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RESEARCH PAPER

Nanocomposites of Transition Metal Oxides: A Multifunctional Platform for Supercapacitor and Biomedical Applications

Govind Bagaria[1*], Mahesh Chandra[2], Abhay Kaushik[3], Suresh K. Verma[4], Anu Vedi[5] and Raaz K. Maheshwari[6]

[1] Department of Physics, Mohan Lal Sukhadia University, Udaipur, Rajasthan
[2] Department of Zoology, Seth P.C. Bagla (P.G.) College, Hathras, Uttar Pradesh
[3] Department of Chemistry, Parishkar College of Global Excellence, Jaipur Rajasthan
[4] Department of Chemistry, Govt Girls College, Chomu, Jaipur, Rajasthan
[5] Department of Botany, Banasthali Vidhyapeeth, Niwai, Tonk, Rajasthan
[6] Department of Chemistry, SBRM Govt PG College, Nagaur, Rajasthan
[1*] Email: govindbagaria3333@gmail.com

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ABSTRACT

Transition metal oxide (TMO) nanocomposites have emerged as a versatile and multifunctional class of materials owing to their exceptional physicochemical properties, which are finely tunable through nanoscale engineering. This review explores the design, fabrication, and application of TMO-based nanocomposites in supercapacitor and biomedical domains. By integrating TMOs such as MnO_2, Co_3O_4, NiO and Fe_3O_4 with polymeric, ceramic or carbonaceous matrices. These composites exhibit synergistic improvements in electrical conductivity, redox activity, mechanical strength and biocompatibility. The structural characteristics including matrix selection, nanofiller dispersion, interfacial bonding and fabrication methods such as sol-gel processing, hydrothermal synthesis and in situ polymerization are critically examined. TMO nanocomposites demonstrate significant promise in energy storage applications especially in electric double-layer capacitors (EDLCs), pseudo-capacitors, and hybrid supercapacitors due to their high specific capacitance and cyclic stability. Concurrently, their biomedical potential spans tissue engineering, drug delivery and biosensing leveraging features like antibacterial activity, porosity and surface functionality. Comprehensive characterization using techniques such as XRD, TEM, CV and EIS is essential for performance optimization. Despite existing challenges in scalability, dispersion and interface control the continued development of TMO nanocomposites holds great promise for advancing both energy and healthcare technologies.

Keywords: *Transition metal oxides, Nanofibers, Electrochemical property, Biosensing, polypyrrole etc.*

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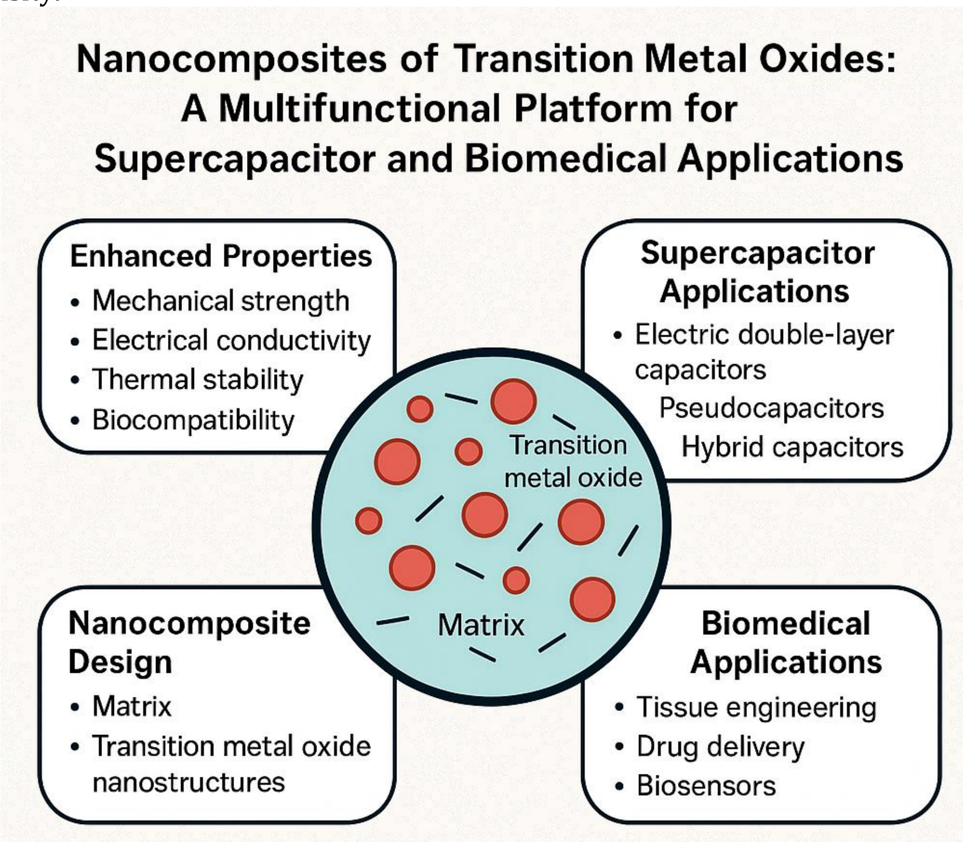
INTRODUCTION

