Development of Nanocomposites for Sensor Applications

Susmita Maity[1], Rabindranath Jana[2,*]

Abstract

The development of nanocomposites for sensor applications represents a significant breakthrough in materials science and engineering, driven by the unique properties of nanomaterials. Nanocomposites, which combine nanoparticles with polymers or other matrices, exhibit enhanced mechanical, electrical, and thermal properties, making them highly suitable for various sensing applications. The integration of nanoparticles, such as metal oxide, carbon nanotubes, and graphene, into a composite framework can dramatically increase sensitivity and selectivity, enabling the detection of low concentrations of target analytes. Recent advancements in nanocomposite materials have led to innovations in gas sensors, biosensors, and environmental monitoring devices. These materials can be tailored to optimize their performance for specific sensing tasks, allowing for rapid response times and improved accuracy. Various studies have highlighted the advantages of integrating nanoparticles into polymer matrices to create materials that exhibit superior sensitivity, selectivity, and stability compared to conventional sensors. One prominent area of research involves metal oxide nanoparticles, such as zinc oxide (ZnO) and tin dioxide (SnO_2), which have been extensively studied for gas sensing applications. These materials benefit from a high surface-to-volume ratio, facilitating increased interactions with target gases. Graphene-based nanocomposites have also emerged as a key focus area due to their exceptional electrical and thermal properties. It is found that graphene oxide incorporated into polymer matrices can significantly improve the sensitivity and selectivity of biosensors, enabling the detection of biomolecules at lower concentrations. The integration of nanocomposite sensors into real-world applications, such as wearable devices and smart environmental systems, remains a challenge. Issues related to scalability, cost-effectiveness, and integration with existing technologies require further investigation to translate laboratory successes into practical solutions. Additionally, the focus on real-world applications, such as wearable devices and environmental monitoring, positions this research at the forefront of addressing practical challenges in sensor technology, ultimately contributing to enhanced safety, health, and environmental monitoring solutions. The development of nanocomposites for sensor applications combines advanced nanotechnology with material science, enabling highly sensitive, selective, and efficient sensors. These innovations address critical challenges across diverse fields, paving the way for smarter, cost-effective, and scalable solutions, and ultimately driving progress in healthcare, environmental monitoring, and industrial automation.

*Author for Correspondence
Rabindranath Jana
E-mail: rabindrajana@hithaldia.in

[1]Assistant Professor, Institute of Fire and Safety Engineering, Brajalalchak, Haldia, Purba Medinipur, West Bengal, India
[2]Associate Professor, Department of Chemical Engineering, Haldia Institute of Technology, Haldia, Purba Medinipur, West Bengal, India

Keywords: Nanocomposites, gas sensor, polymers, graphene, zinc oxide (ZnO)

INTRODUCTION

The rapid advancement of technology has led to an increasing demand for sensitive, selective, and reliable sensors in various fields, including environmental monitoring, healthcare, and industrial processes [1–6]. Traditional sensors often struggle to meet the requirements for sensitivity and specificity, driving the need for innovative materials, such as nanocomposites. The development of nanocomposites for sensor

applications has garnered significant attention in recent years due to their enhanced properties and potential for innovative sensing solutions. Various studies have highlighted the advantages of integrating nanoparticles into polymer matrices to create materials that exhibit superior sensitivity, selectivity, and stability compared to conventional sensors.

One prominent area of research involves metal oxide nanoparticles, such as zinc oxide (ZnO) and tin dioxide (SnO_2), which have been extensively studied for gas-sensing applications [7]. These materials benefit from a high surface-to-volume ratio, facilitating increased interaction with target gases. For instance, ZnO nanocomposites integrated with polymer matrices exhibited notable improvements in response times and sensitivity to volatile organic compounds (VOCs) [8]. Similarly, research involving carbon nanotubes (CNTs) has shown their effectiveness in enhancing the electrical conductivity and response of sensors [9]. A study highlighted that the use of CNTs in polymer nanocomposites results in remarkable improvements in the detection limits of gas sensors [10].

Graphene-based nanocomposites have also emerged as a key focus area due to their exceptional electrical and thermal properties. It was shown that graphene oxide incorporated into polymer matrices can significantly improve the sensitivity and selectivity of biosensors, enabling the detection of biomolecules at lower concentrations [11]. Other research has explored the use of conducting polymers in combination with nanoparticles to create multifunctional sensors capable of detecting multiple analytes simultaneously.

Despite the promising advancements in nanocomposite materials for sensor applications, several knowledge gaps remain. First, while many studies report on the performance improvements of nanocomposite sensors, there is often a lack of standardization in testing methodologies, making it challenging to compare results across different studies. This inconsistency can hinder the reproducibility and scalability of sensor technologies.

Additionally, while the sensitivity and selectivity of nanocomposite sensors have been widely explored, there is a need for more comprehensive investigations into their long-term stability and environmental resilience. Most studies focus on short-term performance, leaving a gap in our understanding of how these materials behave under varying operational conditions over extended periods.

Furthermore, the mechanisms underlying the enhanced sensing properties of nanocomposites are not fully elucidated. More research is needed to understand the interactions at the nanoscale level, including charge transfer processes and the role of the polymer matrix in influencing the overall sensor performance. This knowledge is crucial for optimizing nanocomposite design for specific applications.

The integration of nanocomposite sensors into real-world applications, such as wearable devices and smart environmental monitoring systems, remains a challenge. Issues related to scalability, cost-effectiveness, and integration with existing technologies require further investigation to translate laboratory successes into practical solutions.

However, there are significant progress has been made in the development of nanocomposites for sensor applications, addressing the identified knowledge gaps will be essential to unlocking their full potential and facilitating the next generation of sensing technologies. Continued research efforts should focus on standardization, long-term stability, fundamental mechanisms, and practical applications to bridge these gaps effectively.

Nanocomposites, which are materials composed of nanoparticles embedded within a matrix, have emerged as highly promising materials in the field of sensor technology due to their unique properties and enhanced performance characteristics. The incorporation of nanoparticles – typically ranging from 1 to 100 nanometers – in various matrix materials, such as polymers, metals, or ceramics significantly

increases surface area, which is crucial for sensor functionality. This increased surface area allows for greater interaction with target analytes, leading to improved sensitivity and rapid response times, making nanocomposites ideal for applications in gas, chemical, and biosensors. Nanocomposites leverage the high surface area-to-volume ratio of nanoparticles, providing enhanced interaction with target analytes. Their tunable properties allow for the design of sensors with improved sensitivity, selectivity, and response times, making them ideal candidates for a wide range of sensor applications.

The versatility of nanocomposites enables their use across a wide range of sensing applications, from environmental monitoring to healthcare diagnostics. For instance, metal oxide nanocomposites can effectively detect gases at low concentrations, while conductive polymer-nanoparticle composites exhibit exceptional performance in biosensing applications by facilitating the detection of biomolecules [12]. Moreover, the tunable properties of nanocomposites allow for the design of sensors with specific functionalities, enhancing selectivity and reducing interference from undesired substances.

Despite their advantages, challenges, such as stability, reproducibility, and potential environmental impacts must be addressed to ensure the successful integration of nanocomposites into commercial sensor technologies. As research advances, the incorporation of nanocomposites into smart sensor systems and the Internet of Things (IoT) is anticipated to further enhance monitoring capabilities. Overall, the importance of nanocomposites in sensor applications lies in their ability to revolutionize detection methods, offering higher sensitivity, selectivity, and reliability, ultimately paving the way for innovative solutions in various fields including environmental science, healthcare, and industrial processes.

PRINCIPLES OF NANOCOMPOSITES IN SENSOR APPLICATIONS
Inherent Properties of Nanoparticles
Nanoparticles possess several unique properties that make them ideal for sensor applications. One of the most significant characteristics is their high surface area-to-volume ratio, which enhances their reactivity and interaction with target molecules, leading to increased sensitivity and faster detection times (Figure 1). This property allows nanoparticles to detect trace amounts of gases, chemicals, and biomolecules, making them suitable for a wide range of environmental, healthcare, and industrial sensors.

Additionally, nanoparticles exhibit tunable optical, electrical, and magnetic properties that can be customized based on the material and particle size. For example, gold, silver, and carbon-based nanoparticles show distinct optical responses, such as localized surface plasmon resonance, which is utilized in optical sensors for detecting pathogens or pollutants. Their electrical conductivity can also be modified, which is beneficial for applications like gas sensors and biosensors.

