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Review Article

Review on Synthesis, Physical Properties and Applications of Bismuth Sulfide Nanoparticles for Insight into Its Prominent Multifunction

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Abstract

Bismuth sulfide is valued for its unique physical properties like electrical conductivity, high carrier mobility and concentration, suitable band gap, high X-ray attenuation coefficient, high absorption coefficient and so on, making it suitable for applications in electronics, catalysis, environmental remediation, energy storage, sensors, and biomedical fields. For instance, its semiconducting qualities and high surface area make it effective for processes like adsorption and photocatalysis and suitable band gap, stability, and visible light absorption capabilities, Bi_2S_3 shows promise for hydrogen generation through photocatalytic water splitting. Furthermore, Bi_2S_3 can be prepared utilizing controlled temperatures, precursors, and solvents via various synthesis methods, including the sol-gel method, chemical methods and chemical deposition methods. From these techniques, sol-gel method is the most common due to its cost effectiveness and ability to create high-quality materials at low temperatures. Having these as initiative concept, this review offers further studies to improve synthesis processes, optimize characteristics and explore new applications. Therefore, this work suggested that further investigation on Bismuth sulfide is needed to improve its properties for specific uses through doping as well as utilizing different synthesis techniques.

Keywords

Synthesis, Characterization, Application, Properties, Nanoparticles

1. Introduction

Bismuth is the heaviest stable element on the periodic table, with an atomic number of 83 and an atomic mass of 208. 980. It has various radioactive isotopes, particularly 212Bi and 213Bi, which effectively kill cells due to their particle emissions and limited penetration range of 40 to 80 micrometers, helping to protect surrounding normal tissues [1, 2]. Despite being a heavy metal, bismuth is safe to use as it is nontoxic and noncarcinogenic, unlike toxic elements like arsenic and lead. Bismuth (III) complexes have varied structures due to its lone pair of electrons, resulting in pyramidal and bipyramidal shapes. Bismuth and its compounds are used in many applications [3].

Bismuth-based compounds are a group of materials with special structural and magnetic features, including bismuth sulfide, oxide, alloys, chalcogenides, and more [4]. They are important for various uses in medicine, electronics, thermoelectric applications, photo catalysis, and superconductivity, making them a key area of study in materials science [5].

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Researchers have noted that complex oxides are particularly effective for many uses because of their strong corrosion resistance and beneficial physical traits [6].

Recent studies have focused on Bi compounds, leading to the creation of Bi-based materials with various structures at micro and nanometer sizes. This has been achieved through several methods, resulting in three-dimensional materials like nanotubes, nanospheres, nanosheets, and nanowires, which have special features [7]. These materials can undergo aqueous hydrolysis at room temperature and also work under different conditions like hydrothermal or solvothermal processes, high-temperature annealing, and other techniques [8]. Their light-harvesting and charge transport abilities have made them effective as photocatalysts for breaking down various antibiotics and contaminants [8].

Most bismuth-based compounds are in the form of metal oxides and sulfides. Research on these compounds uses various synthesis techniques like sol gel, chemical methods and chemical depositions. They uses characterization techniques including X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM), and spectroscopy methods like UV-Vis and FTIR to analyze their size, structure, shape, composition, and surface properties, for its prominent applications [8-11].

Interest in bismuth and its compounds has grown in the past decade due to their unusual properties, such as higher density in liquid form, expansion on solidification, oxidized rapidly, high reactivity with nitric acid, low melting point, low cost, low toxicity, safe, stability volume expansion upon freezing, high x-ray absorption coefficient, high diamagnetism, low thermal conductivity, high electrical resistance and hall effect and increasing environmental concerns as well as the need for green reagents [11]. Thus, this review focused on bismuth sulfide, detailing its synthesis methods, physical properties, and applications in electronics, catalysis, environmental remediation, energy storage, sensors, and biomedicine. It involved a systematic literature search across databases like PubMed, Scopus, and Web of Science, aiming to identify limitations in current research and suggest areas for future studies. Overall, the review highlights the significance of bismuth sulfide in science and technology and guides future research. Consequently, this review overviewed the properties, applications, synthesis methods and characterization techniques. Thus, found that, the special properties of Bismuth sulfide, making it valuable in electronics, optics, energy conversion, and environmental cleanup. For instance its semiconducting qualities and large surface area enhance its effectiveness in adsorption and photocatalysis. Bi_2S_3 shows promise for hydrogen generation through photocatalytic water splitting due to its ideal band gap and ability to absorb visible light. From all other synthesis methods, the sol-gel method is the appropriate method due to its cost effective and which produces high-purity materials at lower temperatures. Therefore, this work suggested that further investigation is needed to improve its properties for specific uses.

