International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Bismuth Oxide Nanoparticles: Synthesis, Properties and Emerging Applications - A Short Review

Samadhan M. Nikam[1], Arun V. Patil[2], Chandrakant G. Dighavkar[3]

[1-3]Department of Electronic Science and Research Centre, MGV's L.V.H. College, Panchavati, Nashik, Dist- Nashik-422003, India.

[1]Dept. of Computer Science, Ashoka Center for Business and Computer Studies College, Chandshi, Nashik, India.

[2]Department of Physics, MGV's Arts, Science and Commerce College, Manmad, Dist. - Nashik - 423105, India.

[3]Department of Physics, MGV's, Arts, Science and Commerce College, Surgana, Dist. Nashik 422211, India

Abstract:

Bismuth oxide (Bi_2O_3) nanoparticles have attracted considerable research interest because of their distinctive structural, optical, electrical, dielectric, catalytic and biological characteristics. The combination of a high refractive index, relatively narrow optical band gap, large oxygen-ion conductivity in appropriate polymorphs, high surface-to-volume ratio and tunable surface chemistry makes Bi_2O_3 an attractive functional nanomaterial for environmental, energy, sensing, optical and biomedical technologies. The properties of Bi_2O_3 strongly depend on crystal phase, particle size, morphology, synthesis conditions and surface defects. Bi_2O_3 exhibits several polymorphic structures, among which α-Bi_2O_3 is stable at room temperature, whereas β-, γ- and δ-Bi_2O_3 represent metastable or high-temperature structures under conventional conditions. Phase control therefore represents an important consideration during nanoparticle synthesis. Several synthesis approaches, including precipitation, sol–gel, hydrothermal, solvothermal, combustion, citrate-gel, microwave-assisted and green synthesis, have been reported for producing Bi_2O_3 nanoparticles with controlled particle size and morphology. Green synthesis using plant extracts and biological materials has received increasing attention because it reduces the dependence on harsh chemical reagents and provides surface-functionalized nanoparticles. Bi_2O_3 nanoparticles have demonstrated significant potential in photocatalytic degradation of organic pollutants, antibacterial systems, gas sensors, electrochemical sensors, supercapacitors, batteries, dielectric materials, optical devices and biomedical technologies. This review summarizes the principal synthesis strategies, phase evolution, structural and physicochemical properties and major applications of Bi_2O_3 nanoparticles. Particular emphasis is placed on the relationship between synthesis conditions, structure, morphology and functional performance. Current challenges and future research directions related to phase stability, aggregation, reproducibility, scale-up, toxicity assessment and device integration are also discussed.

Keywords: Bismuth oxide nanoparticles; synthesis; photocatalysis; gas sensing; energy storage applications.

1. Introduction

Nanostructured metal oxides occupy an important position in modern materials science because their properties differ significantly from those of their bulk counterparts. Reduction of particle dimensions to the nanoscale increases the specific surface area and modifies surface energy, defect concentration, optical response, charge transport and chemical reactivity. These characteristics have promoted the development of metal-oxide nanoparticles for catalysis, environmental remediation, sensors, energy storage, electronics and biomedical technologies. Among different metal oxides, bismuth oxide (Bi_2O_3) is particularly interesting because bismuth possesses a high atomic number and Bi_2O_3 exhibits several crystal structures with distinctly different physical properties. Bi_2O_3 has been investigated for applications involving catalysts, solid electrolytes, gas sensors, optical coatings, microelectronics, photoconductive devices and energy-related systems. The material also exhibits a relatively narrow band gap compared with several conventional wide-band-gap metal oxides, which contributes to its visible-light response in photocatalytic systems (Zahid and Han, 2021). The crystal structure of Bi_2O_3 strongly influences its electrical and optical properties. The low-temperature α-phase possesses a monoclinic structure and represents the stable phase under ambient conditions. The high-temperature δ-phase possesses a defective fluorite-type cubic structure and exhibits exceptionally high oxide-ion conductivity. Intermediate β- and γ-phases possess tetragonal and cubic structures, respectively, and generally occur as metastable forms under suitable preparation and thermal conditions (Levin and Roth, 1964; Harwig and Gerards, 1978). At the nanoscale, the phase stability of Bi_2O_3 becomes particularly important because particle size, surface energy, heating rate, precursor chemistry and calcination conditions influence phase formation. Consequently, identical chemical compositions prepared by different synthesis methods often exhibit different phase compositions and morphologies. Zahid and Han (2021) emphasized that phase-selective synthesis of Bi_2O_3 remains challenging because phase transformation occurs over a broad temperature range and the photocatalytic properties depend strongly on the resulting crystal structure. The development of low-temperature synthesis routes has further expanded the potential of Bi_2O_3 nanoparticles. The ultrafine Bi_2O_3 particles were synthesized through a gel-to-crystal conversion route at 80–100 °C, producing particles with an average size of approximately 50 nm. Sol–gel, precipitation, hydrothermal and combustion methods subsequently provided additional control over particle size, morphology and phase composition. More recently, environmentally sustainable synthesis approaches have attracted substantial attention. Plant extracts, microorganisms and biomolecules serve as reducing, stabilizing or capping agents during nanoparticle formation. Green-synthesized Bi_2O_3 nanoparticles exhibit promising antibacterial, antioxidant, photocatalytic and sensing characteristics, while the approach reduces the use of conventional organic solvents and aggressive chemical reagents (Motakef-Kazemi and Yaqoubi, 2020; Fawzy et al., 2022).

The objective of this review is to provide a concise but comprehensive overview of Bi_2O_3 nanoparticles, with emphasis on their synthesis, crystal structure, physicochemical properties and applications. The review particularly discusses photocatalysis, environmental remediation, gas sensing, electrochemical sensing, energy storage, antibacterial activity and biomedical applications.