Nanoparticles also exhibit size-dependent properties, where smaller particles tend to have enhanced chemical reactivity and catalytic activity. This makes them highly efficient in detecting specific chemical species at low concentrations. Furthermore, nanoparticles' flexibility and adaptability enable the creation of sensors that can operate in extreme environments, such as high temperatures or corrosive atmospheres. These combined properties make nanoparticles indispensable in the development of next-generation sensors, offering improved performance, sensitivity, and versatility across various applications.

Key Properties Include
- *Increased Surface Area:* Higher surface area enhances interaction with analytes.
- *Quantum Effects:* Size-dependent properties can improve sensor performance.
- *Enhanced Mechanical Strength:* Increased durability and flexibility.

Interaction Mechanisms in Sensors
The interaction between the sensor material and the target analyte is crucial for sensor performance (Figure 2). Various mechanisms include:
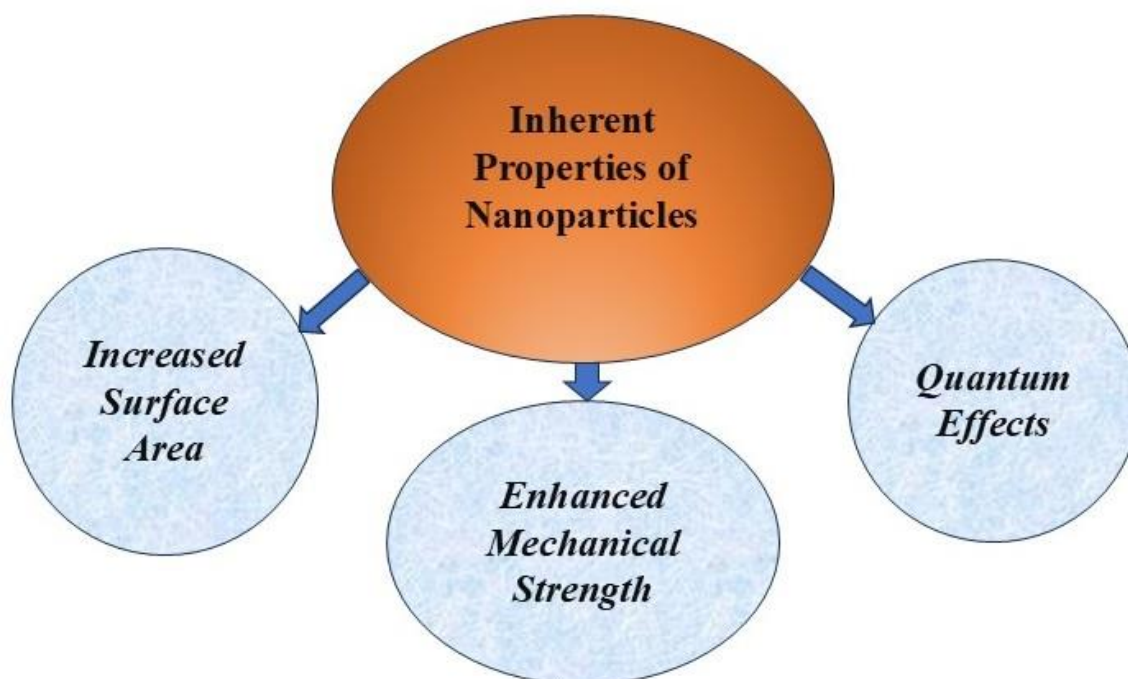
Figure 1. Inherent properties of nanomaterials.

Adsorption

Binding of analytes to the surface of nanoparticles. Adsorption mechanisms play a crucial role in the functioning of sensors, particularly those utilizing nanocomposites. Adsorption refers to the process by which molecules from a gas or liquid phase adhere to the surface of a solid material, forming a film. In sensor applications, this interaction is vital for the detection of target analytes, as it influences sensitivity and response time.

There are two primary types of adsorptions: physisorption and chemisorption. Physisorption involves weak van der Waals forces and is usually reversible, allowing adsorbates to detach easily. This type of adsorption is advantageous for sensors requiring rapid response times. Chemisorption, on the other hand, involves the formation of stronger chemical bonds between the adsorbate and the sensor surface, leading to irreversible adsorption. This can enhance sensor selectivity but may slow down response times.

The high surface area of nanocomposites significantly enhances adsorption capacity, allowing for the detection of low concentrations of target substances [13]. The interaction mechanisms—whether they involve charge transfer, dipole-dipole interactions, or other forces—determine the efficiency of adsorption and, consequently, the overall performance of the sensor. Understanding these mechanisms is essential for designing more sensitive and selective sensors across various applications.

Charge Transfer

Changes in conductivity due to electron transfer during reactions. Charge transfer mechanisms are fundamental to the operation of various types of sensors, particularly those involving nanocomposites. These mechanisms describe the process by which electrons or holes are transferred between the sensor material and the target analytes, significantly influencing the sensor's sensitivity and selectivity.

In many sensor applications, particularly gas and chemical sensors, the detection principle relies on the change in electrical conductivity caused by the interaction of analytes with the sensor surface. When target molecules adsorb onto the surface of the nanocomposite, they can either donate or accept

21

electrons, leading to a change in charge density. This process alters the electrical resistance of the sensor material, enabling the quantification of the analyte concentration.

For example, in metal oxide-based gas sensors, the adsorption of reducing gases (like CO or H_2) leads to the donation of electrons from the gas molecules to the metal oxide, resulting in an increase in charge carriers and a decrease in resistance. Conversely, oxidizing gases (like O_3 or NO_2) can withdraw electrons from the metal oxide, reducing the number of charge carriers and increasing resistance.

In nanocomposites, the incorporation of conductive nanoparticles, such as carbon nanotubes or graphene, enhances charge transfer efficiency due to their high intrinsic conductivity and large surface area. The synergy between the nanoparticles and the matrix material can lead to improved charge transport pathways, facilitating faster response times and higher sensitivity.

Moreover, the ability to tailor the surface chemistry of nanocomposites allows for the optimization of charge transfer processes, enhancing sensor performance. Understanding and manipulating charge transfer mechanisms are essential for developing advanced sensors capable of detecting low concentrations of target analytes with high specificity and rapid response times. Thus, charge transfer mechanisms are pivotal in the design and functionality of modern sensor technologies.
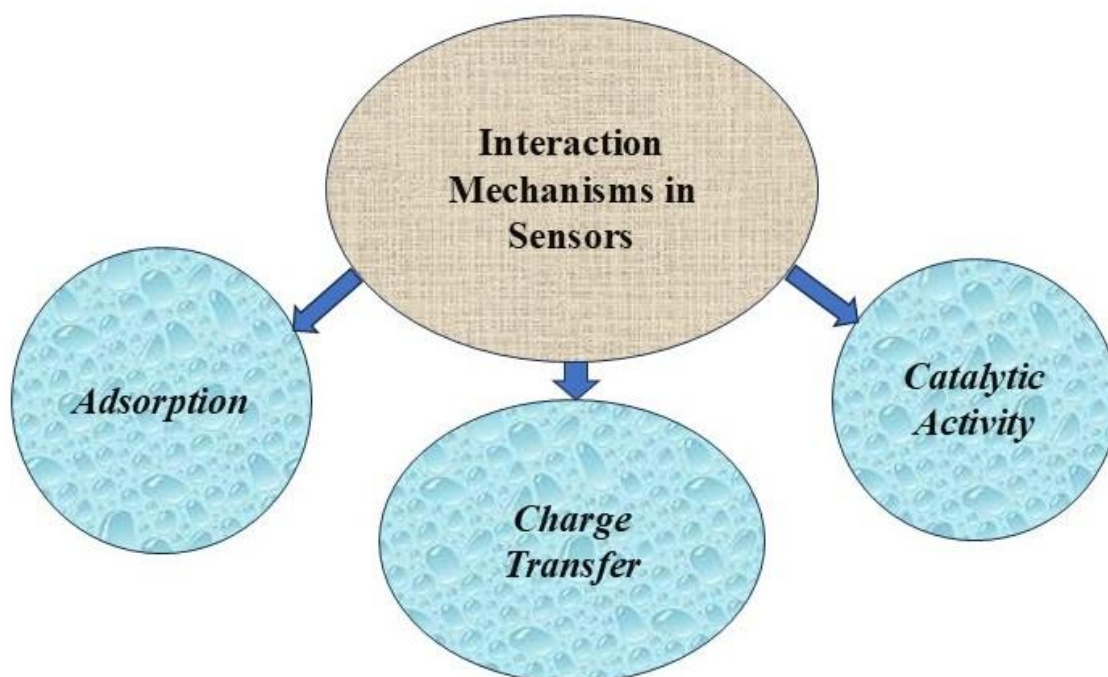
Figure 2. Interaction mechanisms in sensors.