2. Physical Properties and Applications of Bismuth Sulfide

2.1. Highlighted Physical Properties of Bi_2S_3

Bismuth sulfide is a semiconductor with a bandgap energy between 1. 3 and 1. 5 eV, its intrinsic properties like electrical conductivity from 10^{-6} to 10^{-7} Ω^{-1} cm^{-1}, hole mobility around 1100. cm^2/Vs, high carrier concentration and carrier mobility at 300K make it useful for different electronic applications [12, 13]. It has good thermoelectric properties, indicated by a high Seebeck coefficient and low thermal conductivity, which makes it suitable for thermoelectric generators and coolers. Additionally, bismuth sulfide has strong optical absorption from the visible to near-infrared range from 10^4 to 10^5 cm^{-1}, makes it good ligh absorber and beneficial for photodetectors and photovoltaic uses. It is suitable in solar cell fabrication due to its high electron concentration about $3x10^{18}$ cm^{-3} and carrier mobility of around 200 cm^2/Vs at room temperature. Bismuth sulfide has orthorhombic crystal structure and can be made in different nanostructured forms like nanoparticles, nanowires, and nanosheets, improving its surface area and application performance. Some studies also show magnetic properties in doped or nanostructured bismuth sulfide that can be used in spintronic applications [14].

2.2. Applications of Bismuth Sulfide (Bi_2S_3) Nanoparticles

2.2.1. General and Evolutionary Applications

Bismuth sulfide (Bi_2S_3) nanoparticles are highly versatile materials with applications spanning energy, environment, medicine, and optoelectronics. Initially studied as simple photoconductors due to their semiconducting nature, they gradually evolved into multifunctional materials. Their suitable bandgap (1.3-1.7 eV), strong visible-NIR absorption, and high carrier mobility make them ideal for thin-film solar cells, infrared photodetectors, and photodetectors [15]. By the 1990s, Bi_2S_3 was explored in thermoelectric energy conversion, leveraging nanostructuring and alloying for improved efficiency. The 2000s-2010s saw applications in photovoltaics, environmental photocatalysis, and hybrid energy systems (batteries and supercapacitors), using heterojunctions and defect engineering to enhance light absorption and charge separation [16-22, 27]. This evolution demonstrates how the intrinsic properties of Bi_2S_3 have enabled its transition from basic semiconductor research to advanced multifunctional nanomaterials.

2.2.2. Biomedical and Environmental Applications

In biomedical research, Bi_2S_3 nanoparticles serve as contrast agents for computed tomography due to high X-ray attenuation and as photothermal therapy (PTT) agents because of strong NIR absorption. Coupling with immunoactive polymers or drug-delivery systems enables synergistic cancer treatment, improving chemotherapy and radiotherapy outcomes [17-21]. In environmental applications, Bi_2S_3 effectively degrades organic dyes such as methylene blue, rhodamine B, and methyl orange under visible light. Composite photocatalysts, including Bi_2S_3 /ZnO, achieve high degradation efficiencies, while Bi_2S_3 adsorbs heavy metals like lead, cadmium, and arsenic due to its large surface area [23]. These biomedical and environmental functions highlight Bi_2S_3's multifunctionality and eco-friendly potential.

