel processing and emission control systems, such as catalytic converters in automobiles. Bimetallic and alloy nano catalysts offer further improvements by tuning the electronic properties and synergistic interactions between metals. For example, Pt-Pd and Au-Pd alloys show better performance in oxidation reactions than their monometallic counterparts. Supported nano catalysts, where nanoparticles are dispersed on high-surface-area supports like graphene oxide, silica, or alumina, improve dispersion and prevent nanoparticle aggregation. This support interaction enhances the thermal and mechanical stability of the catalysts.

3.2 Photocatalysis

Photocatalysis involves the acceleration of a photoreaction in the presence of a catalyst activated by light. Semiconductor nanomaterials such as titanium dioxide (TiO_2), zinc oxide (ZnO), and cadmium sulphides (CdS) are widely used due to their light absorption properties and ability to generate reactive species under UV or visible light. TiO_2 nanoparticles, for instance, have been applied in self-cleaning surfaces, water purification, and air decontamination. However, their efficiency under visible light is limited. To overcome this, researchers have introduced doping with non-metals (N, C) or metals (Ag, Fe) and developed composites with graphene or other semiconductors to improve visible-light photocatalytic performance.

3.3 Electrocatalysis

Electrocatalysts play a crucial role in energy conversion processes such as water electrolysis, fuel cells, and CO_2 reduction. Nanostructured catalysts provide more active sites and better electron transport than bulk materials. For the Oxygen Reduction Reaction (ORR), Pt/C remains the standard, but alternatives like Fe–N–C nanostructures are under investigation. For the Hydrogen Evolution Reaction (HER), materials like MoS_2 and WS_2 show promising activity due to their layered structures and edge-active sites. For CO_2 Reduction Reaction (CO_2RR), copper-based nanoparticles and bimetallic systems are explored for producing valuable fuels like methane or methanol. The tunability of nanomaterials allows control over morphology (e.g., nanotubes, nanorods), composition, and electronic properties, enabling their use in precise catalytic applications.

4 Applications in Energy Storage

The demand for high-performance, reliable, and sustainable energy storage systems is growing rapidly, driven by the increasing use of renewable energy sources and portable electronic devices. Nanomaterials play a transformative role in energy storage technologies by enhancing capacity, charge/discharge rates, and overall lifespan. Their high surface area, improved conductivity, and ability to accommodate strain during cycling make them ideal for modern devices. Nanomaterials are applied in several types of energy storage systems, including lithium-ion batteries (LIBs), supercapacitors, and fuel cells. Each of these technologies' benefits from the nanoscale engineering of electrode and electrolyte materials.

4.1 Lithium-Ion Batteries (LIBs)

Lithium-ion batteries are widely used in smartphones, laptops, electric vehicles, and renewable energy systems. The performance of LIBs depends heavily on the characteristics of the anode, cathode, and electrolyte materials. Nanomaterials are used in all these components to boost performance:

Anode Materials:

Graphene, silicon nanoparticles, and SnO_2 nanostructures are widely explored. Silicon has a theoretical capacity nearly ten times higher than graphite but suffers from volume expansion. Nanosizing silicon mitigates this issue by providing better structural flexibility and shorter lithium diffusion paths.

Cathode Materials:

Nanostructured $LiFePO_4$ and layered transition metal oxides like NMC (nickel-manganese-cobalt) show improved charge transfer and cycling stability. The nanostructures allow for faster lithium-ion diffusion and more stable intercalation processes.

Electrolytes:

Nanocomposite solid and gel polymer electrolytes improve mechanical stability, ionic conductivity, and safety over traditional liquid electrolytes. Nanoparticles like Al_2O_3 or SiO_2 are often incorporated to enhance ion transport. Additionally, nanocoating's on electrode surfaces prevent side reactions and improve interfacial stability, leading to longer battery life and better thermal management.

4.2 Supercapacitors

Supercapacitors are energy storage devices known for high power density, fast charge/discharge, and long cycle life. However, they typically have lower energy density than batteries. Nanomaterials help bridge this gap: Carbon-based materials like activated carbon, carbon nanotubes (CNTs), and graphene offer high surface areas and excellent electrical conductivity. Metal oxides such as MnO_2 and RuO_2 are used for pseudo capacitance, which contributes additional energy storage through redox reactions. Conducting polymers like polyaniline and polypyrene can be combined with nanostructures to improve capacitance and mechanical flexibility. Nanocomposites combining different materials (e.g., graphene-MnO_2) have demonstrated improved electrochemical performance due to synergistic effects.