Catalytic Activity
Catalysis facilitated by nanoparticles for enhanced detection. Catalytic activity is a critical factor in enhancing the performance of sensors, particularly those designed for detecting gases and chemical species. Catalysis involves the acceleration of a chemical reaction through the presence of a catalyst, which facilitates the transformation of reactants into products without being consumed in the process. In sensor applications, catalytic materials can significantly improve sensitivity, selectivity, and response times.

In gas sensors, for instance, metal oxides, such as tin oxide (SnO_2) and zinc oxide (ZnO) exhibit catalytic properties that enhance the oxidation or reduction of target analytes [14]. When these gases interact with the sensor's surface, they undergo catalytic reactions that lead to changes in the electrical

properties of the material, such as resistance. This change can be measured and correlated to the concentration of the gas, enabling accurate detection. The effectiveness of a sensor is often linked to the catalytic activity of the materials used, as higher catalytic efficiency results in more pronounced changes in the sensor's signal.

Nanocomposites, which combine nanoparticles with a matrix material, can further enhance catalytic activity due to their increased surface area and unique electronic properties. The incorporation of noble metals, like platinum or palladium into nanocomposites, can provide additional catalytic sites, improving the overall reaction kinetics. This is particularly beneficial for applications requiring the detection of low concentrations of hazardous gases in the environment or controlling emissions in industrial settings.

Furthermore, the ability to engineer the surface properties of catalytic materials allows for the design of sensors with tailored selectivity toward specific analytes. This specificity is crucial in complex environments where multiple gases may be present. Overall, catalytic activity is a vital aspect of sensor technology, enabling the development of highly sensitive, selective, and responsive devices for a wide range of applications, including environmental monitoring, industrial safety, and healthcare diagnostics.

PREPARATION METHODS OF NANOCOMPOSITES

The nanocomposites are prepared using methods like sol-gel, in-situ polymerization, melt blending, and solution casting. Sol-gel involves hydrolysis of precursors, while in-situ polymerization embeds nanoparticles during polymer formation (Figure 3). Melt blending disperses nanoparticles in a molten matrix, and solution casting dissolves components before film formation. Each method affects the final properties.

Sol-Gel Method

The sol-gel process involves the transition of a solution into a solid gel phase. This method allows for the uniform distribution of nanoparticles within a matrix and is commonly used for the synthesis of metal oxide nanocomposites. The sol-gel method is a versatile and widely used technique for the preparation of nanocomposites, particularly in the fields of materials science and nanotechnology. This process involves the transition of a solution (sol) into a solid (gel) network, facilitating the formation of nanoscale structures.

In the sol-gel method, metal alkoxides or metal salts are typically used as precursors, which undergo hydrolysis and polycondensation reactions to form a colloidal solution. As the reaction progresses, the sol evolves into a gel-like network, incorporating various nanoparticles or additives to create nanocomposite materials. The process allows for precise control over composition, microstructure, and porosity, leading to tailor-made properties.

One of the key advantages of the sol-gel method is its ability to produce homogeneous and uniform nanocomposites at relatively low temperatures, which is crucial for maintaining the integrity of the incorporated nanoparticles. Additionally, this method supports the incorporation of various functional groups, enhancing the chemical and physical properties of the final product.

The sol-gel-derived nanocomposites find applications in diverse fields, including sensors, catalysts, and biomedical devices, owing to their enhanced mechanical, thermal, and optical properties. Overall, the sol-gel method is a fundamental technique for creating advanced nanocomposites with tailored functionalities.

Co-Precipitation

Co-precipitation involves the simultaneous precipitation of nanoparticles and matrix materials from a solution. This method is advantageous for producing metal-based nanocomposites with controlled size and morphology. Co-precipitation is a widely used method for synthesizing nanocomposites,

particularly in the production of metal oxide nanoparticles and hybrid materials. This technique involves the simultaneous precipitation of multiple components from a homogeneous solution, allowing for the controlled incorporation of different materials at the nanoscale.

In the co-precipitation process, metal salts are typically dissolved in an aqueous solution. By adjusting parameters, such as pH, temperature, and concentration, the solubility of the metal ions can be altered, leading to their precipitation as solid nanoparticles. This method allows for the uniform distribution of various components, enabling the formation of nanocomposites with tailored properties.

One of the significant advantages of co-precipitation is its simplicity and cost-effectiveness, making it suitable for large-scale production. Moreover, it enables the synthesis of composite materials with enhanced magnetic, catalytic, or optical properties due to the synergistic effects of the combined components.

Co-precipitation is particularly valuable in applications, such as sensors, where the incorporation of conductive or catalytic nanoparticles can improve sensitivity and performance. Overall, this method is a versatile approach for developing advanced nanocomposites with diverse functionalities, making it a cornerstone technique in nanomaterial synthesis.
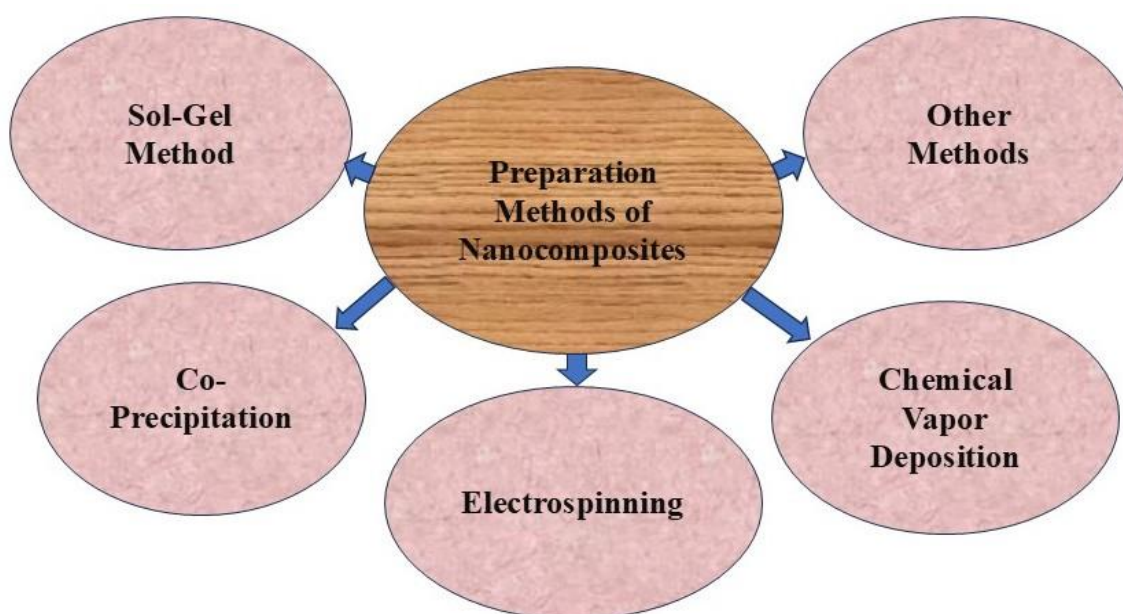
Figure 3. Preparation methods of nanocomposites.

Electrospinning

Electrospinning is used to create nanofibers from polymer solutions, which can then be incorporated with nanoparticles. This technique produces high surface area materials that are ideal for sensor applications. Electrospinning is a versatile and widely used technique for the preparation of nanocomposites, which are materials that incorporate nanoscale fillers into a polymer matrix to enhance their properties. The process involves applying a high voltage to a polymer solution or melt, creating an electrically charged jet that is ejected from a nozzle. As the jet travels through the air, it undergoes solvent evaporation and stretching, resulting in the formation of ultra-fine fibers, typically in the nanometer to micrometer range.

Incorporating nanoparticles, such as metal oxides, carbon nanotubes, or graphene, into the electrospinning solution allows for the development of nanocomposites with improved mechanical, thermal, and electrical properties. The uniform dispersion of nanoparticles within the fiber matrix

enhances interfacial interactions, leading to synergistic effects. Additionally, the porous structure of electrospun fibers can facilitate applications in filtration, drug delivery, and tissue engineering.

The electrospinning method offers several advantages, including the ability to produce continuous fibers, control over fiber diameter, and the possibility of scaling up for industrial applications. Overall, electrospinning is a promising approach for creating advanced nanocomposite materials with tailored properties for various applications across industries, including biomedical, environmental, and electronic fields.