2.2.3. Optoelectronic, Photocatalytic, and Energy Storage Applications

Bi_2S_3 nanostructures have advanced optoelectronic devices, including broadband photodetectors, phototransistors, and sensors, due to their non-toxicity, chemical stability, high crystallinity, and wide spectral absorption [24-26]. As a photocatalyst, Bi_2S_3 generates hydrogen from water under visible light, converts biomass into hydrogen, and synergizes with other semiconductors or metal nanoparticles to boost efficiency [27]. In energy storage, Bi_2S_3 anodes in lithium-ion batteries offer high theoretical capacity and conversion reactions, while supercapacitor electrodes benefit from pseudocapacitance and high surface area. Hybrid battery-supercapacitor systems further improve energy and power density [22]. Collectively, these applications illustrate the integration of Bi_2S_3 into modern energy, electronics, and catalytic technologies.

Table 1. *Applications of Bismuth Sulfide Correspond to its Physical Properties.*

Properties of Bi_2S_3	Applications of Bi_2S_3	References
Suitable band gap and optical properties	Photovoltaics material for thin-film solar cells	[27]
Strong light absorption capabilities in the visible to near-infrared range (1. 3 and 1. 5 eV)	Photodetectors -Infared Photodetectors and photovoltaic applications -photodetector in Imaging and sensing technology	[20, 21]
Good thermoelectric performance and low thermal conductivity.	Thermoelectric Devices -Thermoelectric generators and coolers -Converting waste heat into electrical energy	[28]
magnetic properties in doped or nanostructured Bi2S3,	Electronic devices -Leveraged for spintronic applications.	
Highest coefficient of X-ray attenuation (low cost104 to 105 cm- 1) potential to utilize without leaving any residue in the organisms long time of residence biocompatibility and ability to convert light into heat	Medical applications - tumor or cancer cell distruction, drug delivery and photothermal therapy	[17, 18]
Acts like a semiconductor, which means it can conduct electricity under certain conditions. -It has a high surface area, making it useful in various applications. Its nanostructured forms display pseudocapacitive properties, allowing for better energy storage capabilities.	Energy storage devices -to enhance charge storage capabilities -used as an electrode material in supercapacitors	[19]
cost-effective	-Used in Sodium ion battery rather lithium ion battery	[29]
Absorb heavy and toxic metal ions such as from aqueous solutions due to high surface area and strong attraction to those toxic metals (affinity) for instance laed and arsenal.	Wastewater treatment	
Photocatalytic activity	Photocatalyst -Breakdown of complex organic molecules into less harmful substances and treating industrial	[30]

Properties of Bi_2S_3	Applications of Bi_2S_3	References
	effluents.	
Non-toxic nature, large surface area, chemical stability, high crystallinity and light absorptivity ability in the visible and near infra-red region of the solar spectrum	Sensing devices -laser detector	[24] [25, 26]
Photoelectrochemical catalysis which uses sunlight to split water into hydrogen and oxygen, making it an effective method for generating clean energy.	Catalysis -Water splitting for hydrogen and oxygen generation	[31]
possess sites of hydrogen adsorption that can be influenced by properties such as morphology, pore density and particle size	Hydrogen storage -used as energy source to power automobiles	[32] [33]

Overall, Bismuth sulfide (Bi_2S_3) is a compound of great interest because of its special physical properties and wide range of uses, especially in electronics, optics, and energy conversion. It is useful in energy storage devices due to its semiconducting nature and potential for large surface area in nanostructured forms. In environmental cleanup, it can help remove heavy metals, dyes, and other organic pollutants from wastewater through processes like adsorption and photocatalysis. It acts as a photocatalyst to break down organic dyes like methylene blue and rhodamine B when exposed to visible light, turning harmful substances into less dangerous ones. Additionally, Bi_2S_3 shows promise for hydrogen generation, particularly through photocatalytic water splitting, thanks to its ideal bandgap, stability, and ability to absorb visible light, making it a good option for producing solar-driven hydrogen.