Nanocomposite materials, comprising multiple phases with at least one in the nanometer scale (typically 1–100 nm) have garnered increasing attention due to their ability to exhibit unique and often superior properties not found in conventional micro-composites or monolithic materials. By embedding nanoparticles, nanotubes or lamellar nanostructures into a metal, ceramic or polymer matrix. It is possible to tailor properties such as mechanical strength, corrosion resistance, electrical and thermal conductivity and chemical durability Mohan L., *et al*., (2024). The enhanced performance of nanocomposites originates from the synergy between the filler and matrix which is highly dependent on the interfacial interaction, dispersion uniformity, particle morphology and the nature of bonding be it covalent, ionic, van der Waals or hydrogen bonding. Among various nanocomposite systems polymer nanocomposites (PNCs) reinforced with inorganic nanofillers such as modified clays, boehmite or carbon nanotubes (CNTs) have emerged as a significant class of materials with enhanced thermal, mechanical and barrier properties. Polymer/clay nanocomposites for instance, show notable improvements due to the exfoliation or intercalation of clay layers which drastically increases the interface area and thereby amplifies the matrix–filler interactions. CNTs discovered by Iijima in 1991 brought further momentum to this field due to their high aspect ratio, exceptional mechanical strength, thermal conductivity and flexibility C. Esposito Corcione and M. Frigione (2012). These nanostructures are now commonly integrated into thermoplastic or thermosetting polymer matrices to engineer lightweight, multifunctional materials suitable for structural and functional applications including energy storage, tissue engineering and biosensing.

The integration of nanocomposites into energy storage devices particularly supercapacitors has opened new avenues for high-performance electrochemical systems. Supercapacitors also referred to as electrochemical capacitors or ultracapacitors have drawn immense interest due to their high-power density, rapid charge/discharge capability and long cycle life. Unlike batteries, supercapacitors offer quick energy delivery and superior cyclic stability although they typically suffer from lower energy density. To address this limitation researchers have explored the development of nanostructured electrode materials, particularly those based on transition metal oxides (TMOs) and carbon nanomaterials like graphene and CNTs to enhance capacitance and energy density.



Graphene Navoselov KS *et al*., (2012), with its two-dimensional atomic structure, high electrical conductivity and immense surface area, has become a preferred material for supercapacitor electrodes. However, practical limitations such as restacking reduce the accessible surface area, limiting its performance. To overcome this, graphene–metal oxide nanocomposites incorporating electroactive oxides like MnO_2, NiO, Co_3O_4, Fe_3O_4, TiO_2, RuO_2 and ZnO have been developed. These hybrids utilize the high conductivity of graphene and the pseudocapacitive behavior of TMOs resulting in superior specific capacitance, rate performance and long-term stability. Such hybrid electrodes are capable of operating in electric double-layer capacitors (EDLCs), pseudo-capacitor or hybrid supercapacitors depending on their dominant charge storage mechanism electrostatic, faradaic or a combination of both. The performance of these advanced supercapacitor systems is closely linked to material crystallinity, porosity and interfacial properties. For example, increased crystallinity in TMOs often enhances conductivity and faradaic charge transfer. Structural characterization techniques like X-ray diffraction (XRD), transmission electron microscopy (TEM), differential scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA) are vital in evaluating dispersion, interfacial bonding and thermal transitions, providing insights that guide material design. Beyond energy storage, TMO-based nanocomposites also demonstrate potential in biomedical applications. Due to their biocompatibility, antibacterial activity and ability to support cellular growth and differentiation, these materials are being explored for use in tissue engineering scaffolds, drug delivery systems, biosensors and implantable medical devices. The multifunctionality of such nanocomposites offering electrical conductivity, mechanical reinforcement and bioactivity makes them ideal for next-generation bioelectronic platforms Chaturvedi A. (2022).

Nanocomposites of transition metal oxides, especially when integrated with polymeric or carbonaceous matrices provide a versatile and high-performance platform for both supercapacitor and biomedical applications. Their tunable structure–property relationships driven by nanoscale engineering hold the key to addressing critical challenges in energy and health technologies, positioning them as essential materials in the advancement of 21st-century science and engineering.

STRUCTURAL CHARACTERISTICS AND FABRICATION OF NANOCOMPOSITES

The structural characteristics and fabrication strategies of nanocomposites are pivotal to their functional performance in applications ranging from supercapacitors to biomedical devices. Nanocomposites are engineered by integrating nanoscale fillers into a continuous matrix, forming hybrid systems with enhanced physicochemical properties that surpass those of their individual constituents. Achieving optimal performance requires judicious selection and engineering of both the matrix and nanofiller to ensure compatibility, uniform dispersion, and synergistic interactions.