4.3 Fuel Cells

Fuel cells convert chemical energy directly into electricity using an electrolyte and catalysts. Nanomaterials enhance both the efficiency and durability of these devices. Nano catalysts reduce the use of expensive noble metals like platinum. Pt nanoparticles supported on carbon are common for the ORR in proton exchange membrane fuel cells (PEMFCs). Non-precious catalysts like Fe–N–C or Co–N–C show promise due to lower costs and increasing efficiency. Nanostructured membranes and electrodes provide better ionic conductivity and structural strength. The tailored design of nanoscale features allows fuel cells to operate at lower temperatures and deliver more power with less degradation over time.

5. Applications in Biomedicine

Nanomaterials are playing an increasingly vital role in the biomedical field, offering innovative solutions for diagnosis, therapy, drug delivery, tissue engineering, and imaging. Their nanoscale dimensions allow them to interact with biological systems at the molecular and cellular level. Furthermore, their high surface area, tenable surface chemistry, and unique optical and magnetic properties make them ideal for a variety of medical applications. Biomedical nanomaterials can be classified into several categories, including metallic nanoparticles (e.g., gold, silver), polymeric nanoparticles, liposomes, quantum dots, dendrimers, and carbon-based nanomaterials such as carbon nanotubes and graphene oxide.

5.1 Drug Delivery

Targeted drug delivery is one of the most prominent applications of nanomaterials in medicine. Conventional drug delivery methods often suffer from issues like poor bioavailability, rapid degradation, and side effects due to lack of targeting. Nanocarriers overcome these challenges by improving drug solubility, controlling release, and allowing site-specific targeting. Liposomes and polymeric nanoparticles are widely used as biocompatible drug delivery vehicles.

Gold nanoparticles (AuNPs) can be functionalized with drugs and targeting ligands for tumour-specific delivery. Carbon nanotubes (CNTs) and graphene oxide are used as carriers for anticancer drugs due to their high loading capacity and ability to cross cell membranes'-sensitive and temperature-sensitive nanocarriers release drugs in response to specific stimuli within the body, improving treatment efficacy. These systems have been explored for treatment of cancer, cardiovascular diseases, bacterial infections, and neurodegenerative disorders.

5.2 Diagnostics and Bioimaging

Nanomaterials provide high sensitivity and specificity for disease diagnostics. They enhance the performance of imaging techniques like MRI, CT scans, PET, and fluorescence imaging. Quantum dots (QDs) are fluorescent semiconductor nanoparticles that offer high brightness and photostability for long-term imaging of cells and tissues. Iron oxide nanoparticles (Fe_3O_4) are used as contrast agents in magnetic resonance imaging (MRI). Gold and silver nanoparticles exhibit surface plasmon resonance, making them suitable for optical biosensing and colorimetric assays. Nano sensors can detect biomarkers, DNA, or pathogens with high precision, enabling early diagnosis and real-time monitoring of diseases.

5.3 Cancer Therapy and Theragnostic

Nanomaterials have opened new paths in cancer therapy through photothermal therapy (PTT) and photodynamic therapy (PDT). In PTT, materials like gold nanorods absorb near-infrared light and convert it into heat to destroy cancer cells selectively. Theragnostic nanoplatforms combine diagnostic and therapeutic functions in a single system, allowing simultaneous cancer detection and treatment. These multifunctional systems improve treatment accuracy and reduce systemic side effects.

5.4 Challenges and Safety Concerns

Despite their potential, biomedical nanomaterials raise concerns regarding toxicity, biodegradability, and long-term effects. Some nanoparticles may accumulate in organs or cause oxidative stress and inflammation. Therefore, biocompatibility testing and regulatory approval are essential before clinical use. Current research focuses on developing biodegradable, non-toxic, and targeted nanomaterials that meet safety standards. Green synthesis methods are also being explored to minimize environmental and biological risks. Synthesis Methods of Nanomaterials The performance of nanomaterials in catalysis, energy storage, and biomedical applications is strongly influenced by their size, shape, surface characteristics, and crystallinity. Therefore, selecting an appropriate synthesis method is crucial. Nanomaterials can be synthesized using top-down and bottom-up approaches. Each method has its own advantages and limitations depending on the desired application.