2. Fundamental characteristics of bismuth oxide

2.1 Chemical and physical characteristics

Bismuth oxide has the chemical formula Bi_2O_3 and contains bismuth in the +3 oxidation state. The material possesses a high density and high atomic number, which contribute to its strong interaction with X-rays and electromagnetic radiation. Bi_2O_3 also exhibits a high refractive index, substantial dielectric response and interesting photoconductive properties. The electronic and optical properties of Bi_2O_3 are closely related to its crystal structure. Reported optical band-gap values generally fall within approximately 2.1–2.8 eV, depending on crystal phase, morphology, particle size, synthesis method and measurement conditions (Zahid and Han, 2021). The relatively narrow band gap promotes absorption in the near-visible region, while the electronic structure provides strong oxidative ability in photocatalytic reactions. These properties distinguish Bi_2O_3 from conventional wide-band-gap photocatalysts and support its use in visible-light-driven environmental applications.

2.2 Polymorphism of Bi_2O_3

It is a polymorphic material. The commonly discussed phases include α, β, γ and δ, while ε, ω and other structures have also been reported under special synthesis conditions.

- α-Bi_2O_3: It possesses a monoclinic crystal structure and represents the stable phase at room temperature. It is frequently obtained after calcination of precursor-derived Bi_2O_3 nanoparticles. Its optical and electrical characteristics make it useful in photocatalytic, sensing and dielectric applications.
- β-Bi_2O_3: It has a tetragonal structure and is generally metastable. It has attracted interest for photocatalytic applications because of its relatively narrow band gap and suitable electronic structure.
- γ-Bi_2O_3: It possesses a cubic structure and occurs as a metastable phase under appropriate thermal conditions.
- δ-Bi_2O_3: It has a face-centered cubic defective fluorite structure. The oxygen sublattice contains a high concentration of vacancies, producing exceptionally high oxide-ion conductivity. The δ-phase is stable at high temperatures, while stabilization strategies involving dopants or nanostructuring have been explored to retain related structures at lower temperatures (Harwig and Gerards, 1978; Sammes et al., 1999).

The major phase transformations of Bi_2O_3 are summarized in the table 1. . α-Bi_2O_3 is the stable monoclinic phase at room temperature and transforms to the high-temperature δ-phase at approximately 730 °C. During controlled cooling, metastable β- and γ-phases may form from δ-Bi_2O_3 around 650 °C and 639–640 °C, respectively. Further cooling generally leads toward the stable α-phase. The exact transformation pathway depends on thermal history, cooling rate, sample purity and preparation conditions.

Table 1: Major phase transformations of Bi_2O_3

Phase	Crystal structure	Approx. temperature / stability	Transformation pathway	Key characteristic
α-Bi_2O_3	Monoclinic ($P2_1/c$)	Room temperature to ~730 °C	α → δ on heating; α is the stable low-temperature phase	Stable room-temperature phase; semiconductor
δ-Bi_2O_3	Face-centered cubic, defect-fluorite type ($Fm\bar{3}m$)	~730–825 °C	α → δ on heating; δ → β or γ on controlled cooling	Highly oxygen-deficient structure; exceptionally high oxide-ion conductivity
β-Bi_2O_3	Tetragonal ($P\bar{4}21c$)	~650 °C during cooling; metastable	δ → β on controlled cooling; β → α on further cooling	Metastable semiconductor; useful for photocatalytic studies
γ-Bi_2O_3	Body-centered cubic (I23)	~639–640 °C during cooling; metastable	δ → γ on controlled cooling; γ → α under suitable thermal conditions	Metastable phase; distinct optical and electrical properties
ε-Bi_2O_3	Orthorhombic (Pbnb)	Special synthesis conditions; metastable	Reported from specific hydrothermal/synthetic conditions; transforms toward α on heating	Special metastable polymorph; nanoscale phase engineering
ω-Bi_2O_3	Triclinic ($P\bar{1}$)	Special substrate/high-temperature conditions; metastable	Reported under specific preparation conditions; related to α/δ phase stability	Rare metastable polymorph

3. Synthesis of Bi_2O_3 nanoparticles

Bi_2O_3 nanoparticles are synthesized through various physical, chemical and green approaches, as illustrated in Figure 1. The sol–gel method involves mixing a bismuth precursor with a solvent and chelating agent, followed by gel formation, drying and calcination to obtain fine Bi_2O_3 nanoparticles with good compositional homogeneity. The hydrothermal/solvothermal method uses a bismuth precursor with suitable additives or surfactants in a sealed autoclave under controlled temperature and pressure, producing highly crystalline nanoparticles with controlled morphology. In the precipitation method, bismuth salt reacts with a precipitating agent such as NaOH or NH_4OH, followed by aging, filtration, washing, drying and calcination. The combustion method employs a bismuth precursor and suitable fuels such as urea, glycine or citric acid, producing Bi_2O_3 nanoparticles through rapid combustion. The green synthesis method uses plant extracts as natural reducing and stabilizing agents, providing an eco-friendly route for nanoparticle formation. Overall, these methods offer control over particle size, morphology, crystallinity and surface properties, allowing Bi_2O_3 nanoparticles to be tailored for photocatalytic, sensing, antibacterial, optical and energy-related applications.