MATRIX MATERIALS:

The matrix constitutes the continuous phase that encapsulates and supports the nanofillers. Matrix materials are broadly categorized into Ajayan PM. *et al*., (2003):

- **Polymers:** Due to their flexibility, low cost and ease of processing, polymers are widely employed as matrices. Common examples include polyvinyl alcohol (PVA), polyaniline (PANI), polypyrrole (PPy) and polyethylene oxide (PEO). These materials are particularly advantageous in electrochemical and biomedical applications due to their tunable properties.
- **Ceramics:** Characterized by excellent thermal and chemical stability, ceramics such as alumina (Al_2O_3), zirconia (ZrO_2) and silica (SiO_2) are suitable for environments demanding high durability and inertness.
- **Metals:** Metallic matrices offer superior mechanical strength and electrical conductivity. They are primarily utilized in structural reinforcements and electronic components where robustness and conductivity are essential.

NANOFILLERS:

Nanofillers impart unique electrical, mechanical, and optical functionalities to the composite. Major categories include:

- **Transition Metal Oxides (TMOs):** Nanostructured TMOs such as manganese dioxide (MnO_2), cobalt oxide (Co_3O_4) and nickel oxide (NiO) are valued for their redox activity, high specific capacitance and chemical stability. These features make them highly suitable for energy storage and biosensing platforms.
- **Carbon-Based Materials:** Materials like carbon nanotubes (CNTs), graphene and activated carbon exhibit exceptional electrical conductivity, mechanical resilience and large surface areas all of which are critical for charge transport and mechanical reinforcement.
- **Organically Modified Clays:** Layered materials such as montmorillonite (MMT) and layered double hydroxides (LDHs) contribute to improved thermal stability and act as efficient ion-conductive pathways in various applications.

The interaction between the matrix and nanofillers ranging from covalent and hydrogen bonding to Van der Waals and electrostatic forces plays a crucial role in dictating the mechanical robustness and functional performance of the nanocomposite.

FABRICATION TECHNIQUES:

The synthesis method significantly influences the microstructure and performance of nanocomposites. Common fabrication techniques include:

- **In Situ Polymerization:** Nanofillers are dispersed in monomer solutions followed by polymerization. This technique promotes uniform distribution and strong interfacial bonding, particularly advantageous for conductive polymer-based nanocomposites.
- **Sol-Gel Processing:** Starting from metal alkoxides or salts, this method involves hydrolysis and polycondensation reactions to form a gel matrix that encapsulates nanofillers. It is widely used for ceramic nanocomposites with controlled microstructures.
- **Electrochemical Deposition:** This method enables precise control over nanocomposite film thickness and composition. It is especially useful in the deposition of TMOs and conductive polymers onto electrode substrates for energy storage applications.
- **Hydrothermal and Solvothermal Synthesis:** These high-pressure, high-temperature techniques facilitate the crystallization of nanostructures with well-defined morphologies. They are commonly used for synthesizing TMOs and hybrid composites with tailored functionalities.
- **Melt Intercalation and Solution Mixing:** Suitable for polymer/clay systems these techniques involve the intercalation of polymer chains into clay layers. Exfoliation of the clay enhances barrier properties and mechanical strength Bauera F. *et al*., (2004).

STRUCTURAL MORPHOLOGIES:

- **Intercalated Structures:** Polymer chains penetrate between layered nanofillers increasing interlayer spacing while maintaining some order.
- **Exfoliated Structures:** Nanofiller layers are fully delaminated and dispersed throughout the matrix, maximizing interfacial contact and property enhancement.
- **Phase-Separated Structures:** Poor compatibility may lead to nanofiller aggregation and phase separation, which degrade composite performance. This is typically addressed through surface functionalization and optimized processing conditions.

