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A Review of Maghemite Nanoparticles as Environmental Sensors

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Abstract

The increasing urgency to monitor and mitigate environmental pollution has driven significant interest in the development of advanced sensing technologies. Nanotechnology presents promising solutions through the application of nanoscale materials, among which maghemite nanoparticles (γ-Fe_2O_3) have garnered considerable attention due to their unique physicochemical properties, high chemical stability, a large specific surface area, and superparamagnetic behavior, making them suitable for separation, target deployment, and sensor regeneration. It functionalized maghemite nanoparticles to enhance their selectivity toward specific pollutants, including heavy metals (e.g., Pb^{2+} and Cd^{2+}) and toxic gases (e.g., NO, NH_3, and H_2S). These articles present a review of the structural and physicochemical characteristics of maghemite nanoparticles, including commonly applied synthesis methods, sensor mechanism, and their applications in pollutant detection, such as heavy metals and toxic gases. The review also highlights current challenges and outlines future directions for the development of more efficient, affordable, and sustainable maghemite-based sensors for next-generation environmental monitoring systems.

Keywords: *Maghemite Nanoparticles, Γ-Fe_2O_3, Environmental Sensors, Nanotechnology, Functionalized Maghemite.*

1. INTRODUCTION

Over the past several decades, environmental pollution has exhibited a persistent upward trend, primally driven by urban expansion, intensified industrial operations, and agricultural practices. Pollutants such as heavy metals, toxic gases, and volatile organic compounds (VOCs) not only degrade air and water quality but also pose serious threats to human health and ecosystem stability (Patekari et al., 2021). Environmental sensors are devices designed to detect and quantify the presence of pollutants with high sensitivity and selectivity. However, conventional sensors still face several limitations, including large size, limited portability, slow response time, and dependency on specific environmental conditions (Aftab et al., 2025). To overcome these challenges, nanotechnology offers promising solutions through nanoscale materials that exhibit unique physical and chemical properties (Saleh & Fadillah, 2023). Among these nanomaterials, maghemite nanoparticles (γ-Fe_2O_3) have attracted significant attention in developing advanced environmental sensors.

Maghemite (γ-Fe_2O_3) is a form of iron oxide with a spinel structure composed entirely of Fe^{3+} ions with vacancies, making it more chemically stable compared to other iron oxides, such as magnetite (Fe_3O_4), which contains a mixture of Fe^{2+} and Fe^{3+} ions (Cabrera et al., 2024; Kang & An, 2023). This chemical stability is crucial for environmental applications, which are often subject to fluctuating conditions. Maghemite exhibits a high specific surface area in its nanoscale form, enabling enhanced surface interactions with pollutant molecules (Patekari et al., 2021). One of the key characteristics of maghemite nanoparticles is their magnetic properties. Maghemite can exhibit superparamagnetism at certain nanoscale sizes (typically below 30 nm) (Chauhan et al., 2025). This property is highly beneficial for the separation, controlling, and targeted deployment of sensors in complex environmental matrices. Rajput et.al. (2017) successfully carried out the remediated lead (Pb^{2+}) and copper (Cu^{2+}) from water using superparamagnetic maghemite nanoparticles (Rajput et al., 2017). Yadav & Fulekar (2018) employed maghemite nanoparticles (20-40 nm) for the removal of Pb, achieving up to 85% removal of Pb within only two hours, and up to 96% after 24 hours. In addition, the nanoparticles were able to remove approximately 67.8% of Cd (Yadav & Fulekar, 2018). Moreover, this property also supports the development of regenerative sensors that can be reused after the detection process is completed. Maghemite nanoparticles are also readily chemically modified through surface functionalization, allowing for enhanced specificity and adaptability in sensor design. The surface of nanoparticles can be functionalized using organic compounds, polymers, or target-specific molecules to enhance their selectivity toward specific pollutants. Guivar et al. (2017) successfully synthesized maghemite functionalized with organic acid, amino acids, silica, and carbon nanotubes using the co-precipitation method with particle sizes ranging from 7 to 16 nm, as determined by Rietveld refinement and TEM analysis. The resulting functionalized maghemite nanoparticles exhibited Brunauer-Emmett-Teller (BET) specific surface areas ranging from 74 to 214 $m^2\ g^{-1}$, indicating remarkable uptake capacities to remove Cu(II) and Pb(II) species from aqueous solutions (Ramos Guivar et al., 2017). In heavy metal detection applications, the surface of maghemite nanoparticles can be functionalized with thiol groups (-SH), which exhibit a high affinity toward metal ions. Kothavale et al (2023) successfully synthesized carboxyl and thiol-functionalized magnetic nanoparticles for the removal of Pb(II), Cd(II) and Ni(II) heavy metal ions from aqueous solutions (Kothavale et al., 2023). Meanwhile, to detect gases such as NH_3 or H_2S, the surface can be modified with gas-sensitive organic compounds that react with the target gases, resulting in measurable changes in electrical or optical signals. Yang et.al. (2025) successfully developed a chemiresistive nitric oxide (NO) sensor based on Fe_2O_3 nanoparticles, demonstrating that the NO sensitivity of γ-Fe_2O_3 was enhanced by more than three times at an optimal operating temperature of 250°C. The sensor exhibited a significantly higher NO sensitivity when using maghemite (73.55 %) compared to hematite (58.5%) (Yang et al., 2025).