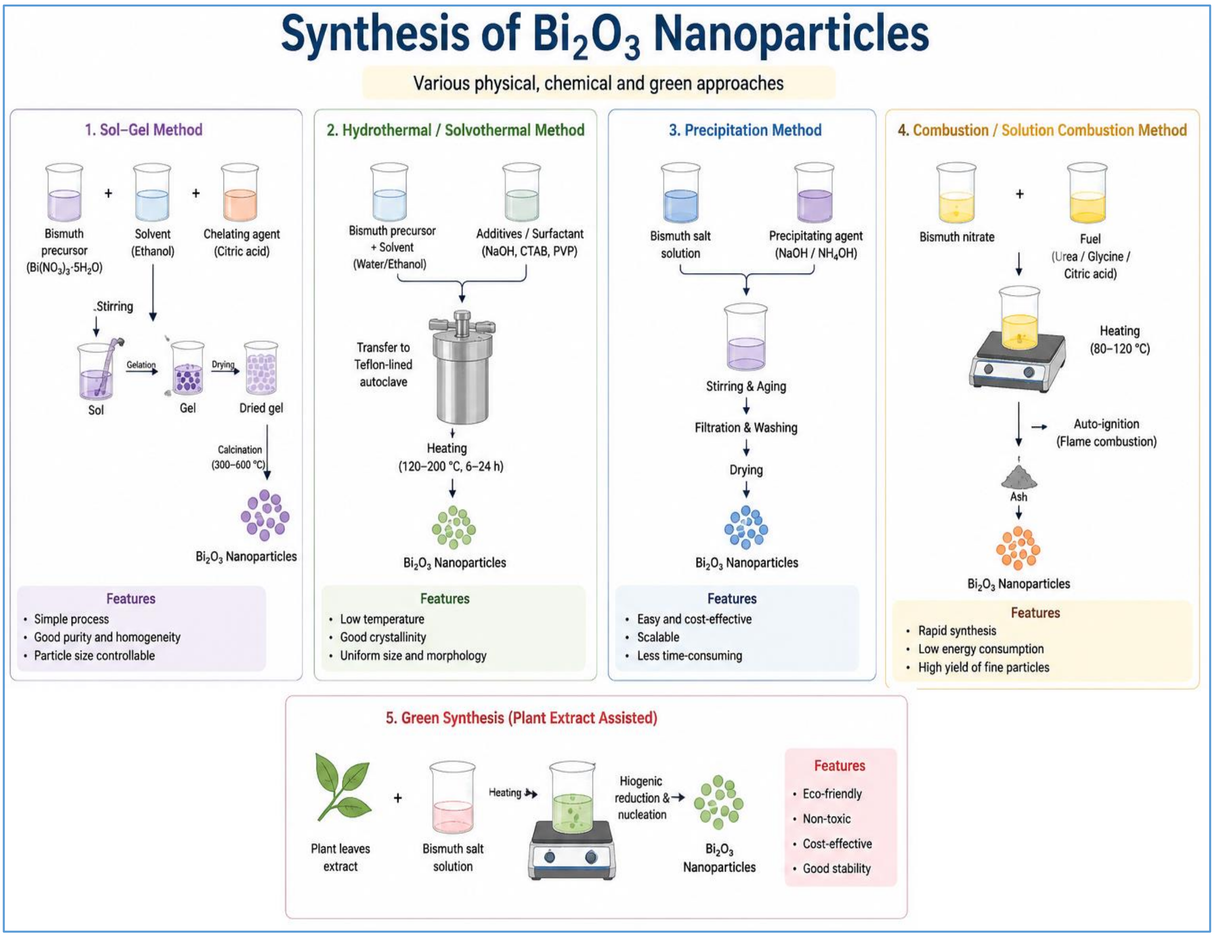

Figure 1: Synthesis methods of Bi_2O_3 nanoparticles

3.1 Precipitation method

Precipitation represents one of the simplest approaches for synthesizing Bi_2O_3 nanoparticles. A soluble bismuth precursor, commonly bismuth nitrate, is dissolved in an appropriate solvent, followed by addition of a precipitating agent such as sodium hydroxide or ammonium hydroxide. The resulting bismuth hydroxide or related precursor undergoes drying and calcination to produce Bi_2O_3. The precipitation route offers straightforward control of precursor concentration, pH and reaction temperature. However, uncontrolled precipitation often produces agglomerated particles. Surfactants, polymers or chelating agents are therefore incorporated to improve particle dispersion and morphology.

3.2 Sol–gel method

The sol–gel technique is widely used for the preparation of high-purity oxide nanoparticles. In a typical process, a bismuth precursor is dissolved in a suitable solvent and complexed with an organic ligand such as citric acid. Hydrolysis, condensation, gelation, drying and calcination subsequently produce crystalline

Bi_2O_3. Sol–gel synthesis offers excellent chemical homogeneity and relatively good control over particle morphology. It also supports the fabrication of nanopowders, thin films and nanocomposite materials. The method is particularly suitable when a uniform distribution of dopants or secondary phases is required. Mallahi et al. (2014) reported the synthesis of Bi_2O_3 nanoparticles through a sol–gel route using bismuth nitrate and citric acid, demonstrating the usefulness of the technique for producing fine Bi_2O_3 structures. The sol–gel process also permits control over pH, precursor concentration and calcination temperature. Khairnar and Shrivastava (2019) used sol–gel-derived α-Bi_2O_3 nanoparticles for the photocatalytic degradation of methylene blue and chlorpyrifos, demonstrating the environmental significance of sol–gel-derived Bi_2O_3.

3.3 Hydrothermal synthesis

Hydrothermal synthesis involves the reaction of precursor solutions in a sealed vessel at elevated temperature and autogenous pressure. This method offers excellent control over crystallinity, morphology and particle growth. The major advantages include relatively low synthesis temperature, controlled nucleation, high crystallinity and reduced aggregation. Particle morphology can be modified through precursor concentration, pH, reaction temperature, reaction time and mineralizers. Recent reviews identify hydrothermal synthesis as one of the important routes for producing bismuth-based nanomaterials because the method permits control over particle size and morphology while maintaining good crystallinity (2024).