Chemical Vapor Deposition (CVD)
CVD allows the deposition of thin films of nanocomposites on various substrates. This method is particularly useful for creating nanoscale coatings for sensor applications. Chemical vapor deposition (CVD) is a sophisticated technique used for the preparation of nanocomposites, wherein a substrate is exposed to gaseous precursors that react and deposit a solid material. This method is particularly valued for its ability to produce high-purity, uniform thin films and nanostructures at the nanoscale. In the context of nanocomposites, CVD allows for the incorporation of various nanomaterials, such as graphene, carbon nanotubes, and metal oxides, into a matrix, thereby enhancing the composite's mechanical, electrical, and thermal properties.

During the CVD process, the gaseous precursors decompose or react on the substrate surface, forming a solid deposit of the desired material. The process can be finely tuned by adjusting temperature, pressure, and gas composition, allowing for precise control over the nanocomposite's morphology and composition. This versatility makes CVD ideal for applications in electronics, energy storage, and catalysis.

Moreover, CVD can be performed at various scales, from laboratory to industrial sizes, enabling the mass production of nanocomposites. The ability to fabricate complex structures with high uniformity and reproducibility positions CVD as a powerful method for developing advanced nanocomposite materials tailored for specific applications in various fields.

Other Methods
Other synthesis methods include mechanical milling, hydrothermal synthesis, and microwave-assisted synthesis, each offering unique advantages for specific types of nanocomposites.

CHARACTERIZATION TECHNIQUES
Structural Characterization
X-ray Diffraction (XRD)
Used to determine crystal structure and phase composition. Structural characterization of nanocomposites using X-ray diffraction (XRD) is a fundamental technique that provides insights into the crystallographic structure, phase composition, and microstrain of materials at the nanoscale. XRD works by directing X-rays at a sample, which are then scattered by the crystal lattice. The resulting diffraction patterns analyzed using Bragg's law, reveal information about the interplanar spacing, crystallite size, and orientation of the nanocomposite materials.

In nanocomposites, XRD can help identify the presence of different phases, such as polymer and inorganic nanoparticles, and assess their interactions. By analyzing the peak positions and intensities, researchers can determine the crystallinity of the composite, which is crucial for understanding its mechanical and thermal properties. Additionally, the Scherrer equation can be employed to estimate crystallite sizes, providing valuable information about how the nanoscale components influence the overall material behavior.

XRD is also instrumental in monitoring changes during the synthesis or processing of nanocomposites, revealing phase transformations or structural modifications. Overall, X-ray diffraction serves as a powerful tool in the characterization of nanocomposites, facilitating the design of materials with tailored properties for applications in electronics, energy, and biomedical fields.

Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is a powerful technique for the structural characterization of nanocomposites, offering high-resolution imaging and detailed information about the morphology, crystallography, and interfaces of nanoscale materials. In TEM, a beam of electrons is transmitted through an ultra-thin specimen, generating magnified images that reveal the internal structure and arrangement of nanocomposite components.

One of the primary advantages of TEM is its ability to visualize individual nanoparticles within a polymer or matrix, providing insights into their size, shape, and distribution. This is critical for understanding the reinforcement mechanisms that enhance the properties of nanocomposites. Furthermore, high-angle annular dark field (HAADF) imaging and electron diffraction can be employed to analyze the crystallinity and phase composition of the nanocomposite, allowing researchers to identify different crystalline phases and assess their interactions.

Additionally, TEM can be combined with energy-dispersive X-ray spectroscopy (EDX) to obtain compositional information at the nanoscale, providing a comprehensive understanding of the elemental distribution within the nanocomposite. Overall, TEM is an invaluable tool in the characterization of nanocomposites, enabling the optimization of material properties and the development of advanced applications in fields, such as electronics, energy storage, and biomedicine.

Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is a widely used technique for the structural characterization of nanocomposites, providing detailed images of surface morphology and topography at high magnifications. SEM operates by scanning a focused beam of electrons across the sample surface, generating secondary and backscattered electrons that form high-resolution images. This method is particularly effective in visualizing the dispersion and distribution of nanoparticles within a composite matrix.

In nanocomposites, SEM can reveal critical information about the size, shape, and arrangement of nanofillers, such as carbon nanotubes or metal nanoparticles, within the polymer or ceramic matrix. By analyzing surface features and texture, researchers can assess the effectiveness of the dispersion process, which is vital for optimizing mechanical, thermal, and electrical properties.

Moreover, SEM can be coupled with energy-dispersive X-ray spectroscopy (EDX), allowing for elemental analysis of specific regions within the nanocomposite. This capability facilitates the study of phase distribution and interfacial interactions between different components.

SEM is an essential tool in the characterization of nanocomposites, enabling the evaluation of structural features that directly influence material properties and performance in various applications, including electronics, coatings, and biomedical devices.

Surface Characterization
Brunauer-Emmett-Teller (BET) Analysis

Brunauer–Emmett–Teller (BET) analysis is a crucial method for surface characterization of nanocomposites, primarily used to determine their specific surface area, pore size, and porosity. This technique employs nitrogen gas adsorption at liquid nitrogen temperature to generate adsorption

isotherms, allowing for the assessment of surface characteristics that significantly influence the properties and performance of nanocomposites.

The BET theory extends the Langmuir model of adsorption to multilayer adsorption, providing a mathematical framework to relate the volume of gas adsorbed to the pressure, from which the surface area can be calculated. For nanocomposites, a high surface area is often desirable as it enhances interactions between the filler and the matrix, leading to improved mechanical, thermal, and electrical properties.

Additionally, BET analysis can reveal insights into the pore structure of nanocomposites, such as microporosity and mesoporosity, which are critical for applications like catalysis and drug delivery. By understanding the surface characteristics, researchers can tailor the synthesis and processing conditions of nanocomposites to optimize their performance for specific applications. BET analysis is an invaluable tool in the surface characterization of nanocomposites, providing essential information that guides the design and application of advanced materials in various industries.

Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) is a vital technique for the surface characterization of nanocomposites, providing insights into molecular structures and functional groups present within the material. FTIR analyzes the absorption of infrared radiation by a sample, allowing for the identification of specific chemical bonds and functional groups based on their characteristic vibrational frequencies.

In nanocomposites, FTIR is particularly useful for examining interactions between the matrix and nanofillers, such as polymers combined with metal or ceramic nanoparticles. By analyzing the FTIR spectra, researchers can detect shifts in peak positions or changes in peak intensities, which indicate chemical interactions, such as hydrogen bonding or covalent bonding at the interface. This information is crucial for understanding how the incorporation of nanofillers affects the overall properties of the composite.

Moreover, FTIR can help in assessing the functionalization of nanoparticles, providing evidence of the presence of surface-modifying agents that enhance compatibility between the filler and the matrix. This is significant for optimizing the mechanical, thermal, and electrical properties of nanocomposites.

FTIR serves as an essential tool in the surface characterization of nanocomposites, enabling the investigation of chemical structures and interactions that dictate material performance in diverse applications, from electronics to biomedical fields.

ELECTRICAL CHARACTERIZATION
Conductivity Measurements

Conductivity measurements of nanocomposites are essential for evaluating their electrical and thermal properties, which are crucial for applications in electronics, sensors, and energy storage. Nanocomposites consist of a matrix material, such as a polymer, ceramic, or metal, embedded with nanostructures like carbon nanotubes (CNTs), graphene, or metallic nanoparticles. The conductivity of these materials depends on factors, such as filler concentration, dispersion, interfacial interactions, and the inherent conductivity of the nanomaterial used.

Electrical conductivity is commonly measured using techniques like the four-point probe method, impedance spectroscopy, and conductive atomic force microscopy (C-AFM). A percolation threshold is often observed, where conductivity sharply increases as the filler content reaches a critical level, forming a continuous conductive network. Thermal conductivity, on the other hand, is evaluated using the laser flash method or steady-state techniques. Enhancing conductivity in nanocomposites involves optimizing filler dispersion and ensuring strong interfacial bonding to reduce electron or phonon scattering.

Impedance Spectroscopy

Impedance spectroscopy is a powerful technique for the electrical characterization of nanocomposites, providing insights into their resistive, capacitive, and dielectric properties over a wide frequency range. This method measures the material's response to an applied AC voltage, analyzing impedance as a function of frequency to understand charge transport mechanisms, interface effects, and polarization phenomena.

In nanocomposites, impedance spectroscopy helps assess conductivity, percolation behavior, and interfacial interactions between the matrix and nanofillers, such as carbon nanotubes, graphene, or metallic nanoparticles. By modeling impedance data using equivalent circuits, researchers can distinguish bulk resistance, grain boundary effects, and electrode contributions. The frequency-dependent behavior provides information on hopping conduction, charge relaxation, and dipole orientation, which are critical for applications in flexible electronics, sensors, and energy storage devices.