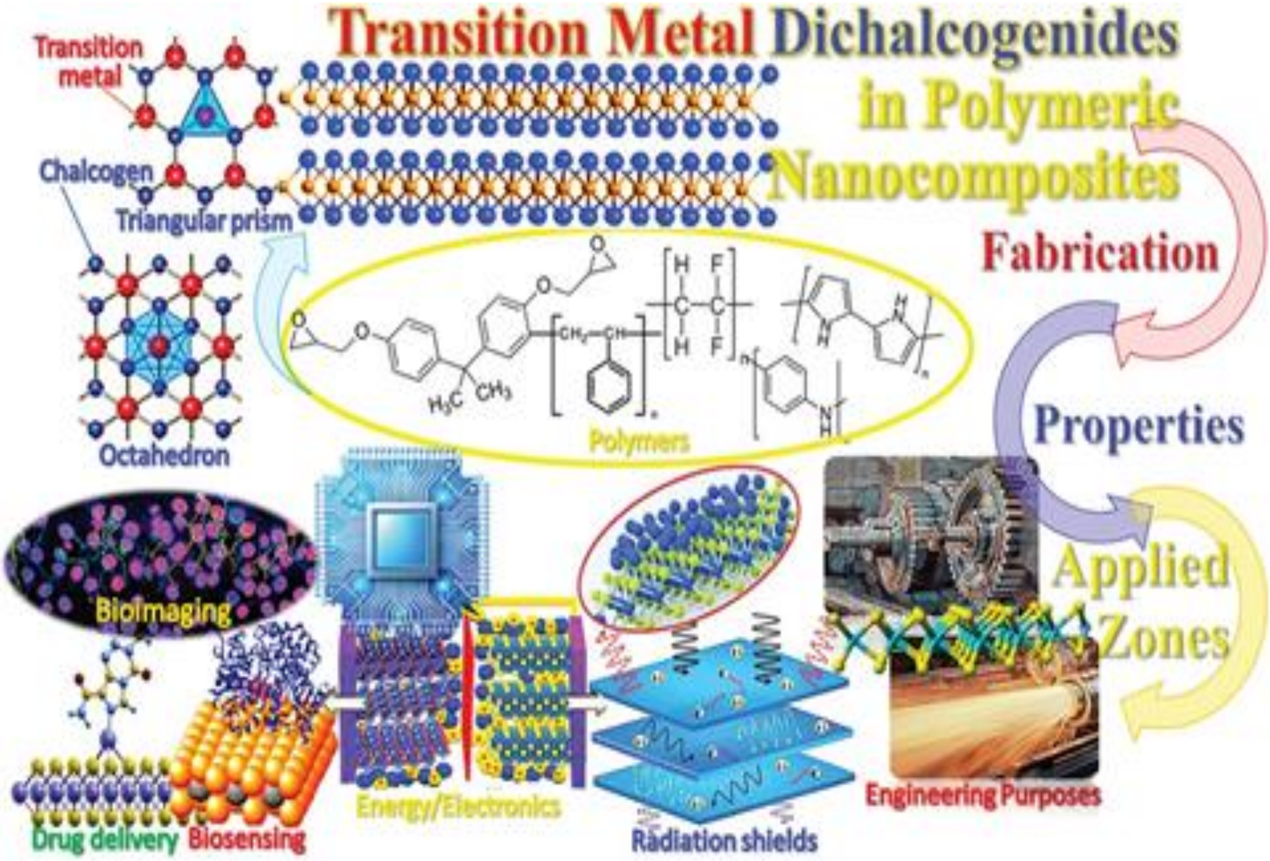
ROLE OF DISPERSION AND INTERFACE ENGINEERING:

Table 1: Role of Dispersion and Interface Engineering

Category	Subtypes / Techniques	Examples	Key Features / Role
Matrix Materials	Polymers	PVA, PANI, PPy, PEO	Flexible, processable, cost-effective
	Ceramics	Al_2O_3, ZrO_2, SiO_2	High thermal and chemical stability
	Metals	Cu, Al, Ti	Excellent electrical conductivity and mechanical strength
Nanofillers	Transition Metal Oxides (TMOs)	MnO_2, Co_3O_4, NiO	High specific capacitance, redox activity, chemical stability
	Carbon-Based Materials	CNTs, Graphene, Activated Carbon	High electrical conductivity, surface area and mechanical strength
	Organically Modified Clays	Montmorillonite (MMT), LDHs	Enhanced thermal stability, ion-conductive pathways
Fabrication Techniques	In Situ Polymerization	-	Ensures uniform dispersion, strong filler-matrix bonding
	Sol-Gel Processing	-	Ideal for ceramic nanocomposites, creates uniform microstructures
	Electrochemical Deposition	-	Precise control of composition and thickness, useful in electrode fabrication
	Hydrothermal / Solvothermal Synthesis	-	Produces crystalline TMOs with controlled morphology
	Melt Intercalation / Solution Mixing	-	Common for polymer/clay systems, improves mechanical and barrier properties
Structural Morphologies	Intercalated Structures	Polymer chains between clay layers	Moderate enhancement of properties
	Exfoliated Structures	Fully dispersed nanofillers	Maximized surface contact, best performance
	Phase-Separated Structures	Aggregated fillers	Poor performance, mitigated by surface functionalization
Interface Engineering	Dispersion Techniques	Ultrasonication, mechanical stirring	Prevents nanoparticle agglomeration
	Surface Functionalization	Carboxylation, sulfonation (e.g., CNTs, Graphene)	Enhances matrix compatibility, load transfer, and electron/ion transport
	Interfacial Bonding	Covalent, hydrogen bonding, Van der Waals, electrostatic	Determines composite mechanical and functional stability

The uniform dispersion of nanofillers and robust interfacial bonding are essential for optimizing nanocomposite properties. Agglomeration leads to localized stress concentrations and reduced performance. Surface functionalization techniques such as carboxylation or sulfonation of CNTs and graphene enhance interfacial compatibility with the matrix facilitating better stress transfer electron mobility and ion transport. Effective interface engineering is therefore a critical factor in the design of high-performance nanocomposites Pokropivnyi VV. (2002), Niihara K. (1991), Guadango L. *et al.*, (2021).