3.4 Combustion synthesis

Solution combustion synthesis is an attractive method for preparing Bi_2O_3 nanoparticles because the process is rapid and generates high temperatures through an exothermic redox reaction between an oxidizing precursor and fuel. Bismuth nitrate commonly acts as the oxidizing precursor, while urea, glycine, citric acid or plant-derived fuels serve as combustion fuels. The fuel-to-oxidizer ratio strongly influences particle morphology, crystallite size and porosity. Karma et al. (2023) synthesized α-Bi_2O_3 nanoparticles using an auto-combustion method and reported monoclinic crystal structure with significant dielectric and AC-conductivity characteristics. Keshava Murthy et al. (2024) prepared Bi_2O_3 nanoparticles using urea and lemon juice as fuels. The products exhibited a monoclinic structure and crystallite sizes in the approximately 40–60 nm range, together with photocatalytic activity toward several organic dyes and electrochemical sensing activity toward ascorbic acid.

3.5 Citrate-gel synthesis

Citrate-gel synthesis is another low-cost wet-chemical route. Bismuth salts react with citric acid to produce a polymeric precursor. Controlled heating decomposes the organic matrix and produces fine Bi_2O_3 particles. The citrate-gel process provides good compositional homogeneity and relatively fine particle sizes. Synthesis of nanocrystalline Bi_2O_3 through this method was reported as an alternative to conventional high-temperature preparation routes.

3.6 Green synthesis

Green synthesis has emerged as an important sustainable approach for producing Bi_2O_3 nanoparticles. Plant extracts contain phytochemicals such as polyphenols, flavonoids, alkaloids, terpenoids and sugars that participate in precursor conversion and nanoparticle stabilization. Motakef-Kazemi and Yaqoubi (2020) synthesized Bi_2O_3 nanoparticles using Mentha pulegium aqueous extract. The nanoparticles were characterized using UV–visible spectroscopy, FTIR, XRD, DLS, SEM, TEM and EDS, and antibacterial activity was evaluated against E. coli, Salmonella and S. aureus. Green synthesis offers several advantages, including reduced chemical consumption, simple processing, lower environmental burden and the introduction of organic surface species. Fawzy et al. (2022) reviewed plant-, microorganism- and biomolecule-assisted synthesis of bismuth-based nanoparticles and highlighted their applications in environmental and energy technologies. In 2024, Dandge et al. reported Mentha arvensis-mediated Bi_2O_3 nanoparticles with a monoclinic phase and an average particle size of approximately 12 nm. The nanoparticles demonstrated antibacterial, antioxidant, anti-inflammatory, antidiabetic and anticancer-related biological activity.

4. Applications of Bi_2O_3 nanoparticles

Figure 2 shows the different applications of Bi_2O_3 nanoparticles. Bi_2O_3 nanoparticles exhibit versatile physicochemical properties that support their use in several technological fields. They are widely investigated in photocatalysis and environmental remediation for the degradation of dyes, pesticides, pharmaceuticals and other organic pollutants under light irradiation. Their semiconducting and surface-sensitive properties make them useful in gas sensing and electrochemical sensing for detecting volatile gases and chemical or biological analytes. Bi_2O_3 nanoparticles also serve as active materials in supercapacitors, batteries and other energy-storage devices because of their redox activity and favorable electrochemical characteristics. Their high refractive index and dielectric response support applications in optical and electronic devices. In addition, Bi_2O_3 nanoparticles demonstrate antibacterial activity, making them useful for antimicrobial coatings and environmental applications. Their high X-ray attenuation ability and photothermal characteristics further promote interest in biomedical applications, including bioimaging, radiation-related applications and therapeutic nanomaterials. Thus, Bi_2O_3 nanoparticles represent multifunctional materials with significant potential in environmental, sensing, energy, optical, electronic and biomedical technologies.