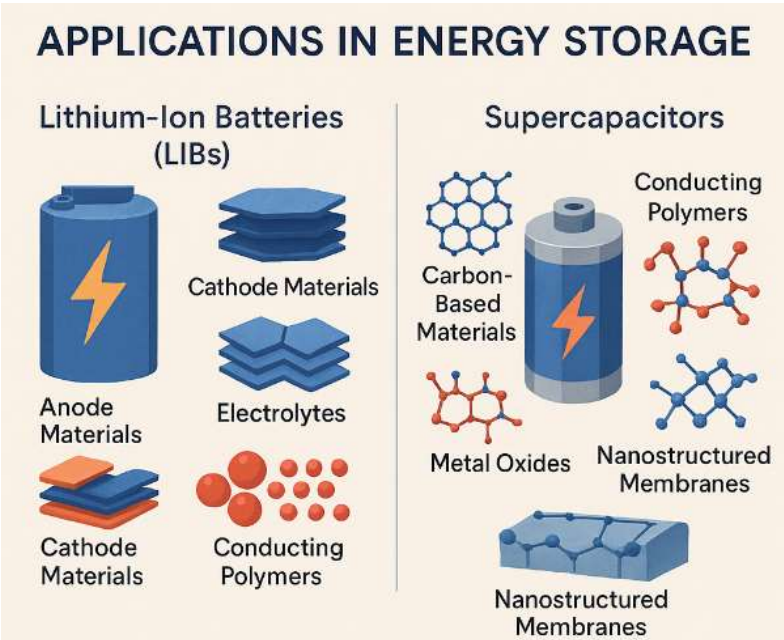

Fig 3 Applications in Energy storage

6.1 Top-Down Approaches

Top-down methods involve breaking down bulk materials into nanoscale structures through physical or mechanical means. These methods are generally simple but may lead to irregular shapes and surface defects.

Ball Milling:

A widely used mechanical method in which bulk materials are crushed into nanoparticles using high-energy collisions. Suitable for metallic and ceramic nanomaterials.

Laser Ablation:

A high-energy laser beam is used to vaporize material from a solid target, forming nanoparticles in a controlled environment.

Etching and Lithography:

Often used in microelectronics, these processes can produce well-defined nanostructures on surfaces. While top-down methods are cost-effective, they offer limited control over particle size distribution and surface chemistry.

6.2 Bottom-Up Approaches

Bottom-up synthesis builds nanomaterials atom by atom or molecule by molecule, offering better control over structure and composition.

Sol-Gel Method:

Involves the hydrolysis and condensation of metal alkoxides to form a gel, which is then dried and calcined to yield metal oxide nanoparticles. Common for TiO_2, ZnO, and SiO_2.

Hydrothermal and Solvothermal Synthesis:

These processes use aqueous or organic solvents under high pressure and temperature to grow nanocrystals. They are ideal for producing uniform nanoparticles with controlled morphology.

Chemical Vapor Deposition (CVD):

A process where gaseous precursors react or decompose on a substrate to form nanomaterials like carbon nanotubes or thin films.

Co-precipitation:

Simple and scalable, this method uses chemical reactions in solution to precipitate nanoparticles, widely used for magnetite (Fe_3O_4) and other oxide nanomaterials.

Microemulsion Technique:

Uses surfactant-stabilized emulsions to control nucleation and growth of nanoparticles, suitable for producing monodispersed metal and oxide particles.

Fig 4: Top down and bottom-up approaches

6.3 Green Synthesis

Green synthesis methods use biological organisms or plant extracts as reducing and stabilizing agents. These eco-friendly techniques are gaining popularity due to reduced toxicity and cost.

Plant Extract-Mediated Synthesis: Phytochemicals like flavonoids, terpenoids, and alkaloids reduce metal salts into nanoparticles.

Microbial Synthesis:

Bacteria, fungi, and algae can produce metal nanoparticles intracellularly or extracellularly. Green methods are especially important for biomedical applications, where biocompatibility and toxicity are critical.

6.4 Surface Functionalization

After synthesis, nanoparticles are often functionalized to improve dispersion, stability, or target specificity. Functional groups like –COOH, $–NH_2$, or PEG chains can be added for biomedical or catalytic use. Surface modification enhances interactions with biological systems or supports, making the materials more effective in applications such as targeted drug delivery, biosensing, and catalyst immobilization.

Nanomaterial	Structure/Form	Key Properties	Applications
Carbon Nanotubes (CNTs)	Cylindrical tubes of carbon atoms	High surface area, electrical conductivity, strength	Batteries, sensors, drug delivery
Graphene	Single layer of carbon atoms	Excellent thermal/electrical conductivity	Supercapacitors, biomedical imaging
Metal Oxide Nanoparticles	Spherical/crystalline forms (e.g., TiO_2, ZnO)	Photocatalytic activity, chemical stability	Catalysis, environmental remediation
Magnetic Nanoparticles	Fe_3O_4, $CoFe_2O_4$	Superparamagnetism, biocompatibility	MRI contrast agents, targeted drug delivery
Quantum Dots	Semiconductor nanoparticles	Size-tunable emission, photostability	Bioimaging, photovoltaics
Silica Nanoparticles	Porous/hollow structures	Biocompatibility, surface modification	Drug delivery, biosensors

Table 1: Common Types of Nanomaterials and Their Properties

7. Characterization Techniques for Nanomaterials

Characterization is essential to understand the physical, chemical, and structural properties of nanomaterials. Accurate characterization ensures proper evaluation of their performance in applications like catalysis, energy storage, and biomedicine. A wide variety of techniques are used to determine particle size, shape, crystallinity, surface area, composition, and functional groups.