PROPERTIES OF TRANSITION METAL OXIDE NANOCOMPOSITES



Transition metal oxides (TMOs) are widely incorporated into nanocomposite systems due to their versatile physicochemical properties, which stem from their variable oxidation states, strong redox activity, and capacity to support rapid ion and electron transport. These characteristics are particularly valuable in applications such as energy storage, catalysis, sensors, and environmental remediation. The integration of TMOs into nanocomposites results in synergistic effects that often surpass the performance of individual components. A key property of TMOs is their high specific capacitance, which arises from pseudocapacitive behavior driven by fast and reversible redox reactions occurring at or near the surface. This makes them especially attractive for use in supercapacitors and battery electrodes. Additionally, their ability to accommodate oxygen vacancies and defects enhances ionic mobility, contributing to improved electrochemical response and catalytic efficiency. When TMOs are incorporated into a nanostructured matrix, the interfacial interactions between the oxide particles and the surrounding material play a crucial role. These interactions influence charge distribution, defect formation, and local conductivity. The nature of the interface can determine how effectively the TMO phase contributes to overall charge transport and structural stability. Particle size and morphology are also critical. Nanoscale TMO particles exhibit a high surface-area-to-volume ratio, increasing the number of active sites for electrochemical or catalytic activity. Furthermore, reducing particle size can shorten ion diffusion paths, thereby improving kinetic performance in applications such as lithium-ion batteries or electrochemical sensors. Crystallinity is another factor that influences functional properties.

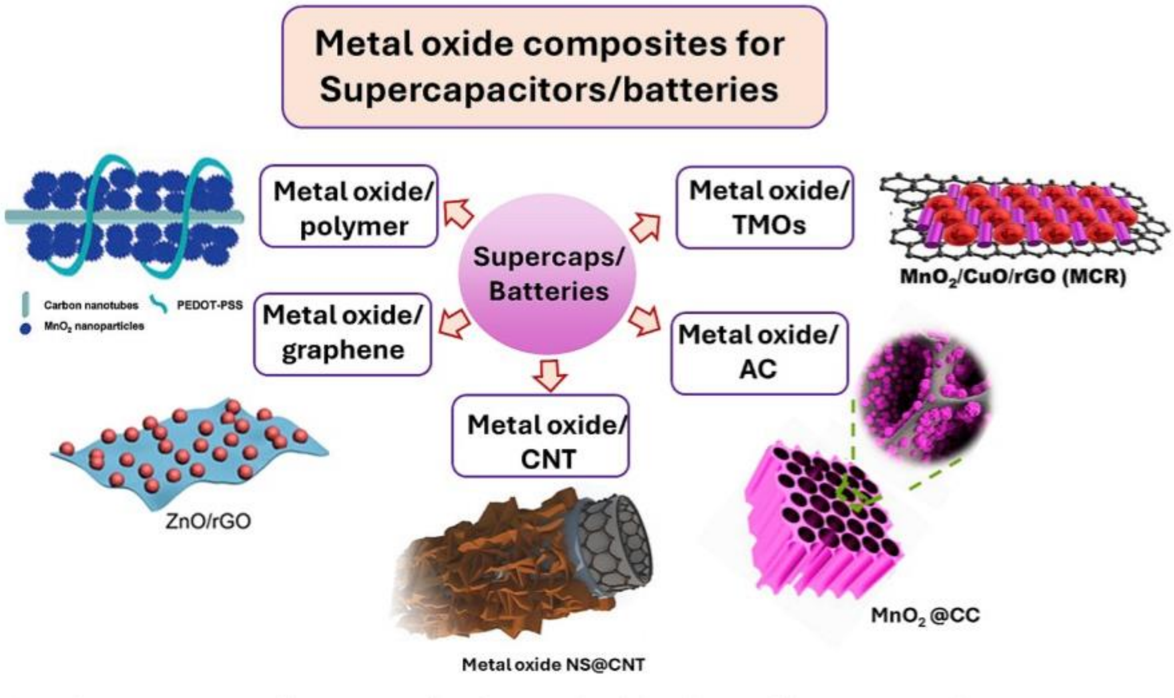
Highly crystalline TMOs typically offer more stable and predictable electronic behavior, whereas amorphous or poorly crystalline materials may provide enhanced surface reactivity but reduced structural integrity. Therefore, optimizing the balance between crystallinity and surface activity is essential for achieving targeted performance. Mechanical reinforcement is an additional benefit. TMOs, when dispersed uniformly in a polymeric or ceramic matrix, can enhance the mechanical strength and thermal stability of the host material. This is particularly important for applications requiring structural integrity under harsh operating conditions. The chemical stability of TMOs, especially in oxidative or high-temperature environments, adds to the durability of the resulting nanocomposite. This makes them suitable for long-term operation in demanding environments such as fuel cells, industrial catalysts, and high-temperature coatings.

Overall, the performance of TMO-based nanocomposites is highly dependent on the careful control of synthesis parameters, including particle size, dispersion uniformity, phase purity and interface engineering. Tailoring these parameters allows researchers to design materials with application-specific functionalities and enhanced overall performance.