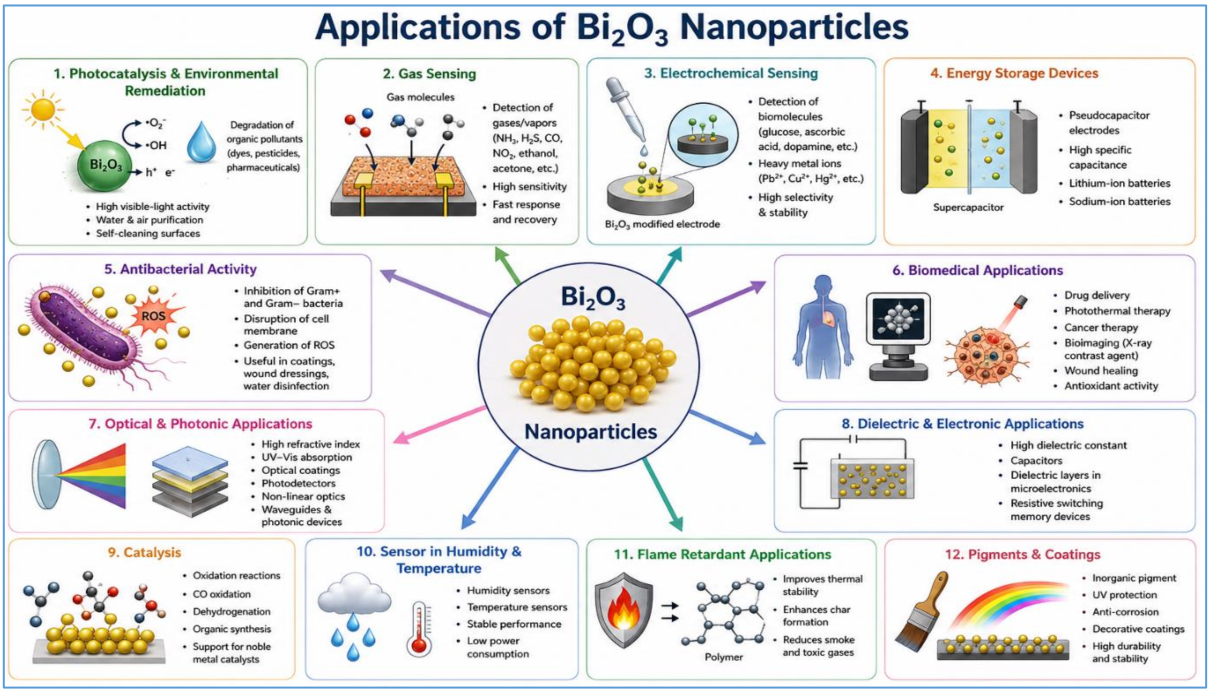

Figure 2: Different applications of Bi_2O_3 nanoparticles

4.1 Photocatalytic Applications

Photocatalysis represents one of the most extensively investigated applications of Bi_2O_3 nanoparticles. The relatively narrow band gap of Bi_2O_3 promotes light absorption, while photogenerated electrons and holes participate in oxidation–reduction reactions. Under irradiation: $Bi_2O_3 + h\nu \rightarrow e^- + h^+$

The photogenerated electrons reduce adsorbed oxygen, whereas holes oxidize water or surface hydroxyl groups. Reactive oxygen species such as superoxide radicals and hydroxyl radicals subsequently attack organic contaminants. Reverberi et al. (2018) reviewed Bi_2O_3-based photocatalysts for environmental remediation and highlighted the role of synthesis conditions, crystal structure and visible-light response in improving pollutant degradation. Zahid and Han (2021) demonstrated that the photocatalytic activity of Bi_2O_3 depends strongly on polymorph, microstructure and phase junction formation. Bi_2O_3 nanoparticles have been investigated for degradation of dyes such as methylene blue, methyl orange, rhodamine B, crystal violet and Rose Bengal. They have also been explored for degradation of pesticides and pharmaceutical pollutants. Khairnar and Shrivastava (2019) investigated α-Bi_2O_3 nanoparticles for degradation of chlorpyrifos and methylene blue. Keshava Murthy et al. (2024) reported photocatalytic activity of combustion-synthesized Bi_2O_3 nanoparticles against Rose Bengal, Acid Orange-88 and crystal violet. Doped Bi_2O_3 provides another route for improving photocatalytic performance. Cobalt-doped Bi_2O_3 nanoparticles demonstrated enhanced visible-light degradation of methylene blue compared with bare Bi_2O_3, with 3% Co-doped material producing the strongest activity in the reported system (2019).

4.2. Environmental Remediation

Bi_2O_3 nanoparticles have significant potential in wastewater treatment because of their photocatalytic activity and surface reactivity. Organic dyes, pesticides, pharmaceuticals and other contaminants represent important targets for photocatalytic degradation. Recent reviews of bismuth-based nanoparticles have emphasized their ability to participate in visible-light-driven pollutant degradation and heavy-metal removal. Jiang et al. (2024) reviewed bismuth-based nanoparticles for wastewater remediation and highlighted their catalytic performance in organic pollutant degradation and heavy-metal removal. The environmental performance of Bi_2O_3 depends on catalyst loading, pollutant concentration, irradiation intensity, pH, reaction time, surface area and crystal structure. A major advantage of Bi_2O_3 is its visible-light response compared with several conventional UV-responsive semiconductor photocatalysts. However, rapid electron–hole recombination, particle aggregation and photocorrosion remain important considerations. Heterojunction formation with other semiconductors, carbon materials and bismuth-based compounds provides an effective strategy for improving charge separation and photocatalytic efficiency.

4.3. Gas-Sensing Applications

Semiconducting metal oxides are widely used in resistive gas sensors because gas adsorption changes the electrical resistance of the sensing layer. Bi_2O_3 possesses surface-active sites and oxygen-related defects that contribute to gas adsorption and charge-transfer reactions. In an n-type sensing material, adsorbed oxygen captures electrons from the semiconductor: $O_2(g) + e^- \rightarrow O_2^-(ads)$.

When a reducing gas such as ethanol interacts with adsorbed oxygen species, electrons return to the conduction band, producing a measurable resistance change. Bi_2O_3 has been explored for detecting gases such as ethanol, acetone and other volatile organic compounds. Its gas-sensing characteristics are influenced by particle size, oxygen vacancies, surface area, operating temperature and heterojunction formation. Shinde et al. (2018) synthesized Bi_2O_3 nanostructures through a room-temperature wet-chemical method and demonstrated their application in acetone gas sensing and electrochemical energy storage. Bi_2O_3 decoration of other semiconductors also produces strong heterojunction effects. Bi_2O_3-decorated In_2O_3 nanorods exhibited substantially enhanced ethanol sensing compared with pristine In_2O_3, with reported responses of 171–1774% for ethanol concentrations of 10–200 ppm at 200 °C. These results demonstrate that Bi_2O_3 functions both as an active sensing material and as a surface modifier for improving the gas response of composite semiconductor structures.

4.4. Electrochemical Sensing Applications

Bi_2O_3 nanoparticles possess attractive electrochemical characteristics because of their surface activity, high specific area and redox behavior. These properties support the development of electrochemical sensors for biological and environmental analytes. Bi_2O_3-modified electrodes have been investigated for detection of ascorbic acid, glucose, heavy-metal ions and pharmaceutical compounds. Keshava Murthy et al. (2024) reported enhanced electrochemical sensing of ascorbic acid using a Bi_2O_3-modified carbon paste electrode. Green-synthesized α-Bi_2O_3 nanoparticles were also investigated for electrochemical sensing of lead and ascorbic acid, demonstrating the multifunctional nature of Bi_2O_3 in environmental and biochemical sensing systems. The performance of Bi_2O_3-based electrochemical sensors depends on electrode architecture, surface area, charge-transfer resistance, analyte adsorption and interfacial electron transport.