7.1 Scanning Electron Microscopy (SEM):

SEM provides detailed surface morphology and particle size images of nanomaterials. It is useful for visualizing the topography and aggregation behaviour of nanoparticles.

One study revealed the spherical magnetite NPs synthesis from natural iron oxide (Fe2O3) ore by top-down destructive approach with a particle size varies from ~20 to ~50 nm in the presence of organic oleic acid. A simple top-down route was employed to synthesize colloidal carbon spherical particles with control size. The synthesis technique was based on the continuous chemical adsorption of polyoxometalates (POM) on the carbon interfacial surface. Adsorption made the carbon black aggregates into relatively smaller spherical particles, with high dispersion capacity and narrow size distribution. It also revealed from the micrographs, that the size of the carbon particles becomes smaller with sonication time. A series of transition-metal dichalcogenide nanodots (TMD-NDs) were synthesized by combination of grinding and sonication top-down techniques from their bulk crystals. It was revealed that almost all the TMD-NDs with sizes <10 nm shows an excellent dispersion due to narrow size distribution. Lately, highly photoactive active Co3O4 NPs were prepared via top-down laser fragmentation, which is a top-down process. The powerful laser irradiations generate well-uniform NPs having good oxygen vacancies (Zhou *et al*., 2016). The average size of the Co3O4 was determined to be in the range of 5.8 nm ± 1.1 nm.

7.2 Transmission Electron Microscopy (TEM):

TEM offers high-resolution internal structure and morphology. It allows direct observation of lattice fringes and the crystallinity of nanoparticles at the atomic scale. TEM is based on electron transmittance principle, so it can provide information of the bulk material from very low to higher magnification. The different morphologies of gold NPs are studied via this technique. Fig. provides some TEM micrographs showing various morphologies of gold NPs, prepared via different methods The size of the NPs obtained by both methods was varied from 100 nm to 500 nm. The details of this study are provided. Green and biogenic bottom-up synthesis attracting many researchers due to the feasibility and less toxic nature of processes. These processes are cost-effective and environment friendly, where synthesis of NPs is accomplished via biological systems such as using plant extracts. Bacteria, yeast, fungi, Aloe vera, tamarind and even human cells are used for the synthesis of NPs. Au NPs have been synthesis from the biomass of wheat and using the microorganism and plant extracts as reducing agent. It provides the merits and demerits of various top-down and bottom-up techniques. TEM also provides essential information about two or more-layer materials, such as the quadrupolar hollow shell structure of Co3O4 NPs observed through TEM. These NPs founded to be exceptionally active as anode in Li-ion batteries. Porous multi shell structure induces shorter Li+ diffusion path length with adequate annulled space to buffer the volume expansion, good cycling performance, greater rate capacity, and specific capacity as well.