SUPERCAPACITOR APPLICATIONS

Supercapacitors, also known as ultracapacitors, are advanced energy storage devices that bridge the gap between conventional capacitors and batteries Zakir S. *et al*., (2020), Dai M *et al*. (2020), Raj S *et al*., (2019). They offer:

- Rapid charge/discharge cycles
- High power density
- Long operational life



Supercapacitors are generally categorized into three types:

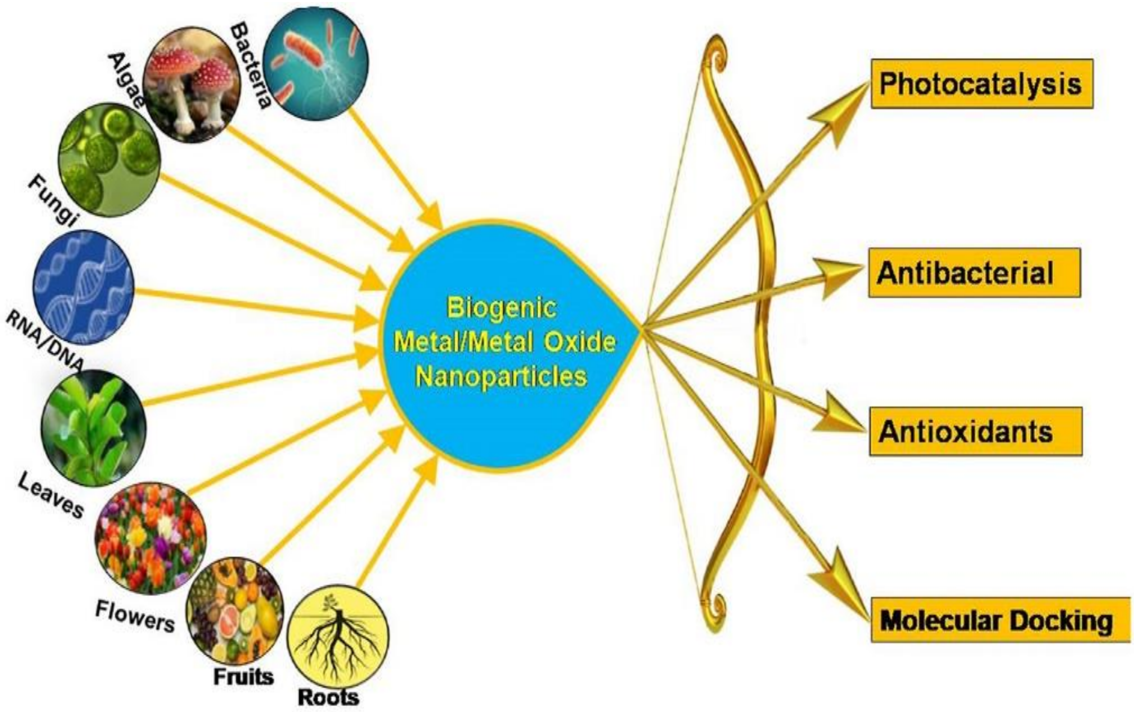
Type	Mechanism	Materials Used
Electric Double-Layer Capacitors (EDLCs)	Store energy via electrostatic charge separation at the electrode-electrolyte interface.	Activated carbon, Graphene
Pseudocapacitors	Rely on fast and reversible redox reactions at or near the electrode surface.	TMOs (e.g., MnO_2, Co_3O_4), Conductive polymers (PANI, PPy)
Hybrid Capacitors	Combine EDLC and pseudocapacitive behavior for balanced performance.	TMO/Carbon hybrids, Polymer/Carbon composites

TMO-based nanocomposites are especially attractive as supercapacitor electrodes because they offer:

- High specific capacitance and redox activity
- Enhanced electrical conductivity (especially when combined with carbon-based materials like graphene)
- Excellent cycling stability due to their robust nanostructures

BIOMEDICAL APPLICATIONS

The tunable properties and multifunctionality of TMO nanocomposites enable their use in various biomedical domains:



Application	Function of Nanocomposite	Example TMOs
Tissue Engineering	Provide 3D scaffolds that support cell adhesion, growth, and differentiation	TiO_2, ZnO
Drug Delivery	Enable controlled and targeted delivery through surface functionalization and porosity	Fe_3O_4, ZnO
Biosensors	Enhance sensitivity, selectivity, and response time for biomolecule detection	ZnO, TiO_2, Co_3O_4