3. Common Synthesis Methods and Characterizations of Bismuth Sulfide

Bismuth sulfide nanoparticle materials were prepared by employing controlled temperatures, precursors, and solvents via multiple synthesis methods, including chemical methods (hydrothermal use of water as solvent, ionothermal use of ionic liquid as solvent, and solvothermal use of different solvents rather than water) and the sol-gel method (use of polymeric precursors and deposition methods) listed as in the Table 2.

Table 2. Comparisons of Synthesis Methods for Preparation of Bismuth Sulfide Nanoparticles Materials.

Requirements	Sol gel methods of preparing Bi_2S_3
Precursors	-Bismuth acetate ($Bi(C_2H_3O_2)_3$) -Bismuth Nitrate pentahydrate ($Bi(NO_3)_3.5H_2O$) and -Hydrogen sulfide (H_2S), -Thiourea ($C5(NH_2)_2$), -Sodium sulphide (Na_2S) [34, 35].
Solvents with their uses	Water or alcohol [34, 35].
Temperature	At low temperature [34, 35].
Advantages	-High purity due to homogeneity at molecular level -reducing processing temperature (reducing energy cost) -control over particle size and morphology by adjusting PH, concentration and drying condition -versatility (used to prepare thin films, powders and bulk materials) -scalability (can be easily scaled up by industrial applications) [34, 35].
Disadvantages	-Time consuming due steps like gelation, aging, drying and calcination -Precise control over parameters is required to achieve desired properties, which may complicate the process. - Uniformity and consistency at larger scales can be challenging. -The final product may exhibit high porosity, which can affect its mechanical strength and stability [34, 35].

Requirements	Sol gel methods of preparing Bi_2S_3
Requirements	Chemical methods of preparing Bi_2S_3
Precursors	-Bismuth acetate ($Bi(C_2H_3O_2)_3$) -Bismuth Nitrate pentahydrate ($Bi(NO_3)_3.5H_2O$) -Bismuth Cloride ($BiCCl_3$) -Hydrogen sulfide (H_2S), -Thiourea ($C5(NH_2)_2$), -Sodium sulphide (Na_2S) -elemental sulfur (S_8) [36].
Solvents	-Water or aqueous solution (chemical precipitation) -water under high pressure and temperature (Hydrothermal) - Organic solvents (like ethylene glycol, alcohols, etc)(solvothermal) -Electrolytic solution or aqueous solution (Electrochemical deposition) - Solvent is not applicable; gas-phase process [36].
Temperature	At High temperature
Advantages	-High purity due to controlled reaction environment -Versatility -Scalability (can be scaled up for larger production without significant loss of quality) -control over morphology (control over particle size and morphology by adjusting reaction parameters) -versatility (used to prepare thin films, powders and bulk materials) -scalability (can be easily scaled up by industrial applications) -Rapid synthesis [36].
Disadvantages	-High cost (may require expensive equipment and operational costs) -Limited control over crystal size -Environmental concern, toxicity and complexity [36].
Requirements	Deposition methods of preparing Bi_2S_3
Precursors	-Chemical Vapor Deposition (CVD): Bismuth chloride ($BiCl_3$), Hydrogen sulfide (H_2S and elemental sulfur (S) - Metal-Organic Chemical Vapor Deposition (MOCVD): Bismuth tris (ethyl) ($Bi(C_2H_5)_3$) and dimethyl sulfide ($(CH_3)_2S$) -Pulsed Laser Deposition (PLD): Solid targets of bismuth sulfide (Bi_2S_3). -Spray Pyrolysis: Aqueous solutions of bismuth nitrate ($Bi(NO_3)_3$) and thiourea ($CS(NH_2)_2$) or sodium sulfide (Na_2S). Electrodeposition: Bismuth salts ($Bi(NO_3)_3$) in an electrolyte solution containing sulfide ions from sodium sulfide (Na2S) [37-39].
Solvents	- Solvent is not applicable; gas-phase process (chemical vapor deposition, Metal-Organic Chemical Vapor Deposition (MOCVD)). -Solvent is not applicable; uses solid targets and a laser source (Pulsed Laser Deposition (PLD)). -Water or organic solvents, depending on the precursor solution (Spray Pyrolysis). -water as a solvent (Electrodeposition) [37-39].
Temperature	At High temperature [37-39].
Advantages	Chemical Vapor Deposition (CVD) Produces high-quality thin films with uniform thickness, Suitable for large-area coatings and complex geometries. high purity and excellent crystallinity of the deposited films [37, 38]. Metal-Organic Chemical Vapor Deposition (MOCVD) Allows for precise control over film composition and thickness.