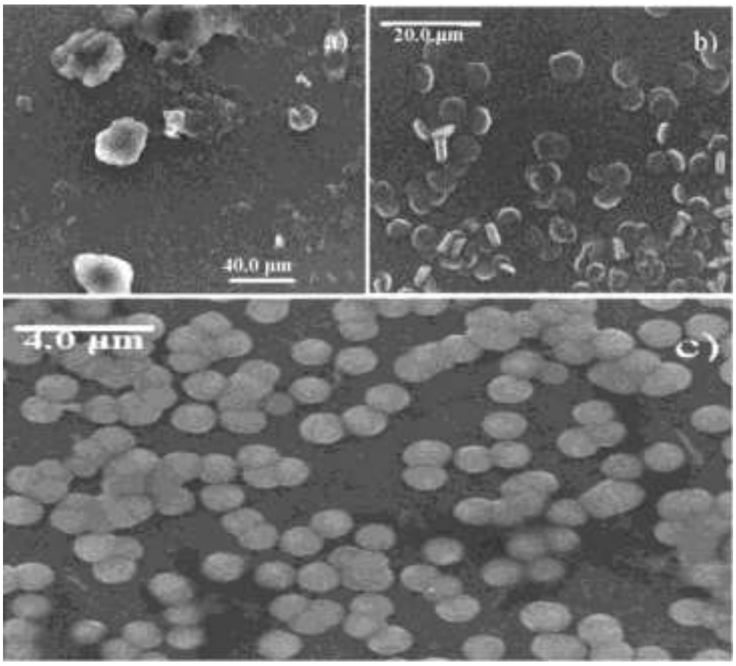

Fig 5: Shows the SEM Image of Nano particles at different size

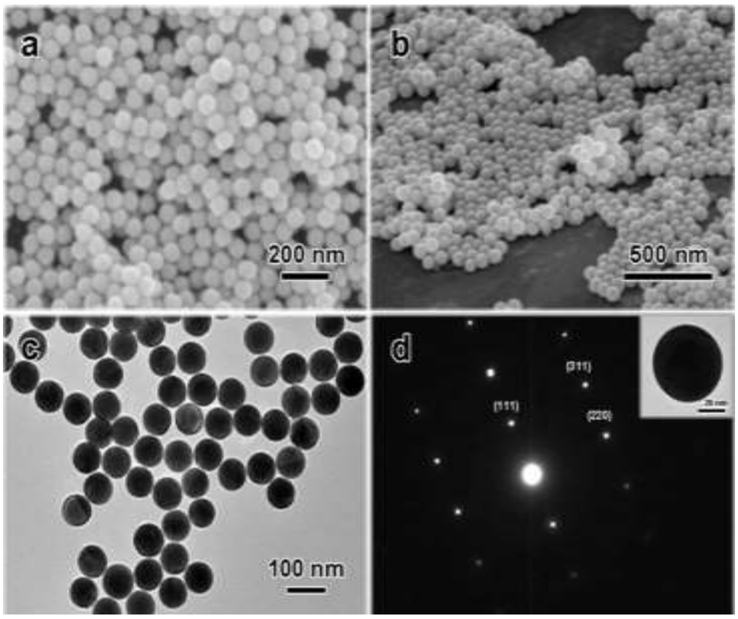

Fig 6: Shows the TEM Images of Nano Particles

7.3 FTIR Analysis

Vibrational characterization of nanoparticles is normally studied via FT-IR and Raman spectroscopies. These techniques are the most developed and feasible as compared to other elemental analytical methods. The most important range for NPs is the fingerprint region, which provides signature information about the material. In one study, functionalization of Pt NPs (1.7 nm mean size) and its interaction with Alumina substrate studied via FT-IR and XPS technique. FT-IR confirms the functionalization as it showed the signature vibrational peaks of carboxylate C–O 2033 cm−1, respectively in addition to a broader O–H peak at 3280 cm−1. The degree of functionalization was revealed from the red shift values of FTIR bands. The stable structures were found thermodynamically stable until high temperature of 1500 °C. However, a disordered–ordered cause instability in the latter case, and thus thermodynamically unstable.

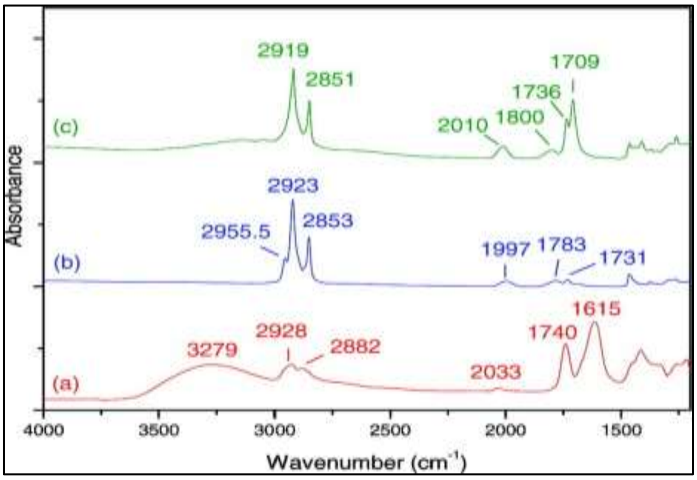

Fig 7: shows FTIR Analysis of Nano particles at different peak

7.4 X-ray Diffraction (XRD):

XRD is used to determine the crystalline phases and average crystallite size. It helps identify the purity and structure of materials based on diffraction patterns. X-ray diffraction (XRD) spectra of Nps showed a series of diffraction peaks at 32.63, 35.67, 38.78, 48.88, 58.34, 61.69, 68.16, and 75.32°, that was related to the (1 1 0), (1 1 1), (2 0 2), (0 2 0), (1 1 3), (3 1 1), and (0 0 4) planes of monoclinic CuO (JCPDS 80–1916), respectively (Fig. 2), (Amin *et al*., 2021). The existence of diffraction peaks (between 2 = 35–39°) indicated the formation of CuO. This affirms the growth of monoclinic crystalline morphology. Copper Oxide nanoparticles are clearly defined and strongly reflected in XRD patterns that provide evidence of CuO nanoparticles' crystalline nature (Bashiri Rezaie *et al*., 2018). As a result, the current findings are similar to previous reports on CuO synthesis (Rangel *et al*., 2019). The sharpness of the peaks in XRD spectrum reveals their crystalline structure. For synthesized CuO NPs, the lattice parameters were a = 4.684, b = 3.425, and c = 5.129. The average size of CuO NPs was calculated using Debye–Scherrer formula from the width of the peaks in the XRD spectrum. The calculated size and peak indexing are presented in figure.