Key advantages of impedance spectroscopy include its non-destructive nature, high sensitivity, and ability to analyze both insulating and conductive nanocomposites. The technique is commonly used in optimizing filler dispersion, evaluating dielectric permittivity, and understanding conduction mechanisms at different temperature and humidity conditions. Ongoing advancements focus on improving measurement accuracy and developing novel nanocomposites with tailored electrical properties for next-generation electronic applications.

Sensor Applications of Nanocomposites

The nanocomposite-based sensors offer high sensitivity, selectivity, and rapid response in detecting gases, biomolecules, and environmental pollutants. They are used in medical diagnostics, food safety, and industrial monitoring. Enhanced conductivity, mechanical strength, and surface area improve performance in electrochemical, optical, and piezoresistive sensors, enabling advanced real-time detection applications (Figure 4).

Gas Sensors

Nanocomposites have shown great promise in gas detection. Nanocomposites are widely used in gas sensors due to their high surface area, tunable electrical properties, and enhanced sensitivity to gaseous molecules. These materials consist of a host matrix, such as a polymer, metal oxide, or carbon-based material, embedded with nanostructures like carbon nanotubes (CNTs), graphene, metal nanoparticles, or metal-organic frameworks (MOFs). The combination of these components results in improved adsorption, charge transfer, and signal response upon gas exposure [15].

Gas sensing in nanocomposites typically relies on changes in electrical resistance, work function, or optical properties when target gases interact with the material's surface. For instance, metal oxide nanocomposites exhibit high sensitivity to gases, like CO, NO_2, and NH_3, due to their ability to facilitate redox reactions at the surface. Similarly, CNT- and graphene-based nanocomposites enable rapid response times and enhanced selectivity due to their high conductivity and functionalization capabilities. These nanocomposite-based sensors are used in environmental monitoring, industrial safety, and medical diagnostics. Key research areas focus on improving sensor stability, selectivity, and low-power operation through novel material engineering and surface functionalization. Their versatility and superior sensing performance make nanocomposites a promising choice for next-generation gas sensor technologies. For example:

- *Metal Oxide Nanocomposites:* Such as SnO_2 and ZnO, exhibit enhanced sensitivity to gases like CO, NOx, and VOCs.
- *Conductive Polymers with Nanoparticles:* Enhance the sensitivity and selectivity of gas sensors.

Biosensors

Nanocomposites are utilized in biosensors for the detection of biological molecules. Nanocomposites are widely used in biosensors due to their high sensitivity, biocompatibility, and ability to enhance signal

transduction. These materials consist of a matrix, such as a polymer, metal oxide, or carbon-based material, combined with nanostructures like carbon nanotubes (CNTs), graphene, metal nanoparticles, or quantum dots. This unique combination enables improved biomolecule interactions, rapid electron transfer, and enhanced detection capabilities.

Biosensors based on nanocomposites function by detecting biological analytes, such as proteins, DNA, glucose, or pathogens through various mechanisms, including electrochemical, optical, and piezoelectric responses. For instance, graphene- and CNT-based nanocomposites facilitate highly sensitive electrochemical detection due to their excellent conductivity and large surface area for biomolecule immobilization. Similarly, metal nanoparticle composites enhance plasmonic and fluorescence-based detection methods, improving specificity and signal amplification.
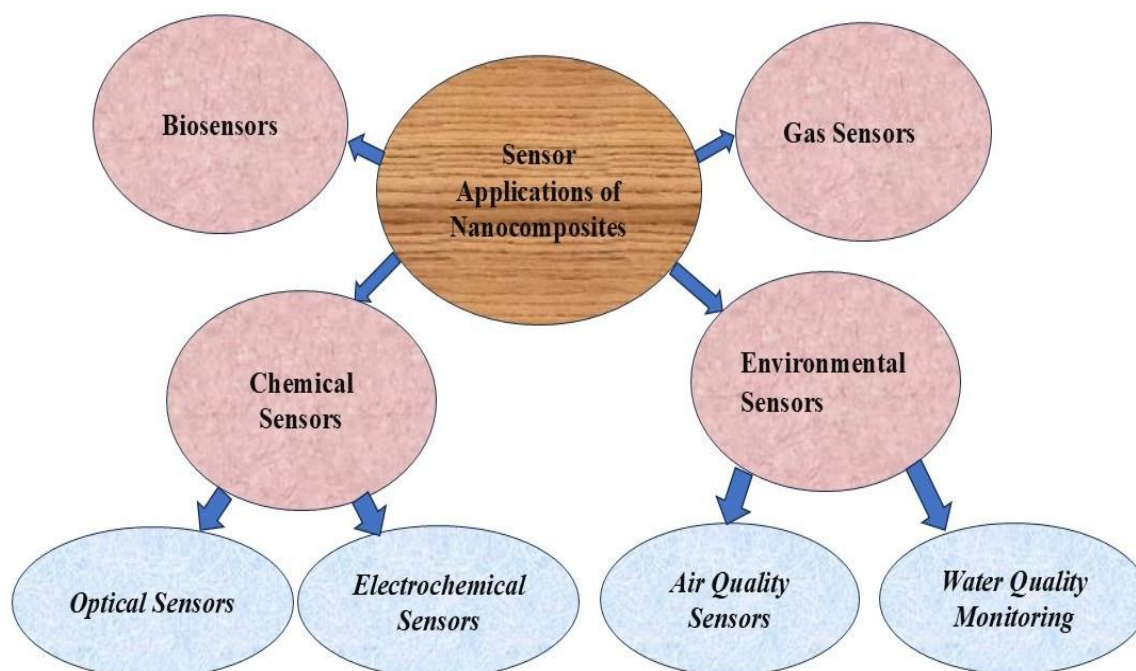
Figure 4. Sensor applications of nanocomposites.

Nanocomposite biosensors are used in medical diagnostics, environmental monitoring, and food safety applications. Their advantages include rapid response times, low detection limits, and the ability to detect multiple biomarkers simultaneously. Current research focuses on improving selectivity, stability, and integration with portable and wearable devices for real-time health monitoring, making them a key component of next generation biosensing technologies. Key applications include:
- *Glucose Sensors:* Enhanced performance using gold nanoparticles and conducting polymers.
- *Pathogen detection:* Functionalized nanocomposites for rapid and sensitive detection of pathogens.

Chemical Sensors
Nanocomposites are extensively used in chemical sensors due to their high surface area, enhanced sensitivity, and tunable physicochemical properties. These materials combine a matrix – such as polymers, metal oxides, or carbon-based materials – with nanostructures like carbon nanotubes (CNTs), graphene, metal nanoparticles, or quantum dots. This synergy enhances adsorption, charge transfer, and signal transduction, making nanocomposites highly effective for detecting chemical species.

Chemical sensors based on nanocomposites operate through various mechanisms, including changes in electrical resistance, optical properties, or electrochemical signals when exposed to target analytes.

For instance, metal oxide nanocomposites are widely used for detecting toxic gases (e.g., CO, NO_2, and H_2S) due to their ability to facilitate gas-solid interactions. Similarly, CNT- and graphene-based nanocomposites provide rapid and selective detection of volatile organic compounds (VOCs) through functionalization and high electron mobility [16].

These sensors are applied in environmental monitoring, industrial safety, and healthcare for detecting hazardous chemicals, pollutants, and biomarkers. Ongoing research focuses on improving sensor stability, selectivity, and miniaturization for real-time and wearable sensing applications. The unique properties of nanocomposites make them a promising platform for next-generation chemical sensor technologies. Their high surface area and reactivity enable:

Electrochemical Sensors

Utilizing carbon nanotubes and graphene for improved sensitivity. These sensors leverage nanocomposite materials – such as carbon nanotubes (CNTs), graphene, metal nanoparticles, and conductive polymers – to improve sensitivity, selectivity, and stability in detecting various chemical and biological analytes.

Electrochemical sensors operate by measuring electrical signals generated from redox reactions occurring at the electrode surface. Nanocomposites enhance electron transfer, lower detection limits, and improve signal response due to their unique structural and electronic properties. For example, graphene-based nanocomposites provide a high surface area for immobilizing biomolecules, while metal nanoparticle composites boost electrocatalytic activity for detecting glucose, heavy metals, or toxins.

These sensors are widely applied in medical diagnostics, environmental monitoring, and food safety, detecting biomarkers, pollutants, and pathogens with high precision. They offer advantages, such as fast response times, real-time monitoring, and miniaturization potential for portable devices. Ongoing research focuses on improving sensor selectivity, anti-fouling properties, and integration with flexible and wearable technologies, making nanocomposite-based electrochemical sensors a crucial innovation for next-generation analytical and biomedical applications.