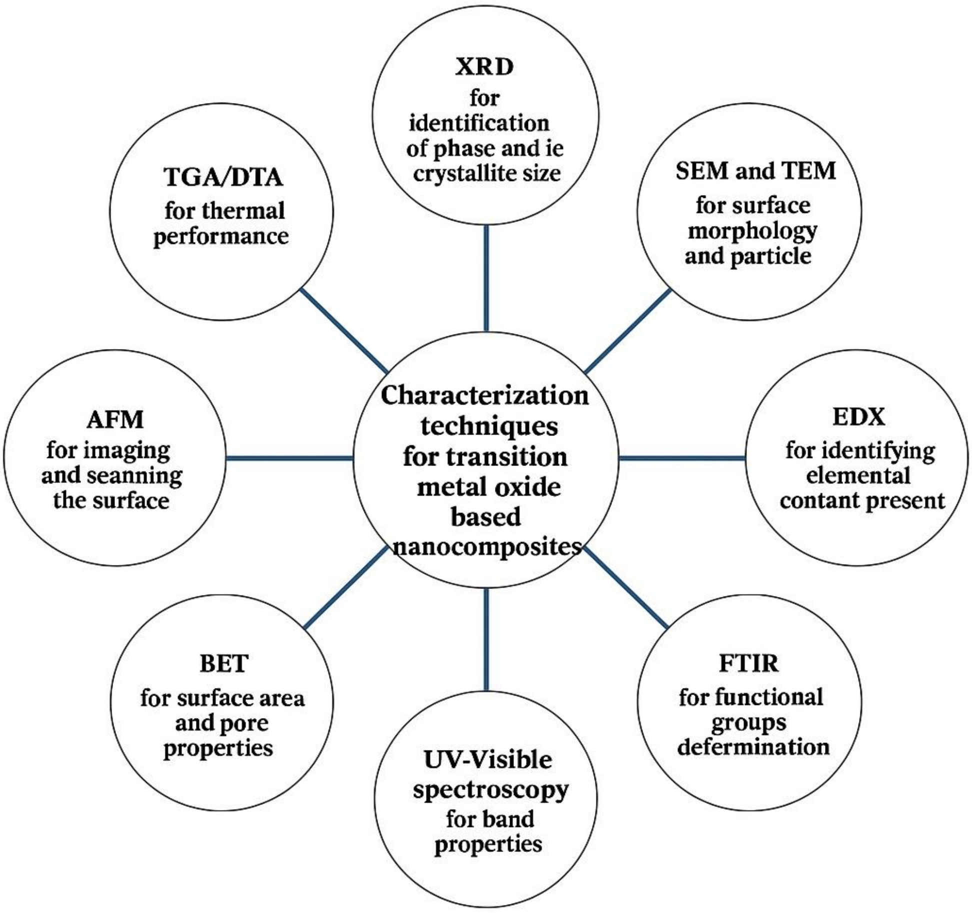
These TMOs offer a unique combination of biocompatibility, chemical reactivity, and low toxicity, which supports:

- Cellular interaction
- Reactive oxygen species (ROS) regulation
- Magnetic targeting and imaging (in the case of Fe_3O_4)

CHARACTERIZATION TECHNIQUES

Characterization of nanocomposites involves both structural analysis and functional performance assessment:

Technique	Purpose
X-Ray Diffraction (XRD)	Determines crystallinity and phase composition
Transmission Electron Microscopy (TEM)	Examines morphology, nanostructure and particle dispersion
Differential Scanning Calorimetry (DSC)	Measures thermal transitions such as glass transition, melting and crystallization
Dynamic Mechanical Thermal Analysis (DMTA)	Assesses mechanical properties across temperature ranges
Cyclic Voltammetry (CV)	Analyzes redox behavior and capacitance
Electrochemical Impedance Spectroscopy (EIS)	Measures resistance and conductivity
Galvanostatic Charge-Discharge (GCD)	Evaluates cycle performance and specific capacitance



CHALLENGES AND LIMITATIONS

Despite the substantial progress made in the design and application of TMO-based nanocomposites several critical challenges must be addressed to translate laboratory successes into scalable, reliable and commercially viable technologies. These challenges span across synthesis, characterization, performance optimization, long-term stability and biocompatibility concerns.

SYNTHESIS AND STRUCTURAL CONTROL:

- Uniform Dispersion of Nanofillers: Achieving homogeneous dispersion of TMO nanoparticles within polymeric or carbon-based matrices is often difficult due to agglomeration caused by high surface energy. Agglomeration leads to reduced active surface area, lower electrochemical accessibility, and poor mechanical properties.
- Reproducibility and Scalability: Many synthesis techniques, such as hydrothermal, sol-gel and co-precipitation methods provide high-quality nanocomposites at a laboratory scale. However, translating these methods to industrial-scale production while maintaining consistency, purity and performance remains a major hurdle.
- Control over Morphology and Size: The electrochemical and biomedical performance of TMO nanocomposites is highly dependent on morphology (e.g., nanowires, nanosheets, nanospheres) and particle size. Precise control over these features during synthesis is challenging, especially when integrating multiple components.

INTERFACIAL ENGINEERING:

- Weak Interfacial Interactions: In hybrid nanocomposites, poor bonding between the TMO phase and the matrix (e.g., carbon or polymer) can hinder efficient electron/ion transfer and compromise structural integrity under cycling or physiological conditions.
- Surface Defects and Impurities: Residual surfactants or defects introduced during synthesis may block active sites, reduce conductivity or introduce cytotoxicity in biomedical applications.