This article aims to comprehensively review the characteristics and applications of maghemite nanoparticles in environmental sensing. The study involves the structural and physicochemical characteristics of maghemite, synthesis techniques, operational principles of maghemite-based sensors, their applications in pollutant detection, alongside the challenges and prospective developmental trajectories. The properties and performance of maghemite nanoparticles will be investigated to facilitate the development of more efficient, cost-effective, and sustainable maghemite-based environmental sensors.

2. METHOD

This study aims to collect and evaluate empirical evidence regarding maghemite nanoparticles for environmental sensor applications. This approach enables a comprehensive assessment of the quality and limitations found in current research related to maghemite nanoparticles. The type of literature review used in this study is a descriptive-analytical approach. This approach involves organizing and presenting previous research while critically analyzing and interpreting the data to identify patterns, gaps, and relevant insights. The illustration of the research stages undertaken in this study is presented in Figure 1. The first step, identification of data sources, was conducted through reputable academic databases, including Google Scholar, ScienceDirect, Scopus, MDPI, ResearchGate, and ACS Publications, focusing on studies published in the last ten years (2015-2025). The selection criteria included the use of specific keywords to guide the search, such as “maghemite,” “synthesis of maghemite nanoparticles,” “maghemite nanoparticles method,” “nanomaterial sensor,” “functionalized maghemite”, and “environmental sensors.” Inclusion criteria focused on peer-reviewed journal articles that discussed the synthesis, properties, or environmental sensor applications of maghemite nanoparticles. Exclusion criteria eliminated studies that did not directly address maghemite, lacked relevance to sensor technology, or were not available in full-text sources. Relevant studies were summarized to identify key findings related to the synthesis, properties, and sensor applications of maghemite nanoparticles. Data processing was carried out by organizing the selected data according to key themes, such as synthesis techniques of maghemite nanoparticles, surface functionalization of maghemite, and sensor mechanisms. The data were critically interpreted to evaluate the role of maghemite nanoparticles in enhancing sensor performance, particularly in terms of sensitivity, selectivity, and stability. The last step is writing the review articles, which was conducted in a structured and analytical manner, synthesizing relevant literature to provide a comprehensive overview of the topic.

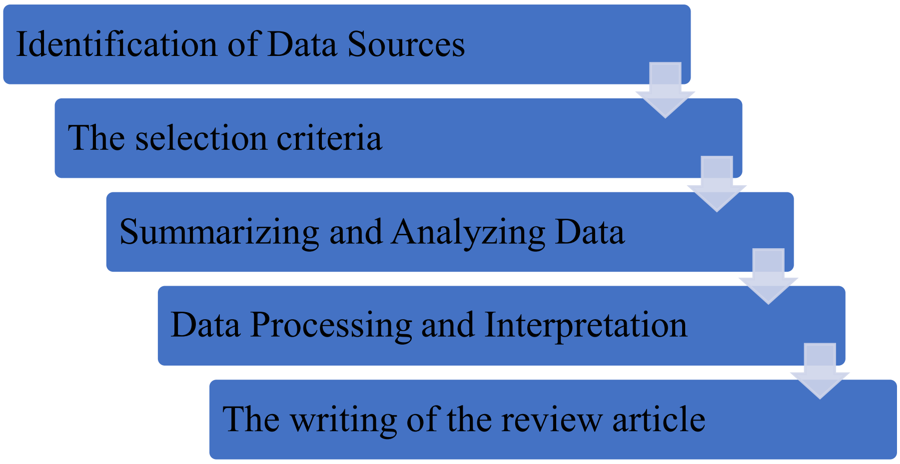

Figure 1. illustrates the sequential stages of the research process conducted in this study