Optical Sensors

Nanocomposites play a crucial role in optical sensors due to their unique optical, plasmonic, and photonic properties, enabling high sensitivity and rapid detection. These materials combine a host matrix – such as polymers, ceramics, or metal oxides – with nanostructures, like quantum dots, metal nanoparticles, graphene, or carbon nanotubes (CNTs), enhancing their ability to interact with light and detect target analytes.

Optical sensors based on nanocomposites operate through various mechanisms, including fluorescence, surface plasmon resonance (SPR), and Raman scattering. For instance, quantum dot-based nanocomposites exhibit strong fluorescence properties, making them ideal for detecting biomolecules, heavy metals, and environmental pollutants. Metal nanoparticle composites, such as gold or silver nanostructures, enhance SPR-based sensing, enabling real-time and label-free detection of chemical and biological analytes. Additionally, graphene and CNT-based nanocomposites enhance Raman spectroscopy signals (SERS), significantly improving detection sensitivity at ultra-low concentrations.

These optical nanocomposite sensors find applications in medical diagnostics, environmental monitoring, and food safety. Their key advantages include high selectivity, fast response times, and the ability to perform real-time, non-invasive detection. Current research focuses on improving stability, miniaturization, and integration with wearable and portable devices for advanced sensing applications.

Environmental Sensors

The use of nanocomposites in environmental monitoring is critical for:

Water Quality Monitoring

Nanocomposite-based sensors play a crucial role in water quality monitoring due to their high sensitivity, selectivity, and ability to detect contaminants at ultra-low concentrations. These sensors are composed of a host material, such as polymers, metal oxides, or carbon-based materials, combined with nanostructures like graphene, carbon nanotubes (CNTs), metal nanoparticles, or quantum dots. The synergy between these components enhances the sensor's performance by providing a large surface area, improved conductivity, and efficient signal transduction.

Nanocomposite sensors can detect a variety of water pollutants, including heavy metals (e.g., lead, mercury, arsenic), organic pollutants (e.g., pesticides, pharmaceuticals), and biological contaminants (e.g., bacteria, viruses). Electrochemical sensors, based on nanocomposites, operate by monitoring changes in electrical signals when contaminants interact with the sensor surface. Optical sensors, incorporating quantum dots or plasmonic nanoparticles, enable fluorescence or colorimetric detection for rapid and highly specific analysis.

These sensors are used for real-time water monitoring in environmental protection, industrial wastewater management, and drinking water safety. Ongoing research focuses on improving sensor stability, miniaturization, and wireless integration for portable water monitoring systems. Nanocomposite sensors offer a promising solution for ensuring clean and safe water globally.

Air Quality Sensors

These materials combine nanoscale components, such as metal oxides, carbon-based nanomaterials, and polymers, to enhance gas detection performance. Their high surface area, tunable electrical properties, and catalytic activity enable rapid response to pollutants, including volatile organic compounds (VOCs), nitrogen oxides (NOx), and carbon monoxide (CO).

Metal oxide nanocomposites, such as SnO_2–ZnO or TiO_2-graphene hybrids, improve gas adsorption and charge transfer, leading to enhanced sensor performance [17]. Carbon-based nanocomposites, including graphene and carbon nanotubes (CNTs), provide excellent conductivity and stability, reducing energy consumption. Additionally, polymer nanocomposites allow for flexible, wearable sensor applications.

Nanocomposites also enable real-time monitoring of air quality with high precision. Their ability to function at lower temperatures reduces power consumption, making them ideal for portable and smart sensor systems. With advancements in nanotechnology, these materials are revolutionizing environmental monitoring by providing cost-effective, durable, and highly efficient air quality sensors. Future developments in machine learning integration and miniaturization will further enhance their capabilities for widespread deployment in smart cities and industrial safety applications.

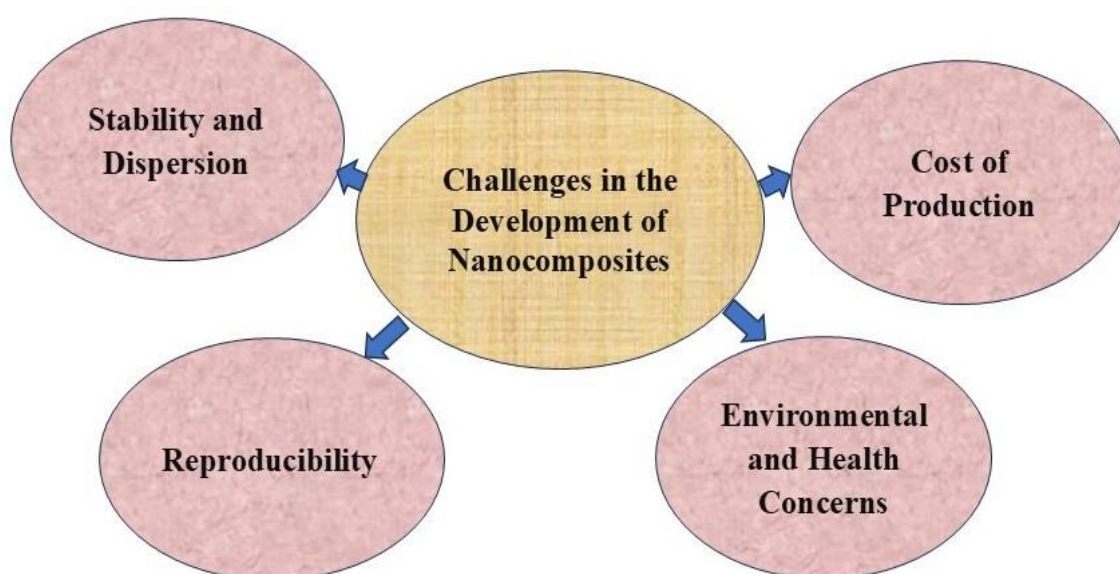## Challenges in the Development of Nanocomposites

The development of nanocomposites faces challenges like high production costs, complex fabrication techniques, dispersion issues, and weak interfacial bonding. Scaling up production without compromising properties is difficult. Controlling nanoparticle agglomeration and ensuring uniformity remain obstacles. Additionally, environmental concerns, toxicity risks, and regulatory constraints hinder widespread commercialization and application (Figure 5).

STABILITY AND DISPERSION

The development of nanocomposites faces significant challenges related to stability and dispersion, which directly impact their performance and reliability. Stability issues arise due to the tendency of nanoparticles to aggregate, reducing their effective surface area and altering their intended properties. This aggregation is driven by high surface energy and van der Waals forces, leading to uneven distribution within the composite matrix. Poor stability can result in structural degradation, loss of functionality, and reduced sensor sensitivity in applications like air quality monitoring.

Dispersion challenges involve achieving a uniform distribution of nanoparticles within a host material, whether polymeric, ceramic, or metallic. Inadequate dispersion can create weak spots in the composite, leading to mechanical failure, inconsistent electrical or thermal conductivity, and reduced efficiency in catalytic or sensing applications. Surface functionalization, surfactants, and advanced mixing techniques, such as ultrasonication or high shear mixing, are often required to enhance dispersion. However, achieving long-term stability while maintaining desired nanocomposite properties remains a critical hurdle.

Addressing these challenges requires optimizing synthesis methods, improving material compatibility, and exploring novel stabilizing agents. Advances in computational modeling and machine learning may further aid in predicting and controlling nanoparticle behavior, leading to more robust, high-performance nanocomposites for various applications.

Figure 5. Challenges in the development of nanocomposites.

REPRODUCIBILITY

Reproducibility remains a major challenge in the development of nanocomposites due to variations in synthesis methods, material properties, and processing conditions. Small changes in precursor concentration, temperature, reaction time, or synthesis techniques (e.g., sol-gel, hydrothermal, chemical vapor deposition) can lead to significant differences in nanocomposite structure, composition, and performance.

One key issue is the difficulty in achieving uniform dispersion of nanoparticles within a matrix. Agglomeration or phase separation can occur, leading to inconsistent mechanical, electrical, or chemical properties. Additionally, batch-to-batch variations in nanoparticle size, shape, and surface chemistry impact reproducibility, making it difficult to compare results across different research studies.

Standardization of characterization techniques is also a concern. Variations in measurement methods, equipment calibration, and data interpretation can introduce discrepancies in reported findings. Moreover, the influence of environmental factors, such as humidity and temperature, on nanocomposite behavior further complicates reproducibility.