ELECTROCHEMICAL PERFORMANCE LIMITATIONS:

- Poor Electrical Conductivity of TMOs: Although TMOs exhibit high pseudocapacitance many (e.g., MnO_2, TiO_2) suffer from inherently low electrical conductivity, which limits rate performance and power density. Conductive additives or hybridization strategies help but often at the expense of energy density or stability.
- Cycling Stability: Repeated charge–discharge cycling may lead to volume changes in TMO particles, causing cracking, delamination or detachment from the electrode matrix. This degradation reduces long-term cyclic stability.
- Low Practical Energy Density: While lab-scale devices demonstrate high energy or power densities translating this into practical devices with high areal or volumetric capacitance is still challenging.

BIOMEDICAL APPLICATION CHALLENGES:

- Biocompatibility and Toxicity: Some TMOs (e.g. CuO, ZnO) can release metal ions or generate reactive oxygen species (ROS) potentially causing cytotoxicity in biological environments. Long-term biocompatibility and degradation behavior must be rigorously evaluated.
- In Vivo Stability and Clearance: Ensuring that nanocomposites retain their functional integrity in complex physiological environments and are eventually biodegraded or cleared without harmful residues is a significant concern.
- Immunogenic and Inflammatory Responses: Interaction of TMO nanocomposites with biological systems may trigger immune responses or inflammation, especially in sensitive applications like tissue engineering or drug delivery.

CHARACTERIZATION AND MECHANISTIC UNDERSTANDING:

- Inadequate Understanding of Structure Function Relationships: Although many performance improvements have been observed the underlying mechanisms (e.g., ion transport, electron hopping, cell-nanomaterial interaction) remain incompletely understood limiting rational material design.
- Lack of Standardization: Inconsistent testing methods, different electrolyte systems, and diverse reporting metrics in literature make it difficult to directly compare results or establish universal performance benchmarks.

ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS:

- Use of Hazardous Chemicals: Some synthesis protocols involve toxic solvents, surfactants or reagents raising environmental and safety concerns.
- Cost and Material Availability: TMOs such as RuO_2 offer excellent electrochemical performance but are prohibitively expensive and rare. Alternatives like MnO_2 or NiO are more abundant but may not match performance or stability.

CONCLUSION

Transition metal oxide (TMO)-based nanocomposites represent a rapidly evolving and highly versatile class of materials that have shown immense potential in addressing critical challenges in both energy storage and biomedical applications. Their multifunctionality stems from the intrinsic redox activity, tunable surface chemistry and structural diversity of TMOs, which when combined with polymers, ceramics or carbon-based materials, lead to remarkable enhancements in physicochemical and functional performance. In supercapacitor applications, the integration of TMOs with conductive polymers (such as polyaniline and polypyrrole) or carbonaceous materials (like graphene and CNTs) leads to synergistic effects that significantly improve specific capacitance, energy density, power output, and cyclic stability. The pseudocapacitive nature of TMOs owing to their fast and reversible faradaic redox reactions plays a central role in enhancing charge storage capabilities. Hybrid electrodes formed from TMO carbon or TMO polymer composites can be tailored to exploit the benefits of both electric double-layer capacitance (EDLC) and pseudocapacitance, enabling the design of next generation hybrid supercapacitors with balanced energy and power characteristics.

In the biomedical domain, TMO nanocomposites demonstrate a unique combination of bioactivity, biocompatibility and chemical reactivity making them ideal for applications such as tissue scaffolds, drug delivery vehicles, biosensors, and antimicrobial coatings. TMOs like TiO_2, ZnO and Fe_3O_4 offer excellent support for cell adhesion and proliferation, while their surface properties can be functionalized for targeted therapeutic action or diagnostic sensitivity. Additionally, their ability to regulate reactive oxygen species (ROS) generate local magnetic fields or facilitate electron transfer adds significant value in therapeutic and sensing platforms.

The successful realization of these applications, however, relies heavily on careful control over the structural design and synthesis of the nanocomposites. Key factors include the choice of matrix material, the morphology and dispersion of nanofillers the strength and type of interfacial interactions and the fabrication method employed. Techniques such as in situ polymerization, sol-gel processing, electrochemical deposition and hydrothermal synthesis allow precise manipulation of these factors leading to materials with tailored functionalities.

Despite the promising outlook, several challenges remain. Uniform dispersion of nanofillers, long-term material stability, scalable synthesis, and control over interface chemistry are persistent hurdles. Moreover, a deeper understanding of the fundamental mechanisms that govern the interplay between structure and function in these systems is required. Advanced characterization tools-such as X-ray diffraction (XRD), transmission electron microscopy (TEM), cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS)-are essential to probe these properties and guide material optimization.

Looking forward, the convergence of materials science nanotechnology and bioengineering offers a fertile ground for innovation. Emerging approaches such as machine learning-driven material design, 3D printing of nanocomposite structures, and the development of bioinspired or stimuli-responsive nanomaterials could further expand the utility of TMO nanocomposites. With continued interdisciplinary research and technological integration, TMO-based nanocomposites are well-positioned to play a transformative role in the development of sustainable energy systems and advanced biomedical solutions, driving progress across multiple scientific and industrial frontiers.

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