4.5. Energy Storage Applications

Bi_2O_3 nanoparticles have attracted considerable attention as electrode materials for supercapacitors and other energy-storage systems. The redox activity of bismuth oxide provides pseudocapacitive charge-storage behavior. Rod-like β-Bi_2O_3 nanoparticles investigated as pseudocapacitor electrodes exhibited a specific capacitance of approximately 528 F g^{-1} at a scan rate of 5 mV s^{-1} and good cycling performance over 1000 cycles. However, the relatively low electrical conductivity of Bi_2O_3 limits its standalone electrochemical performance. Combining Bi_2O_3 with conductive carbon materials such as reduced graphene oxide represents an effective strategy for overcoming this limitation. Li et al. (2019) synthesized Bi_2O_3/rGO composites and reported a maximum specific capacitance of 1423 F g^{-1} at 1 A g^{-1}, together with good rate capability and long-term cycling behavior. Gote et al. (2019) developed Bi_2O_3/Bi_2WO_6 and Au-decorated Bi_2O_3/Bi_2WO_6 nanocomposites for supercapacitor applications, further demonstrating the importance of composite and heterostructure engineering. Bi_2O_3-based composites have also been investigated with two-dimensional materials. Such architectures improve electrical conductivity, surface accessibility and electrochemical reaction kinetics.

4.6. Dielectric and Electronic Applications

Bi_2O_3 possesses attractive dielectric and optical properties, making it useful in electronic and optoelectronic systems. Its high dielectric response, refractive index and frequency-dependent conductivity support applications in capacitors, dielectric layers, optical coatings and integrated electronic components. Karma et al. (2023) reported significant dielectric characteristics in combustion-synthesized α-Bi_2O_3 nanoparticles, including frequency-dependent AC conductivity and dielectric relaxation behavior. Bi_2O_3 nanoparticles have also been incorporated into polymer matrices to modify dielectric constant, optical properties and energy-storage characteristics. Bi_2O_3/polymer nanocomposites exhibit improved dielectric parameters and high refractive-index behavior, supporting applications in energy-storage and optical technologies.The optical properties of Bi_2O_3 include high refractive index, strong optical nonlinearity and photoconductivity. These features support applications in optical coatings, photonic devices, nonlinear optical components and related optoelectronic technologies.

4.7. Antibacterial Applications

The antibacterial activity of Bi_2O_3 nanoparticles has received growing attention because of their surface reactivity and ability to interact with microbial cells. Motakef-Kazemi and Yaqoubi (2020) reported antibacterial activity of green-synthesized Bi_2O_3 nanoparticles against E. coli, Salmonella and S. aureus. Mane et al. (2024) reviewed Bi_2O_3 nanomaterials for photocatalytic and antibacterial applications and emphasized the strong relationship between synthesis parameters, morphology, crystal phase and biological performance. The combination of photocatalytic and antibacterial activity makes Bi_2O_3 particularly attractive for multifunctional environmental coatings and antimicrobial surfaces.

4.8. Biomedical Applications

Bismuth-containing nanomaterials have attracted considerable interest in biomedical applications because bismuth exhibits a relatively favorable biological profile compared with several heavy metals and possesses strong X-ray attenuation characteristics. Bi_2O_3 and related bismuth-based nanomaterials have been explored for: X-ray contrast enhancement; radiation therapy; photothermal therapy; drug delivery; bioimaging; biosensing; antibacterial systems; tissue engineering; and cancer-related therapeutic strategies. Bartoli et al. (2020) reviewed nanostructured bismuth oxide and related materials for biomedical applications and discussed the chemical behavior, phase transformations and biological characteristics of bismuth oxides. Shahbazi et al. (2020) provided a broader review of bismuth-based nanoparticles for therapeutic, diagnostic, biosensing and regenerative applications. Their review highlighted the high X-ray attenuation coefficient, near-infrared absorption and photothermal properties of bismuth-based nanostructures. Bi_2O_3 nanoparticles therefore represent an interesting component of multifunctional biomedical nanoplatforms. Nevertheless, systematic toxicity, pharmacokinetic and long-term biological studies remain essential before clinical translation.

4.9. Optical Applications

Bi_2O_3 possesses a high refractive index and strong optical response, making it attractive for optical coatings and photonic materials. Nanostructuring provides additional control over light absorption, scattering and interfacial interactions. The optical band gap and refractive index depend on phase, particle size, defects and synthesis conditions. Polymer/Bi_2O_3 nanocomposites have demonstrated modified transmittance, band-gap energy, Urbach energy and refractive index, supporting their use in high-refractive-index materials and optical coatings. The combination of optical transparency, high refractive index and dielectric response provides opportunities in integrated photonic devices, optical filters and nonlinear optical systems.

5. Advantages of Bi_2O_3 nanoparticles

Bi_2O_3 nanoparticles possess several important advantages arising from their unique structural, optical, electrical, chemical and surface properties. Their relatively simple chemical composition and multiple crystal phases provide flexibility in tailoring functional properties for specific applications. The comparatively narrow band gap and strong visible-light response make Bi_2O_3 nanoparticles attractive for photocatalytic and optoelectronic applications. Their high refractive index and dielectric response support their use in optical and electronic devices, while the high surface-to-volume ratio of nanoparticles provides abundant active sites for surface reactions. Bi_2O_3 nanoparticles exhibit strong photocatalytic activity, antibacterial characteristics and electrochemical activity, supporting applications in environmental remediation, antimicrobial systems and chemical sensing. Their semiconducting nature also makes them suitable for gas-sensing applications. Furthermore, Bi_2O_3 nanoparticles combine effectively with carbon materials, graphene-based materials and other semiconductors to form heterostructures with enhanced charge transport and functional performance. Their compatibility with green synthesis approaches provides an environmentally favorable route for nanoparticle production. In addition, their high atomic number, X-ray attenuation ability and surface activity support their potential in biomedical applications. The ability to incorporate Bi_2O_3 nanoparticles into polymers, ceramics, carbon materials and other semiconductor matrices further enables the development of multifunctional nanocomposites with tailored optical, electrical, catalytic, sensing and biological properties.