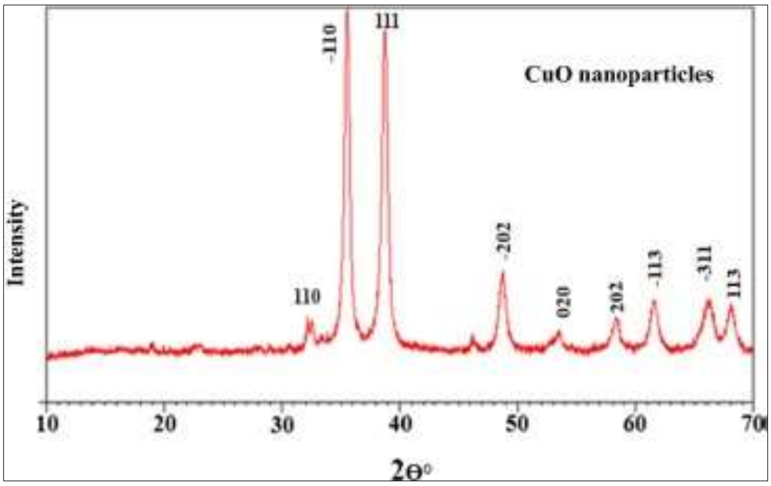

Fig 8: shows Peaks of the nano particles at different angle

7.5 Thermogravimetric Analysis (TGA) Curve of Nanomaterials

The thermogravimetric analysis (TGA) curve illustrates the general thermal stability and decomposition behaviour of nanomaterials commonly used in catalysis, energy storage, and biomedicine. The analysis was conducted over a temperature range of 25 °C to 800 °C under an inert atmosphere.

The TGA profile is divided into three distinct regions:

Region I (25 °C – 150 °C):

This initial phase shows a minor weight loss (~2–3%), attributed to the evaporation of physically adsorbed water and loosely bound moisture on the surface of the nanomaterials. This stage is typical for hydrophilic nanomaterials and is not associated with chemical decomposition.

Region II (150 °C – 400 °C):

A moderate weight loss (~20%) is observed in this region due to the decomposition of surface-bound organic molecules, such as surfactants, capping agents, or unreacted precursors used during synthesis. In composite or functionalized nanomaterials, this stage also indicates the breakdown of organic moieties or polymers used for surface modification.

Region III (400 °C – 800 °C):

This phase exhibits a slower weight loss (~10–15%) corresponding to the thermal degradation of more stable components, such as carbon backbones or core nanostructures. In metal oxide-based nanomaterials, this stage may also involve oxidation or structural rearrangement. The overall thermal profile confirms that nanomaterials retain substantial thermal stability up to high temperatures, supporting their suitability for use in harsh environments, such as catalytic reactors, battery systems, and biomedical sterilization processes. The TGA data serve as a critical reference for determining safe operating temperatures and evaluating the purity and structural integrity of synthesized nanomaterials.