3. RESULTS AND DISCUSSION

3.1 Crystal Structure and Composition of Maghemite (γ-Fe_2O_3)

Maghemite nanoparticles have attracted considerable attention in the development of environmental sensor technologies due to their unique combination of physical, chemical, and magnetic properties. Maghemite possesses a distorted spinel crystal structure, in which all iron is present in the Fe^{3+} oxidation state (Chauhan et al., 2025). The spinel structure consists of two types of crystallographic sites for metal ions: tetrahedral (A sites) and octahedral (B sites). In maghemite, most Fe^{3+} ions are randomly distributed between these two sites, and the presence of vacancies in the octahedral positions is a distinctive feature of its structure (Chauhan et al., 2025; D. S. Chaudhari et al., 2024). The spinel structure of maghemite is highly similar to that of magnetite (Fe_3O_4), with the primary differences being the oxidation state and chemical stability

(Chauhan et al., 2025; D. Chaudhari & Panda, 2023; Roca et al., 2023). These properties make maghemite more stable under oxidative conditions, making it more suitable for long-term applications in environmental sensor technologies (D. Chaudhari & Panda, 2023; Bushra et al., 2024). Table 1 presents a comparison of the properties of maghemite with other iron oxides, namely magnetite (Fe_3O_4) and hematite (α-Fe_2O_3).

Table 1 The Comparison focuses on key properties maghemite (γ-Fe_2O_3), magnetite (Fe_3O_4) and hematite (α-Fe_2O_3) (Sharma et al., 2025; Chauhan et al., 2025; Chaudhari & Panda, 2023)

Key Properties	Maghemite (γ-Fe_2O_3),	Magnetite (Fe_3O_4)	Hematite (α-Fe_2O_3)
Crystal structure and morphology	Cubic spinel structure, spherical nanoparticles with uniform size distribution. Structurally and oxidatively stable	Cubic spinel structure containing Fe^{2+}/Fe^{3+}, more susceptible to oxidation into maghemite. Similar morphology with maghemite, but less stable	Hexagonal corundum structure, more variable shapes, less homogeneity, and low magnetism
Magnetic properties	Ferrimagnetic, superparamagnetic at sizes below 30 nm, reduces agglomeration, and exhibits magnetic stability under environmental conditions	Higher magnetic saturation, but prone to oxidation, leading to reduced magnetic stability	Antiferromagnetic or weakly ferromagnetic, with very low magnetization, making it less suitable for magnetic applications
Chemical and thermal stability	High chemical stability, oxidation-resistant, and thermal stable within the typical operating temperature range of environmental sensors (≤600 °C).	Prone to oxidation into maghemite under aerobic conditions and elevated temperatures	Highly thermally stable at elevated temperatures (> 600), but exhibits limited magnetic and chemical stability under typical sensor environmental conditions
Surface modification	Active surface with various functional groups, easily modifiable, suitable for sensor applications	Can be modified, but surface stability is lower due to susceptibility to oxidation	Less reactive surface compared to maghemite, with more limited and less efficient modification potential

3.2 Morphology and Particle Size

The size of maghemite nanoparticles typically ranges from 5 to 50 nanometers, depending on the synthesis method used. Helmiyati & Masriah (2019) successfully synthesized spherical maghemite nanoparticles with a particle size of approximately 22 nm using the one-step sol-gel method with $Fe(NO_3)_3$ as a precursor and citric acid as a chelating agent (Helmiyati & Masriah, 2019). This nanoscale dimension yields a high surface-to-volume ratio, which significantly enhances the interaction area with target molecules such as heavy metals or gaseous pollutants (Chauhan et al., 2025). Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) are widely utilized characterization techniques to examine the morphology and particle size distribution of maghemite nanoparticles. These nanoparticles typically exhibit nearly spherical surfaces, although their morphology can vary depending on the synthesis conditions. Figure 2 presents the TEM image analysis, illustrating the morphology of maghemite nanoparticles synthesized via a one-pot method using a single precursor ($FeCl_2.4H_2O$). The TEM images with high resolution indicate that the synthesized maghemite nanoparticles via the one-pot method are monodisperse, exhibiting a mixture of spherical and cubic shapes (Abbas et al., 2015).