6. Future Research Perspectives

Future research on Bi_2O_3 nanoparticles should focus on controlled synthesis, phase engineering, defect engineering and multifunctional heterostructure development to enhance their functional performance and practical applicability. Phase-selective synthesis at low temperatures requires further development to achieve stable preparation of specific α-, β-, γ- and δ-related phases with controlled oxygen-vacancy concentrations, providing improved control over their electrical, optical and catalytic properties. Green synthesis also deserves greater attention through the development of standardized extraction protocols and quantitative control of phytochemical composition to obtain reproducible nanoparticle characteristics. Heterojunction engineering represents another important research direction, particularly through the integration of Bi_2O_3 with graphene, reduced graphene oxide (rGO), TiO_2, ZnO, SnO_2, WO_3, $BiVO_4$ and Bi_2WO_6 to improve interfacial charge separation and enhance photocatalytic and sensing performance. For Bi_2O_3-based gas sensors, systematic investigation of oxygen vacancies, surface adsorption mechanisms and heterojunction interfaces is required, together with optimization of operating temperature, response time, recovery time, selectivity and long-term stability. Bi_2O_3/carbon and Bi_2O_3/polymer composites also provide promising platforms for energy-storage and dielectric applications, where interface engineering, electrical conductivity and cycling stability require further optimization. In addition, the integration of Bi_2O_3 nanoparticles into flexible devices, functional coatings, membranes and miniaturized sensors represents an important pathway toward practical and next-generation applications. The future research should emphasize reproducible synthesis, structure–property relationships, scalable fabrication and device-level integration to translate the multifunctional properties of Bi_2O_3 nanoparticles into technologically useful systems.

Conclusion

Bismuth oxide nanoparticles represent a versatile class of functional nanomaterials with significant potential in environmental, energy, sensing, optical and biomedical technologies. Their performance strongly depends on crystal phase, particle size, morphology, surface defects and synthesis conditions. Precipitation, sol–gel, hydrothermal, combustion, citrate-gel and green synthesis routes provide diverse strategies for controlling these parameters. Among these methods, green synthesis has gained particular attention because plant extracts and biological materials provide environmentally favorable alternatives to conventional chemical processing. The polymorphic nature of Bi_2O_3 represents both an advantage and a challenge. α-Bi_2O_3 provides stable room-temperature properties, β- and γ-phases offer metastable structures with useful optical and catalytic behavior, while δ-Bi_2O_3 possesses exceptional oxide-ion conductivity. These phase-dependent properties support applications ranging from photocatalytic pollutant degradation and antibacterial coatings to gas sensors, electrochemical sensors, supercapacitors, dielectric materials and biomedical nanotechnology. Recent studies demonstrate that dopants, oxygen vacancies, heterojunctions and carbon-based composites significantly improve the functional performance of Bi_2O_3 nanoparticles. Photocatalytic activity is enhanced through improved visible-light absorption and charge separation, while sensing and electrochemical performance benefits from increased active surface area and interfacial charge transport. Green synthesis further introduces opportunities for sustainable nanoparticle production. Bi_2O_3 nanoparticles provide a strong platform for multifunctional nanotechnology. Future research should concentrate on reproducible phase-controlled synthesis, sustainable scale-up, defect engineering, heterostructure design, long-term stability and comprehensive safety assessment. Such developments are expected to accelerate the transition of Bi_2O_3 nanoparticles from laboratory-scale materials toward practical environmental, energy, sensing and biomedical technologies.

Acknowledgement:

The authors are thankful to the Head of Department of Research centre in Electronics Science, L.V.H. Arts, Commerce and Science College Panchavati, Nashik, Dist. Nashik, Maharashtra, India for providing required lab and computer facilities for the present research work.

Conflict of Interest: There are no any conflict of interest.

REFERENCES:

1. Levin, E.M. and Roth, R.S. (1964). Polymorphism of bismuth sesquioxide. I. Pure Bi_2O_3. Journal of Research of the National Bureau of Standards Section A: Physics and Chemistry, 68A, 189–195.
2. Harwig, H.A. and Gerards, A.G. (1978). Electrical properties of the α-, β-, γ- and δ-phases of bismuth sesquioxide. Journal of Solid State Chemistry, 26, 265–274.
3. Sammes, N.M., Tompsett, G.A., Näfe, H. and Aldinger, F. (1999). Bismuth based oxide electrolytes—structure and ionic conductivity. Journal of the European Ceramic Society, 19, 1801–1826.
4. Mallahi, M., Shafieizad, G. and Shamsipur, M. (2014). Synthesis and characterization of bismuth oxide nanoparticles via sol–gel technique. American Journal of Engineering Research, 3, 162–165.
5. Motakef-Kazemi, N. and Yaqoubi, M. (2020). Green synthesis and characterization of bismuth oxide nanoparticle using Mentha pulegium extract. Iranian Journal of Pharmaceutical Research, 19, e124421.
6. Reverberi, A.P., Varbanov, P.S., Vocciante, M. and Fabiano, B. (2018). Bismuth oxide-related photocatalysts in green nanotechnology: A critical analysis. Frontiers of Chemical Science and Engineering, 12, 878–892.