Addressing these challenges requires stringent process control, standardized synthesis protocols, and improved material characterization techniques. The integration of machine learning and automation in material design may enhance reproducibility by optimizing synthesis parameters. As nanocomposites

play a crucial role in various applications, overcoming these challenges is essential for their reliable commercialization and large-scale production.

Environmental and Health Concerns

While nanocomposites offer significant advantages in various applications, their development raises critical environmental and health concerns. The production, usage, and disposal of nanomaterials can lead to unintended consequences, including potential toxicity and ecological disruption. Due to their nanoscale size, these materials can penetrate biological membranes, posing risks to human health through inhalation, ingestion, or dermal exposure. Studies suggest that some nanomaterials, such as carbon nanotubes and metal oxide nanoparticles, may cause oxidative stress, inflammation, and cytotoxicity in living organisms.

From an environmental perspective, the persistence and bioaccumulation of nanoparticles in soil and water ecosystems remain a major concern. Nanocomposite waste, if not properly managed, can enter natural water bodies, affecting aquatic life and potentially entering the food chain. Additionally, the energy-intensive production processes of certain nanocomposites contribute to carbon emissions and resource depletion.

To mitigate these risks, researchers are exploring green synthesis methods, biodegradable nanocomposites, and improved safety regulations. Rigorous risk assessment frameworks, along with standardized guidelines for nanomaterial disposal and recycling, are essential to minimizing environmental and health hazards. As nanotechnology continues to advance, ensuring the safe and sustainable development of nanocomposites is crucial for their responsible integration into commercial and industrial applications.

COST OF PRODUCTION

The cost of production in the development of nanocomposites is influenced by factors, such as raw material expenses, synthesis techniques, processing methods, and scalability. High-quality nanomaterials, including carbon nanotubes, graphene, and metal oxides, often require sophisticated production methods, increasing costs. The choice of synthesis technique, such as chemical vapor deposition (CVD), sol-gel processing, or hydrothermal methods, significantly impacts the overall expense due to variations in energy consumption, equipment requirements, and material yield.

Processing and functionalization of nanocomposites further contribute to costs. Achieving uniform dispersion of nanoparticles within a matrix requires specialized techniques, like ultrasonication or plasma treatment, which add to manufacturing complexity. Additionally, safety measures for handling nanomaterials increase operational costs, as strict regulations are necessary to mitigate environmental and health risks.

Scalability remains a major challenge in cost reduction. While laboratory-scale production may be feasible, transitioning to large-scale manufacturing requires cost-effective strategies, such as adopting eco-friendly synthesis methods or utilizing abundant raw materials. Advances in automation, 3D printing, and roll-to-roll processing are helping reduce costs, making nanocomposites more viable for commercial applications. Continued research and development efforts aim to optimize cost-efficiency while maintaining the superior properties that make nanocomposites desirable across various industries.
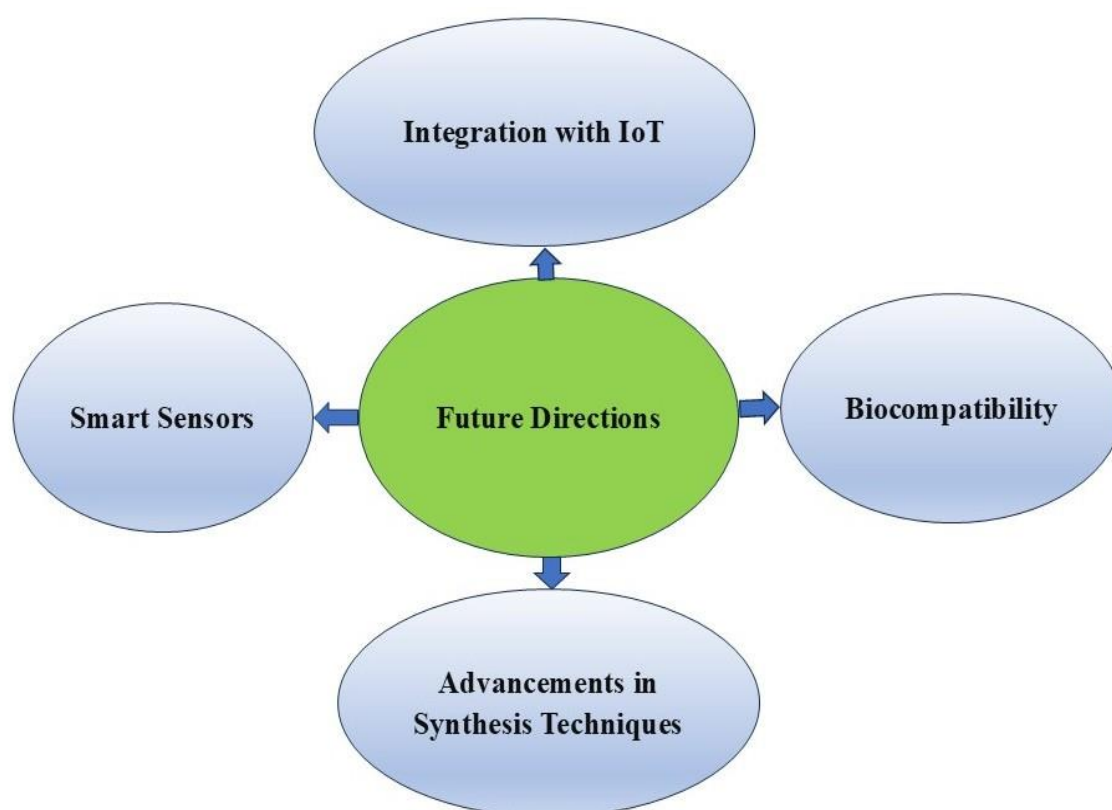
FUTURE DIRECTIONS

Future nanocomposite sensor development focuses on enhancing sensitivity, selectivity, and stability using advanced nanomaterials like graphene, MXenes, and quantum dots. Integration with AI and IoT will enable real-time monitoring. Sustainable, biocompatible materials and 3D printing innovations will drive commercialization, expanding applications in healthcare, environmental monitoring, and wearable technology (Figure 6).

Advancements in Synthesis Techniques

Recent advancements in synthesis techniques have significantly improved the development of nanocomposites, enhancing their structural, mechanical, and functional properties. These techniques enable precise control over the composition, morphology, and dispersion of nanomaterials, leading to superior performance in various applications, including sensors, catalysis, and biomedical devices.

One major advancement is sol-gel processing, which allows for the formation of highly uniform nanocomposites with controlled porosity and high surface area. Hydrothermal and solvothermal methods enable the synthesis of nanocomposites with well-defined crystalline structures at relatively low temperatures. In situ polymerization techniques facilitate strong interfacial interactions between nanoparticles and polymer matrices, enhancing mechanical strength and electrical conductivity.

Figure 6. Future directions.

Emerging approaches, such as atomic layer deposition (ALD) and laser-assisted synthesis, provide precise thickness control and enable the development of highly stable nanocomposites with tailored properties. Additionally, green synthesis methods, utilizing plant extracts or bio-based precursors, offer eco-friendly alternatives to conventional chemical routes.

These advancements contribute to the scalable and cost-effective production of nanocomposites with enhanced functionalities. As synthesis techniques continue to evolve, they will further expand the potential applications of nanocomposites in fields, such as energy storage, environmental remediation, and next-generation electronics.

Integration with IoT

The integration of nanocomposites with the Internet of Things (IoT) is transforming sensor technology, enabling real-time monitoring and smart decision-making in various applications, including environmental monitoring, healthcare, and industrial safety [18]. Nanocomposites, with their enhanced

sensitivity, selectivity, and stability, are ideal for IoT-based sensors, as they enable accurate detection of gases, biomolecules, and mechanical stress at nanoscale precision.

IoT integration allows nanocomposite-based sensors to collect, process, and transmit data wirelessly, reducing human intervention and improving efficiency. For instance, nanocomposite-based air quality sensors embedded in IoT networks can detect pollutants and send alerts in real-time to cloud-based platforms or mobile applications. Similarly, wearable biosensors utilizing nanocomposites can continuously monitor health parameters and transmit data for remote diagnostics.

Advancements in energy-efficient nanomaterials, such as self-powered nanocomposite sensors, further enhance IoT compatibility by reducing power consumption. Additionally, artificial intelligence (AI) and machine learning (ML) integration help analyze large datasets generated by these sensors, optimizing performance and predictive capabilities.

The future of IoT-enabled nanocomposites lies in their miniaturization, scalability, and deployment in smart cities, autonomous systems, and precision medicine, offering intelligent, adaptive, and highly responsive solutions for a connected world.