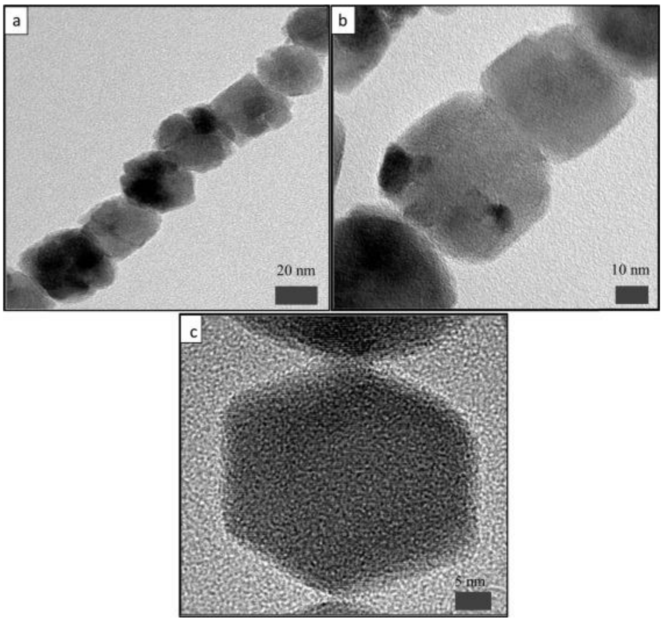

Figure 2. TEM images with high resolution of maghemite nanoparticles synthesized via one-pot method using a single precursor (Abbas et al., 2015)

3.3 Properties of Maghemite Nanoparticles

The magnetic properties of maghemite nanoparticles represent a key advantage in their development for environmental sensor applications. At certain particle sizes, typically below 30 nanometers, these materials exhibit superparamagnetism, a condition in which the particles possess a high magnetic moment that can be manipulated by an external magnetic field, but do not retain magnetization once the field is removed (Kour et al., 2019). Abbas et al (2015) successfully synthesized maghemite nanoparticles exhibiting a high magnetic moment of 65 emu/g with superparamagnetic properties (Abbas et al., 2015). This superparamagnetic property is crucial for sensor applications, as it enables non-contact manipulation and separation of the sensing material, enhances sensor regenerability i.e., the ability to reuse the sensor after purification, and minimizes the risk of particle agglomeration.

3.4 Chemical and Thermal Stability

Maghemite exhibits high chemical stability, particularly in oxidative media or within a neutral to acidic pH range. This chemical stability is crucial in environmental prone to fluctuations, such as sensors exposed to reactive chemicals, fluctuating temperatures, or changing atmospheric conditions. (Tian et al., 2023). Additionally, maghemite exhibits good thermal stability up to temperatures of around 300-350°C, beyond which it begins to undergo phase conversion into hematite (α-Fe_2O_3) at higher temperatures. Ramos-Guivar et al. (2022) successfully modified the surface of maghemite nanoparticles using type 5A zeolite to enhance their thermal stability (Ramos-Guivar et al., 2022).

3.5 Surface Modification

The surface of maghemite nanoparticles can be modified with various functional groups. Thiol (-SH) or amine (-NH_2) groups are commonly used to improve selectivity towards heavy metals. Conductive polymers, such as polyaniline, are used in environmental sensors to enhance the sensor's response to gas pollutants. Organic ligands or biomolecules (such as enzymes or antibodies) can also be used in environmental sensors to enhance selectivity towards specific molecules. Xiao et al (2023) successfully functionalized maghemite nanoparticles with 3-aminopropyltriethoxysilane (APTES) and diethylenetriamine-pentaacetic acid (DTPA) using the ultrasonification method to enhance uranium adsorption from simulated water and magnetic harvesting (Xiao et al., 2023). Abouelkheir et al. successfully functionalized superparamagnetic maghemite nanoparticles (7.68 nm) with amylase enzyme for biofuel applications (Abouelkheir et al., 2023). This modification is essential for enhancing selectivity and compatibility, particularly in complex sensor applications.

3.6 Synthesis Methods

Several common methods used in the synthesis of nanomaterials can be also be applied to the synthesis of maghemite nanoparticles. Table 2 outlines the advantages and disadvantages of various maghemite nanoparticle synthesis methods.