7. Khairnar, S.D. and Shrivastava, V. (2019). Photocatalytic degradation of chlorpyrifos and methylene blue using α-Bi_2O_3 nanoparticles fabricated by sol–gel method. SN Applied Sciences, 1.
8. Gote, G.H., Pathak, M., More, M.A., Late, D.J. and Rout, C.S. (2019). Development of pristine and Au-decorated Bi_2O_3/Bi_2WO_6 nanocomposites for supercapacitor electrodes. RSC Advances, 9, 32573–32580.
9. Li, J., Huang, S., Gu, J., Wu, Q., Chen, D. and Zhou, C. (2019). Facile synthesis of well-dispersed Bi_2O_3 nanoparticles and rGO as negative electrode for supercapacitor. Journal of Nanoparticle Research, 21.
10. Shinde, P.V., Ghule, B.G., Shinde, N.M., Xia, Q.X., Shaikh, S., Sarode, A.V., Mane, R.S. and Kim, K.H. (2018). Room-temperature successive ion transfer chemical synthesis and the efficient acetone gas sensor and electrochemical energy storage applications of Bi_2O_3 nanostructures. New Journal of Chemistry.
11. Zahid, A.H. and Han, Q. (2021). A review on the preparation, microstructure, and photocatalytic performance of Bi_2O_3 in polymorphs. Nanoscale, 13, 17687–17724.
12. Bartoli, M., Jagdale, P. and Tagliaferro, A. (2020). A short review on biomedical applications of nanostructured bismuth oxide and related nanomaterials. Materials, 13, 5234.
13. Shahbazi, M.-A., Faghfouri, L., Ferreira, M.P.A., Figueiredo, P., Maleki, H., Sefat, F., Hirvonen, J. and Santos, H.A. (2020). The versatile biomedical applications of bismuth-based nanoparticles and composites: therapeutic, diagnostic, biosensing, and regenerative properties. Chemical Society Reviews, 49, 1253–1321.
14. Fawzy, M.A., et al. (2022). Green synthesis of bismuth based nanoparticles and its applications—A review. Sustainable Chemistry and Pharmacy, 25, 100547.
15. Karma, N., Siddiqui, K., Harinkhere, D., Yadav, A. and Kaurav, N. (2023). Structural and dielectric properties of Bi_2O_3 nanoparticles synthesized at different temperatures. Materials Today: Proceedings, 74, 146–148.
16. Mane, V.A., Dake, D.V., Raskar, N.D., Sonpir, R.B., Stathatos, E., Dole, B. et al. (2024). A review on Bi_2O_3 nanomaterial for photocatalytic and antibacterial applications. Chemical Physics Impact, 8, 100517.
17. Jiang, S., Zhang, Y. and Gong, J. (2024). Applications of bismuth-based nanoparticles for the removal of pollutants in wastewater: a review. Environmental Science: Nano, 11, 1332–1367.
18. Keshava Murthy, R.N., Shivanna, M., Ahamed, N.N., Bhoomika, V., Ravikumar, C.R. and Ananda Murthy, H.C. (2024). Photocatalytic and electrochemical sensor study of combustion synthesized bismuth oxide (Bi_2O_3) nanoparticles using lemon and urea fuels. Materials Science in Semiconductor Processing, 178, 117487.
19. Dandge, P., et al. (2024). Minting progress: multifunctional bismuth oxide nanoparticles via Mentha arvensis extract for biomedical advancements. ChemistrySelect.
20. Synthesis of bismuth oxide nanoparticles at 100 °C (2005). Materials Letters, 59, 2523–2525.
21. Facile synthesis of rod-like Bi_2O_3 nanoparticles as an electrode material for pseudocapacitors (2015). Ceramics International.
22. Synthesis, structure, and ethanol gas sensing properties of In_2O_3 nanorods decorated with Bi_2O_3 nanoparticles (2015). ACS Applied Materials & Interfaces.

23. Visible light mediated photocatalytic activity of cobalt doped Bi_2O_3 nanoparticles (2019). Journal of Materials Research and Technology, 8, 127–133.
24. Photocatalytic degradation of chlorpyrifos and methylene blue using α-Bi_2O_3 nanoparticles fabricated by sol–gel method (2019). SN Applied Sciences, 1.
25. Decolourization of Fast Red Acid dye using photoactive Bi_2O_3 nanoparticle under solar irradiation (2019).
26. Characterization and the physical properties of nano-sized Bi_2O_3/polymer for energy and high-refractive-index applications (2024). Results in Physics, 61, 107746.
27. Bismuth-based nanoparticles and nanocomposites: synthesis and applications (2024). RSC Advances, 14, 39523–39542.
28. Polymorphism of bismuth sesquioxide. II. Effect of oxide additions on the polymorphism of Bi_2O_3 (1964). Journal of Research of the National Bureau of Standards.
29. Phase transitions and electrical properties of Bi_2O_3 up to 2.5 GPa (2008). Solid State Sciences.
30. Ionic conduction and unipolar resistance switching in δ-phase Bi_2O_3 thin films (2018). Solid State Ionics.
31. Structural, morphological, and optical properties of Bi_2O_3 thin films grown by reactive sputtering (2017). Thin Solid Films.
32. Opto-electronic properties of bismuth oxide films presenting different crystallographic phases (2015). Thin Solid Films.
33. Stabilization of the δ-Bi_2O_3-like structure down to room temperature by thermal nanocrystallization of bismuth oxide-based glasses (2018). Journal of Non-Crystalline Solids.
34. Identification of distinctive structural and optoelectronic properties of Bi_2O_3 polymorphs controlled by tantalum addition (2023). Journal of Materials Chemistry C.