Biocompatibility

Biocompatibility is a critical factor in the development of nanocomposites, especially for biomedical applications, such as drug delivery, tissue engineering, and biosensors. It ensures that these materials interact safely with biological systems without causing toxicity, inflammation, or immune responses. Achieving biocompatibility requires careful selection of nanomaterials, surface modifications, and synthesis techniques to minimize adverse effects while maintaining functionality.

Nanocomposites incorporating biocompatible polymers, ceramics, or metal oxides – such as hydroxyapatite, chitosan, or silica – enhance biointegration and reduce cytotoxicity. Carbon-based nanomaterials, like graphene and carbon nanotubes, can be modified with biopolymers or peptides to improve their safety profile. Additionally, surface coatings, functionalization with hydrophilic molecules, and controlled degradation rates contribute to their compatibility with living tissues.

In medical applications, nanocomposites are engineered to mimic natural biological structures, promoting cell adhesion and proliferation. For example, bioactive nanocomposites in bone scaffolds facilitate osteointegration, while nanoparticle-based drug carriers ensure controlled release with minimal side effects. Regulatory challenges remain, requiring extensive in vitro and in vivo studies to confirm their safety. However, advancements in nanotechnology and biomaterials continue to drive innovation, making biocompatible nanocomposites a cornerstone of next-generation biomedical devices and therapies.

Smart Sensors

Smart sensors play a crucial role in the development and optimization of nanocomposites by enabling real-time monitoring, analysis, and control of material properties. These advanced sensors integrate artificial intelligence (AI), the Internet of Things (IoT), and machine learning (ML) to enhance the fabrication and performance evaluation of nanocomposite materials. By providing precise data on factors, like temperature, humidity, pressure, and chemical composition, smart sensors help researchers fine-tune nanocomposite synthesis for improved mechanical, electrical, and thermal properties.

In material characterization, smart sensors facilitate in-situ monitoring of nanocomposite structures during manufacturing, ensuring consistency and quality control. For example, optical and electrochemical sensors track nanoparticle dispersion and bonding behavior in polymer matrices, leading to more effective material formulations. Additionally, smart sensors aid in the development of responsive nanocomposites that adapt to environmental conditions, such as self-healing coatings or gas-sensing materials.

CONCLUSIONS

The development of nanocomposites for sensor applications represents a promising frontier in materials science and engineering. The development of nanocomposites for sensor applications represents a significant advancement in materials science, offering enhanced sensitivity, selectivity, and durability across various fields. By leveraging the unique properties of nanoscale materials, such as high surface area, tunable conductivity, and catalytic activity, nanocomposites have revolutionized sensor technology. Their ability to detect gases, chemicals, and biomolecules with improved precision has led to breakthroughs in environmental monitoring, healthcare diagnostics, and industrial safety. The integration of metal oxides, carbon-based nanomaterials, and polymer matrices in sensor design has enabled the creation of highly efficient and cost-effective sensing devices. These materials enhance signal transduction mechanisms, allowing for faster response times and lower detection limits. Furthermore, advancements in smart sensor technology, including artificial intelligence (AI) and the Internet of Things (IoT), have further optimized nanocomposite-based sensors for real-time monitoring and predictive analytics. Despite these advancements, challenges remain in the large-scale production, stability, and long-term performance of nanocomposite sensors. Researchers continue to explore novel fabrication techniques, such as 3D printing and self-assembly, to enhance reproducibility and commercial viability. Additionally, efforts to develop eco-friendly nanocomposites with minimal environmental impact are gaining momentum. Looking ahead, the continued synergy between nanotechnology, machine learning, and flexible electronics will further expand the capabilities of nanocomposite-based sensors. These innovations will contribute to the development of next-generation smart sensing platforms with applications in smart cities, healthcare, and environmental protection. As research progresses, nanocomposites will play an increasingly vital role in shaping the future of sensor technologies, driving efficiency, accuracy, and sustainability in diverse real-world applications. Their unique properties pave the way for the creation of highly sensitive, selective, and reliable sensors across various fields. Despite the challenges that remain, ongoing research and innovation in synthesis, characterization, and application will undoubtedly lead to breakthroughs that enhance the capabilities of sensor technologies in the future.

REFERENCES

1. Abimaheshwari R, Abinaya R, Navaneethan M, Harish S. Enhanced sensitivity and selectivity of ZnSe/PANI nanocomposite for Low-ppm NO2 detection at room temperature gas sensor application. Surf Interf. 2024;55:105295.
2. Priya AK, Muruganandam M, Venkatraman Y, Sagadevan S. Recent advances and synergistic interactions in graphene-based polymer nanocomposites for enhanced gas sensing applications. J Alloys Compounds. 2024:176599.
3. Mohanty B, Kumari S, Yadav P, Kanoo P, Chakraborty A. Metal-organic frameworks (MOFs) and MOF composites based biosensors. Coordinat Chem Rev. 2024;519:216102.
4. Sivasubramanian P, Kumar M, Chen CL, Kiran-kumar VS, Samuel MS, Chang JH. A review of metal nanomaterials-based electrochemical biosensors for environmental wastewater monitoring and their remediation. Environ Nanotechnol Monitor Manag. 2024:101023.
5. Anwer AH, Saadaoui M, Mohamed AT, Ahmad N, Benamor A. State-of-the-Art advances and challenges in wearable gas sensors for emerging applications: Innovations and future prospects. Chem Eng J. 2024:157899.
6. Liu C, Wang Q, Wang C, Wang Q, Zhao W, He Z, Zheng Y, Jing Y, Sun X, Zhang S. State of the art overview wearable biohazard gas sensors based on nanosheets for environment monitoring applications. Trend Environ Anal Chem. 2023:e00215.
7. Motsoeneng RG, Swart HC, Motaung DE. The influence of Fe loading on the optical and gas sensing characteristics of SnO2/ZnO heterostructures. Phys B Cond Matter. 2023;668:415256.
8. Hajivand P, Jansen JC, Pardo E, Armentano D, Mastropietro TF, Azadmehr A. Application of metal-organic frameworks for sensing of VOCs and other volatile biomarkers. Coord Chem Rev. 2024;501:215558.
9. Ali Z, Yaqoob S, Yu J, D'Amore A. Critical review on the characterization, preparation, and enhanced mechanical, thermal, and electrical properties of carbon nanotubes and their hybrid filler polymer composites for various applications. Compos C Open Access. 2024:100434.

10. Soni SK, Thomas B, Thomas SB, Tile PS, Sakharwade SG. Carbon nanotubes as exceptional nanofillers in polymer and polymer/fiber nanocomposites: An extensive review. Mater Today Commun. 2023;37:107358.

11. Sharma D, Kanchi S, Sabela MI, Bisetty K. Insight into the biosensing of graphene oxide: Present and future prospects. Arab J Chem. 2016;9(2):238–261.

12. Kumar S, Bukkitgar SD, Singh S, Pratibha, Singh V, Reddy KR, Shetti NP, Venkata Reddy C, Sadhu V, Naveen S. Electrochemical sensors and biosensors based on graphene functionalized with metal oxide nanostructures for healthcare applications. ChemistrySelect. 2019;4(18):5322–5337.

13. Quang HH, Dinh NT, Truong QM, Nguyen PK, Nguyen VH. Unlocking the potential of environmentally friendly adsorbent derived from industrial wastes: A review. Chemosphere. 2024;367:143662.

14. Wang C, Yin L, Zhang L, Xiang D, Gao R. Metal oxide gas sensors: sensitivity and influencing factors. Sensors. 2010;10(3):2088–2106.

15. Hammad SF, Abdallah IA, Bedair A, Abdelhameed RM, Locatelli M, Mansour FR. Metal organic framework-derived carbon nanomaterials and MOF hybrids for chemical sensing. TrAC Trends Anal Chem. 2024;170:117425.

16. Khoramshahi V, Azarang M, Nouri M, Shirmardi A, Yousefi R. Metal oxide/g-C3N4 nanocomposites chemiresistive gas sensors: A review on enhanced performance. Talanta Open. 2024:100290.

17. Alaizeri ZM, Alhadlaq HA, Aldawood S, Ahamed M. SnO2-TiO2/reduced graphene oxide nanocomposites: Green synthesis and enhanced photocatalytic efficiency for dye removal. J Radiation Res Appl Sci. 2024;17(4):101181.

18. Verma D, Singh KR, Yadav AK, Nayak V, Singh J, Solanki PR, Singh RP. Internet of things (IoT) in nano-integrated wearable biosensor devices for healthcare applications. Biosens Bioelectron X. 2022;11:100153.