Table 2. Advantages and disadvantages of various maghemite nanoparticle synthesis methods (Sharma et al., 2025;Chauhan et al., 2025; Chaudhari & Panda, 2023; Austria et al., 2024)

Method	Advantages	Disadvantages
Sol-Gel	Particle size can be controlled, high purity, homogeneous material	Complex, Time-consuming process
Co-precipitation	Cost-effective, Straightforward, large-scale production, easy	The particle size distribution is non-uniform
Thermal decomposition	High crystallinity, Uniform particle size distribution	Requires high temperatures, organic solvents
Hydrothermal	Controlled morphology, Suitable for surface modification, low defect rate	Prolonged reaction time, requires specialized reactors
Microemulsion	Controlled morphology, monodispersed	High-cost, excess surfactants may affect the maghemite nanoparticle
Sonochemical reaction	Controlled morphology, can be used to produce maghemite nanoparticle of various shapes	Large energy requirements to up-scale
Electrodeposition	Fast, scalable	High specificity and dependency on the electrolyte system

The selection of the synthesis method is a crucial factor, as it influences the characteristics of maghemite nanoparticles, including size, shape, and surface functionalization capabilities (Sharma et al., 2025). The synthesis of maghemite nanoparticles can be carried out using two main approaches. The direct synthesis method involves the use of a single precursor of iron (III), such as $FeCl_3$ or Fe $(NO_3)_3$. In this route, the iron (III) precursor undergoes direct oxidation to form maghemite (γ-Fe_2O_3) without passing through a magnetite intermediate. Abbas et al (2015) utilized $FeCl_2.4H_2O$ as a precursor to synthesized monodisperse chain-like superparamagnetic maghemite nanoparticles with a particle size of 25 nm (Abbas et al., 2015). Helmiyati & Masriah (2019) successfully synthesized maghemite nanoparticles through direct synthesis using Fe(III) ion precursor via the sol-gel method (Helmiyati & Masriah, 2019). Alternatively, the indirect synthesis method involves the initial formation of magnetite (Fe_3O_4) using two precursors (Fe^{2+} and Fe^{3+} ions). The resulting magnetite is oxidized to γ-Fe_2O_3 through thermal treatment at temperatures ranging from 200-300 °C. Arul et al. (2023) also successfully synthesized maghemite nanoparticles via an indirect sol-gel method using $FeCl_2.4H_2O$ and $FeCl_3.6H_2O$ as precursors (Arul et al., 2023). Meanwhile, Yang et al. (2025) and Patekari et al (2021), successfully synthesized maghemite nanoparticles using an indirect co-precipitation method with two precursors, $FeCl_3$ and $FeSO_4.7H_2O$, producing spherical maghemite nanoparticles with particle sizes of approximately 20 nm. A summary of maghemite nanoparticle synthesis using various methods, including particle size, precursors employed, and resulting morphology, is presented in Table 3.

Table 3. Synthesis of Maghemite Nanoparticles Using Various Methods

Method	Precursors	Particle size in nm	Morphology	Ref
Carbon-templaed solution combustion	$Fe(NO_3)_3.9H_2O$ and triethylenetetramine ($C_6H_{15}N_4$) as template	8-12	Spherical	(Ianoş et al., 2018)
Co-precipitation	$FeCl_3$ and $FeSO_4.7H_2O$	10-20	Spherical	(Yang et al., 2025)
Co-precipitation	$FeCl_3$ and $FeSO_4.7H_2O$	20	Spherical	(Patekari et al., 2021)
Co-precipitation	$FeCl_2$ and $FeCl_3$	18	N/A*	(Babay et al., 2015)
Co-Precipitation	$FeCl_3$ and $FeSO_4.7H_2O$	50-120	Spherical with high aggregation	(Yadav & Fulekar, 2018)
Co-precipitation	Zeolite 5A; $FeCl_3$; $FeSO_4.7H_2O$	3-20	Spherical	(Ramos-Guivar et al., 2021)
Hydrothermal carbonisation	Sucrose; Ascorbic acid, γ-Fe_2O_3	11 (γ-Fe_2O_3); 4.5-6.5 (CQD@ γ-Fe_2O_3)	Spherical	(Panda et al., 2020)
Polyol method	Fe(II)acetate as metal precursor and triethylene glycol (TEG) as solvent	10±2	Spherical	(Xiao et al., 2023)
Sol-gel	$FeCl_2.4H_2O$ and $FeCl_3.6H_2O$	N/A**	Spherical	(Arul et al., 2023)
Sol-gel	$Fe(NO_3)_3.9H_2O$	22	Spherical	(Helmiyati & Masriah, 2019)
Sol-gel	$C_{15}H_{21}FeO_6$	10±0.9	Spherical	(Benamara et al., 2023)
Sol-gel combustion	P123; nitric acid; citric acid; $Fe(NO_3)_3.9H_2O$	10-30	Spherical	(Tian et al., 2023)