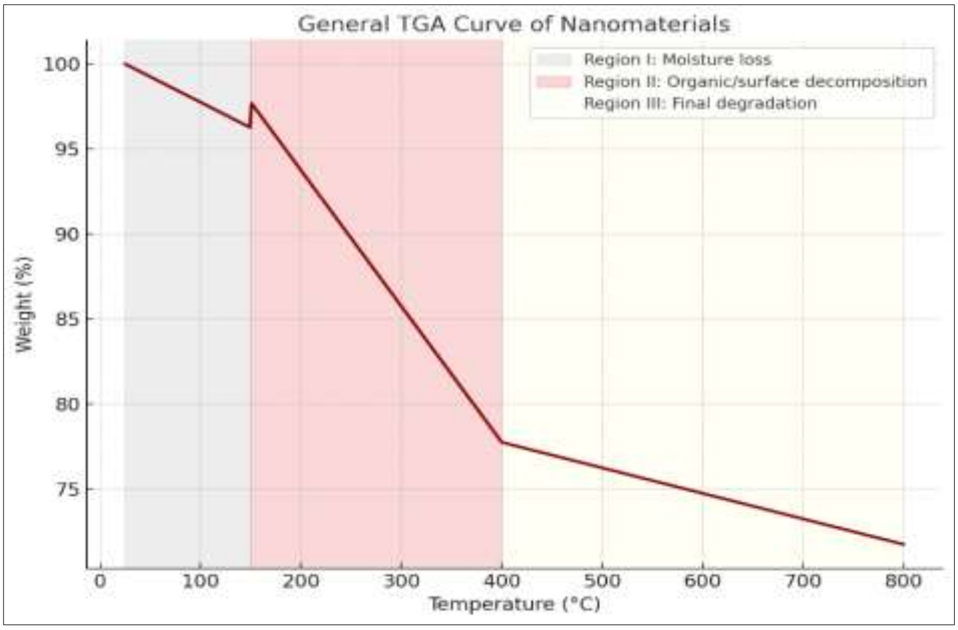

Fig 9 shows TGA Analysis of Nano Materials at different Regions

8 Advantages and Challenges of Nanomaterials in Chemistry

Nanomaterials have opened new possibilities in chemical applications by enabling enhanced reactivity, improved selectivity, and multifunctional properties. However, despite their promising advantages, several challenges must be addressed for their safe, cost-effective, and large-scale use in real-world applications.

8.1 Advantages

8.1.1 High Surface Area

One of the most significant benefits of nanomaterials is their high surface-to-volume ratio. This feature allows more active sites to participate in chemical reactions, which is especially useful in catalysis, energy storage, and drug delivery. For example, nanoparticles of platinum or palladium provide more reaction sites per gram than their bulk counterparts.

8.1.2 Tuneable Properties

The physical and chemical properties of nanomaterials—such as optical absorption, magnetism, and electrical conductivity—can be precisely tuned by changing their size, shape, and composition. This tunability allows custom design of materials for specific needs in catalysis, batteries, and medical imaging.

8.1.3 Enhanced Performance in Devices

Nanostructured electrodes in lithium-ion batteries enable faster ion transport and reduce charge time. Similarly, nanomaterials used in supercapacitors, sensors, or fuel cells provide higher power density and longer lifespan.

8.1.4 Targeted Delivery and Diagnostic Accuracy

In biomedicine, functionalized nanoparticles can selectively target diseased cells, reduce side effects and improve treatment outcomes. Nano sensors and imaging agents increase diagnostic sensitivity and accuracy.

8.2 Challenges

8.2.1 Toxicity and Biocompatibility

Many nanoparticles can induce oxidative stress, inflammation, or organ accumulation when introduced into biological systems. This is a significant concern for medical and environmental applications. More research is needed on the long-term effects of nanomaterials on human health and ecosystems.

8.2.2 Environmental and Safety Regulations

The environmental release of nanomaterials during manufacturing, use, or disposal may pose ecological risks. Regulatory guidelines are still evolving, and there is a lack of standardized methods for toxicity testing and risk assessment.

8.2.3 Scalability and Cost

Many synthesis methods produce nanomaterials in small quantities and require expensive equipment or hazardous chemicals. Developing scalable, low-cost, and green synthesis methods remains a challenge, especially for industrial applications.

8.2.4 Stability and Aggregation

Nanoparticles tend to agglomerate due to their high surface energy, which can reduce their effectiveness. Ensuring long-term stability and dispersibility in solvents or biological fluids is essential for consistent performance.

8.3 Ethical and Societal Considerations

The rapid development of nanotechnology raises ethical questions regarding privacy (in medical diagnostics), consent (in drug delivery trials), and unequal access to advanced treatments. Transparent communication, public awareness, and ethical guidelines are needed to build trust in nanotechnology applications.

9. Recent Developments and Case Studies

Recent research has shown remarkable progress in the development and application of nanomaterials in chemistry. These advances demonstrate how nanotechnology is being translated from laboratory-scale innovation to real-world impact. This section highlights some notable case studies and trends in catalysis, energy storage, and biomedical applications.

9.1 Catalysis: Gold Nanoparticles in Green Chemistry

Gold nanoparticles (AuNPs), once considered chemically inert in bulk, have demonstrated high catalytic activity at the nanoscale. A notable case involves the use of AuNPs for low-temperature CO oxidation, where they outperform traditional catalysts. These catalysts have been tested in automotive emission control and air purification systems.

In another example, Au–Pd alloy nanoparticles have shown enhanced activity in the selective oxidation of alcohols in water, a reaction relevant for pharmaceutical industries. Researchers are exploring biomass-derived supports, such as carbon from agricultural waste, to anchor nano catalysts and promote sustainable green chemistry.

9.2 Energy Storage: Silicon Nanoparticles in Lithium-Ion Batteries

Silicon (Si) nanoparticles are being developed to replace graphite as the anode material in lithium-ion batteries. Si offers a theoretical capacity nearly ten times higher than graphite. A recent study introduced graphene-coated Si nanoparticles, which maintained over 80% capacity after 200 charge–discharge cycles, solving the problem of volume expansion. Nanostructured $LiFePO_4$ cathodes with carbon nanotube coatings have been successfully commercialized for high-power battery applications, especially in electric vehicles (EVs).