Requirements	Sol gel methods of preparing Bi_2S_3
	Capable of producing high-quality epitaxial layers. Pulsed Laser Deposition (PLD) Can produce films with excellent stoichiometry and crystalline quality. Allows for the deposition of complex heterostructures [39]. Spray Pyrolysis Cost effective method suitable for large-area coatings. Can be applied to various substrates including flexible ones. Electrodeposition Allows for precise control over film thickness and morphology. Cost-effective and scalable for large-area applications.
Disadvantages	Chemical Vapor Deposition (CVD) Requires high temperatures and specialized equipment and the process can be hazardous due to the use of toxic gases [37, 38]. Metal-Organic Chemical Vapor Deposition (MOCVD) High equipment costs and complexity. Requires careful handling of organometallic precursors due to toxicity [38]. Pulsed Laser Deposition (PLD) Requires vacuum conditions and sophisticated laser equipment. The process can lead to non-uniformity in film thickness [39] Spray Pyrolysis May result in lower film quality compared to other deposition methods. Requires optimization of spray parameters for uniformity. Electrodeposition Requires careful control of electrochemical parameters to avoid defects. Limited to conductive substrates.

Therefore, Bismuth sulfide (Bi_2S_3) is a semiconductor material with applications in photodetectors, solar cells, and thermoelectric devices. It can be synthesized using various techniques, including the sol-gel method, chemical deposition methods, and other chemical approaches. The sol-gel method is a widely used synthesis technique for producing Bi_2S_3, as it effectively creates uniform and high-purity materials at relatively low temperatures. In this process, the solution is stirred until a gel forms; this gel is then dried and calcined to yield Bi_2S_3.

4. Summary and Conclusions

Bismuth sulfide (Bi_2S_3) is covered in detail in this review, along with its synthesis techniques, physical ad chemical characteristics, and several uses in biomedicine, electronics, energy storage, sensors, environmental remediation, and catalysis. In processes including photocatalysis, hydrogen generation via water splitting, adsorption, and optoelectronic applications, Bi_3S_3 is a highly flexible material due to its semiconducting characteristics, small bandgap, strong visible NIR absorption, high carrier mobility and low toxicity. Sol-gel is preferred for creating high quality materials at low temperatures, although they can also be manufactured using ionothermal, sol thermal, hydrothermal, and sol-gel procedures. X-ray diffraction and UV Vis spectroscopy are two examples of characterization techniques that are crucial for comprehending its optical and structural characteristics.

From simple photoconductors to multifunctional nanomaterials for advanced energy, environmental, and biomedical applications, Bi_2S_3 nanoparticles have undergone a remarkable evolution. In the future, sustainable commercialization will depend on the development of scalable, green and mechanochemical synthesis methods; further optimization through bandgap engineering, heterostructure integration, and multifunctional design will improve performance in photocatalytic, sensing, optoelectronic and biomedical systems; and systematic studies on long-term biocompatibility, stability, and recyclability are crucial for safe and successful real-world deployment. In general, these directions highlight Bi_3S_3 nanoparticles as a cornerstone material in next-generation nanotechnology, bridging clean energy, environmental sustainability, and healthcare innovation while filling existing research gaps and directing future investigations.

Abbreviations

XRD	X-ray Difraction
SEM	Scaning Electron Microscopy
PLD	Pulsed Laser Deposition
CVD	Chemical Vapour Deposition
AFM	Atomic Force Microscopy
TEM	Transition Electron Microscopr

Author Contributions

Abdi Yirdew is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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