* the morphological analysis results, whether obtained using TEM or SEM, were not reported
**the particle size results were not reported

3.7 Principle of Environmental Sensors Based on Maghemite Nanoparticles

Environmental sensors based on maghemite nanoparticles utilize their distinctive physical and chemical properties to detect the presence of pollutants with high sensitivity and selectivity. The principle of these sensors depends on the type of target pollutant (heavy metals, gases, or organic compounds) and the transduction mechanism (electrochemical (Jjagwe et al., 2024), resistive (Patekari et al., 2021), optical, or magnetic). Maghemite nanoparticles interact with target pollutants through various mechanisms. In the surface adsorption mechanism, pollutants (such as metal ions or gases) adsorb to the surface of maghemite nanoparticles through physical or chemical bonding. In sensors with electrochemical transduction, redox reactions occur, involving electron exchange between the maghemite nanoparticles and the target pollutant (Jjagwe et al., 2024). Electrochemical sensors based on maghemite typically utilize a working electrode modified with a maghemite nanoparticle layer. When heavy metal ions such as Pb^{2+} or Cd^{2+} are present in the sample, these pollutants are adsorbed onto the particle surface and generate an electrical current signal through redox processes. Arul et al (2023) successfully utilized coated maghemite nanoparticles in activated carbon for the removal Pb(II) dan Cd(II) ions from an aqueous system (Arul et al., 2023).

In gas detection, such as NH_3, NO_2 (Patekari et al., 2021), or H_2S, maghemite nanoparticles are employed as the sensitive layer in resistive sensors (Yang et al., 2025). Yang et al. (2025) utilized maghemite nanoparticles as sensors for nitric oxide (NO) detection. The results demonstrated that the maghemite nanoparticles could detect ultra-trace levels of NO in the range of 0.2 -10 ppm under optimal temperature conditions. (Yang et al., 2025). Patekari et al. (2021) utilized spherical maghemite nanoparticles for nitrogen dioxide (NO_2) gas detection. The sensor selectively detected NO_2 at a concentration of 40 ppm under optimal temperatures ranging from 100 to 200 °C. Upon exposure to 40 ppm, the sensor demonstrated the ability to oxidize and reduce gases such as CO_2, NO_2, NH_3, acetone (C_3H_6O), and liquified petroleum gas (LPG) (Patekari et al., 2021). The selectivity of the maghemite-based sensor indicates high-level heterogeneous interactions and surface decompositions, which are attributed to the presence of a lone pair of electrons in the NO_2 gas molecule, leading to its high reactivity (Patekari et al., 2021). Patakeri et al. (2021) proposed a schematic mechanism of a chemiresistive-type gas sensor based on maghemite nanoparticles, which exhibited selective detection of NO_2 gas at low concentrations (as low as 1 ppm) with an upper detection limit of 25 ppm at an operating temperature of 150 ℃ (Patekari et al., 2021). When gas molecules adsorb onto the surface of the maghemite particles, they induce changes in the number of charge carriers (electrons or holes), resulting in variations in electrical resistance. In chemiresistive sensors, the ionization process facilitates the formation of O^- ions on the sensor surface. When the sensor is exposed to a specific concentration of NO_2 gas (in ppm) within the test chamber, the gas molecules react with the chemisorbed oxygen ions (O^-). As an oxidizing gas by nature, NO_2 tends to attract high-energy conduction electrons, which are derived from these oxygen ions. These interactions lead to an increase in the sensor's resistance, enabling the maghemite—based sensor to detect NO_2 gas with high selectivity and sensitivity (Patekari et al., 2021). Figure 3 presents a schematic representation of the sensing mechanism of a chemiresistive-type gas sensor based on maghemite nanoparticles for selective NO_2 sensing. The reaction between NO_2 gas and oxygen ions on the sensor surface is represented by equations (1-3) (Patekari et al., 2021).