9.3 Biomedicine: Iron Oxide Nanoparticles in MRI and Cancer Therapy

Iron oxide (Fe_3O_4) nanoparticles are approved by the FDA for use as contrast agents in magnetic resonance imaging (MRI). They offer high contrast with low toxicity and are easily functionalized. Researchers have developed dual-function magnetic nanoparticles for simultaneous imaging and hyperthermia treatment of tumours. In another example, dendrimer-coated quantum dots have been used to image live cells with high clarity and minimal background noise.

9.4 Hybrid and Multifunctional Nanomaterials

Modern trends focus on creating multifunctional hybrid nanomaterials. For example: Metal–organic frameworks (MOFs) combined with nanoparticles enhance gas storage, catalysis, and drug delivery. Janus nanoparticles, which have two chemically distinct faces, are being explored for directional drug delivery and emulsion stabilization. Core–shell nanoparticles, such as $Au@SiO_2$, offer improved thermal stability and controlled surface properties for diverse applications.

10. Future Perspectives and Research Directions

The continuous evolution of nanomaterials opens new possibilities for innovation in chemistry. Future research aims not only to enhance the performance of nanomaterials but also to address the existing limitations related to safety, cost, and scalability. The following directions highlight key areas expected to shape the next decade of nanomaterials research.

10.1 Smart and Stimuli-Responsive Nanomaterials

An emerging trend is the development of smart nanomaterials that respond to external stimuli such as pH, temperature, light, or magnetic fields. These materials are especially useful in drug delivery systems, where controlled release at targeted sites is critical. For example, pH-sensitive polymer-coated nanoparticles can release drugs specifically in acidic tumour environments. In catalysis, photo responsive nano catalysts are being developed for efficient solar-to-chemical energy conversion, which is vital for photocatalytic water splitting and environmental remediation.

10.2 Sustainable and Green Nanotechnology

Green synthesis methods will likely become standard practice. Future efforts will focus on replacing toxic solvents and reagents with biocompatible, renewable plant extracts and biodegradable templates. In parallel, the concept of circular nanotechnology recycling nanomaterials from waste products—will gain attention to reduce environmental footprints. Development of bio-based nanomaterials from cellulose, chitosan, or lignin offers promise for applications in biodegradable packaging, sensors, and environmental cleanup.

10.3 Integration with Artificial Intelligence (AI) and Machine Learning

AI is expected to revolutionize nanomaterials research. Machine learning algorithms can predict the optimal composition, synthesis conditions, and performance characteristics of nanomaterials based on large datasets. This approach can reduce experimental time and cost while improving material design efficiency.

AI tools are already being used to predict nanotoxicity, assist in high-throughput screening, and optimize nano catalyst formulations for specific reactions.

10.4 Regulatory and Safety Frameworks

For successful commercialization, there is a pressing need for standardized protocols to evaluate nanomaterial safety, toxicity, and environmental impact. Researchers must collaborate with regulatory bodies to establish guidelines for safe production, handling, and disposal of nanomaterials. Future research must also include life cycle assessments (LCA) and eco-toxicity studies to ensure long-term sustainability.

10.5 Interdisciplinary Collaboration

Nanomaterials research increasingly relies on collaboration between chemists, materials scientists, biologists, engineers, and data scientists. Interdisciplinary research centres and industry-academia partnerships will play a crucial role in transforming laboratory innovations into scalable, market-ready solutions. From energy and environmental science to medicine and electronics, nanomaterials will be central to solving some of the world's most pressing challenges.

11. CONCLUSION

Nanomaterials have transformed the landscape of modern chemistry through their unique properties and multifunctional capabilities. Their nanoscale dimensions enable unprecedented control over reactivity, selectivity, and transport phenomena, making them ideal for cutting-edge applications in catalysis, energy storage, and biomedicine. In catalysis, nanomaterials offer high surface area and tenable active sites, contributing to more efficient and environmentally friendly chemical processes. In energy storage, the development of nanostructured electrodes has improved the capacity, stability, and rate performance of lithium-ion batteries and other electrochemical devices. In biomedicine, functionalized nanoparticles have revolutionized targeted drug delivery, imaging, and diagnostics, enhanced therapeutic outcomes while minimized side effects. However, the widespread use of nanomaterials also presents significant challenges, including toxicity, environmental concerns, and production scalability. These issues demand ongoing attention to ensure that nanotechnology develops in a safe, ethical, and sustainable manner.

Looking ahead, advances in smart nanomaterials, green synthesis, and AI-driven design are expected to drive the next wave of innovation. Interdisciplinary collaboration will be critical in translating laboratory research into real-world technologies that address global needs in energy, healthcare, and sustainability.

Nanomaterials are no longer limited to research labs they are rapidly becoming integral components of modern technology and society. Continued research, responsible development, and global cooperation will ensure that their full potential is realized safely and equitably.

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