$$NO_2 + e^- \rightarrow NO_2^- \quad (1)$$

$$NO_2 + O_2^- + 2e^- \rightarrow NO_2^- + 2O^- \quad (2)$$

$$NO_2 + O^- + 2e^- \rightarrow NO_2^- + O^{2-} \quad (3)$$

The superparamagnetic properties of maghemite are utilized in sensors based on magnetic field variation. By integrating maghemite with fluorophores or gold nanoparticles, magnetic sensors can be developed to detect pollutants based on changes in color or fluorescence intensity. Panda et al. (2020) utilized CQD@γ-Fe_2O_3 multifunctional nanoprobe for selective fluorescence sensing and removal of Hg(II) (Panda et al., 2020).

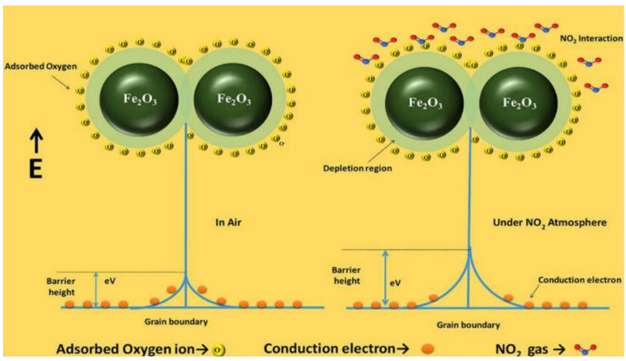

Figure 3. Schematic representation of sensing mechanism of chemiresistive-type gas sensor based on maghemite nanoparticles for selective NO2 selection (Patekari et al., 2021)

3.7 Advantages, Challenges and Future Prospects of Maghemite Nanoparticle-Based Sensors

Further development of nanomaterial-based sensors is desirable due to their inherent flexibility, stretchability, and breathability (Aftab et al., 2025). Among these, maghemite nanoparticles stand out as promising candidates owing to their unique magnetic and physicochemical properties that are well-aligned with the complex demands of environmental sensing (Yang et al., 2025). Specifically, the high surface-area-to-volume ratio of maghemite nanoparticles increases their interactive surface, thereby enhancing adsorptive interaction with target pollutants. The intrinsic property contributes to an improved limit of detection (LOD) and faster response times. The superparamagnetic behavior facilitates non—contact manipulation, easy separation, and sensor regeneration. Maghemite nanoparticles' chemical and thermal stability make them well-suited for application under extreme and variable environmental conditions. Furthermore, surface functionalization enables selectivity toward specific pollutants, rendering these sensors highly adaptable for detecting heavy metals, hazardous gases, or organic contaminants.

The several barriers still limit the broader application of maghemite-based sensors. The primary challenge is the lack of uniformity in particle size and morphology, which directly affects the reproducibility and consistency of sensor performance. The synthesis of monodisperse maghemite nanoparticles often requires precise control over parameters such as pH, temperature, precursor concentration, and reaction time, conditions that are difficult to maintain during large-scale production. The sensitivity of nanoparticle performance to environmental factors such as humidity, temperature, and pH can also affect sensor functionality and impact long-term stability and reproducibility (Thakur & Kumar, 2022). Fluctuations in humidity or pH may alter the surface charge distributions and redox behavior. Encapsulation strategies such as embedding maghemite into protective hydrogel matrices or porous nanocomposites can be employed to reduce environmental interference while maintaining analyte accessibility. The tendency of nanoparticles to agglomerate, particularly during integration onto sensor substrates, may also occur. This agglomeration reduces active surface area and magnetic properties. The chemical modification strategies utilizing surfactants and capping agents are implemented to minimize agglomeration and maintain colloidal stability without compromising sensor performance (Shaikh et al., 2025). Shaikh et al. (2025) reported on the effect of surfactant-functionalized iron oxide nanoparticles in preventing agglomeration. Surfactants such as CTAB, EDTA, and SDS reduce the surface energy of nanoparticles, which arises from their high surface-to-volume ratio, by capping the active surface sites and stabilizing them. The long hydrophobic alkyl chains of these surfaces extend outward from the nanoparticle surface, thereby regulating interparticle interaction and effectively preventing agglomeration (Shaikh et al., 2025) The advantages and challenges associated with maghemite nanoparticle-based sensors are summarized in Table 4.

Table 4. The advantages and challenges of maghemite nanoparticle-based sensors

Advantages	Challenges
High sensitivity due to the large specific surface area	Nanoparticle agglomeration can reduce sensor performance
Can be manipulated using an external magnetic field	Sometimes requires high operating temperatures for gas sensing applications
Easy to modify through chemical functionalization to enhance selectivity	Requires specialized fabrication techniques to ensure long-term stability
Sensor regeneration facilitated by the use of an external magnetic field	Challenges in scale-up production and surface stability

However, the integration of maghemite nanoparticle-based sensors into electronic systems, such as portable IoT-based sensors, remains challenging due to difficulties in achieving uniform deposition and ensuring compatibility with the substrate. The combination of maghemite with other nanomaterials such as carbon-based materials, semiconductors, or noble metals can enhance the sensitivity and stability of sensors through synergistic effects. Maghemite nanoparticles hold great potential for application in portable sensors or IoT-based systems for real-time environmental monitoring. In IoT integrations, maghemite nanoparticles are commonly utilized as active elements in sensor systems to detect gaseous pollutants and heavy metal ions in water. These sensors are integrated into electronic systems comprising controllers, wireless communication modules (Wi-Fi), and cloud-based data processing and visualization platforms (Devnath et al., 2024). Effective maghemite-IoT sensor integration requires addressing key technical and practical challenges. Sensor miniaturization must preserve sensitivity and selectivity, while power efficiency and energy management are crucial for ensuring system stability and long-term functionality.

Future developments are expected to focus on improving the sensitivity and selectivity of sensors for multiple parameters (multi-target), such as heavy metals, pH, gases, and temperature simultaneously (Aftab et al., 2025). Sensors based on maghemite nanoparticles can simultaneously detect and adsorb pollutants, thereby offering a novel alternative for integrated environmental management. Maghemite nanoparticles can also play an active role in environmental remediation processes. The dual role of maghemite as a remediation agent and environmental sensor is rooted in its unique physical, chemical, and magnetic properties, which enable active interaction with pollutants and detectable changes in its physicochemical characteristics. The surface of maghemite, within hydroxyl groups (-OH), can interact with heavy metal ions, organic compounds, and other pollutants through ionic bonding, complexation, and physical and chemical adsorption. Surface area enables maghemite to adsorb and remove contaminants from water or soil effectively. In addition, the hydroxyl radicals ($\cdot OH$) generated on the maghemite surface exhibit high reactivity and can oxidise organic pollutants into less harmful compounds (Rajput et al., 2017). This characteristic positions maghemite as a highly promising material for developing sustainable environmental technologies, offering high efficiency and multifunctionality. Using maghemite nanoparticles as active materials in environmental sensors demonstrates significant potential in sensitivity, magnetic manipulability, and surface modification capability. Although several challenges remain, advances in nanomaterial-based sensor technology, fabrication techniques, and integration with IoT-based sensor systems provide a pathway for developing a new generation of innovative, efficient, and sustainable environmental sensors.

4. CONCLUSION

Maghemite nanoparticle-based sensors represent a promising approach for developing environmental monitoring systems that detect pollution. Their spinel crystal structure gives them unique physical, chemical, and magnetic properties. Depending on the synthesis method employed, the particle size of maghemite nanoparticles typically ranges from 5 to 50 nanometers. Numerous previous studies have successfully synthesized maghemite nanoparticles using various techniques, including both direct and indirect approaches. Characterization results using transmission electron microscopy (TEM) and scanning electron microscopy (SEM) have shown that the nanoparticles generally possess a spherical morphology.

Maghemite nanoparticles with particle sizes below 30 nm often exhibit superparamagnetic behavior, a key feature that supports their application in sensors, sensor regenerability, and minimizes the risk of agglomeration. Maghemite demonstrates high chemical stability, particularly in oxidative environments and across neutral to acidic pH ranges. Surface modification of maghemite nanoparticles is crucial for enhancing selectivity and compatibility, especially in complex sensor applications.

Various nanomaterial synthesis methods, such as sol-gel, co-precipitation, combustion, and the hydrothermal method, can be employed to prepare maghemite nanoparticles. Maghemite nanoparticles interact with target pollutants through several mechanisms. Although several challenges remain, ongoing advances in nanomaterial-based sensing technology, sensor fabrication techniques, and integration with IoT platforms provide a promising foundation for developing next-generation, efficient, and sustainable environmental sensors.

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