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Mini-review on Synthesis and Characterization of Metal/Silver Iodides Nanostructures and Their Applications to Optical Sensors

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Abstract: Currently, metal/silver iodide (AgI) nanomaterials are considered one of the most promising material candidates for future optical sensor applications because of their inherent optical, electronic, and photoactive properties. The integration of AgI is beneficial because it has a wide bandgap of about 2.8–3.0 eV, a high refractive index, and a high light absorption in the ultraviolet-visible region that improves the sensor's performance. With the incorporation of metal nanoparticles such as silver (Ag) and gold (Au), AgI possesses photochromic characteristics, plasmonic behavior, and surface-enhanced Raman spectroscopy as well as localized surface plasmon resonance properties, which offer higher sensitivity for real-time and label-free sensing. These nanocomposites are analyzed by gas sensing, sensing application of biology, sensing of pH, sensing of environmental pollution, and the application of optical imaging, where receptor-colorable properties enhance quantities of analyte especially in a high noise background. However, there are some drawbacks to their synthesis and application. The major limitations include instability of the environment, difficulties in reproduction when synthesizing, and challenges in mass production. Specifically, future work will involve investigating new approaches to creating layers of protection, solid-state stabilizers, and low-cost synthesis techniques for the purpose of enhanced stability and scalability. Besides, the scope of their uses in diagnostics, environment monitoring, and biomedical imaging will assure a steady position of metal/AgI nanocomposites as the materials for enhanced optical detection in the creation of future high-performance sensing systems.

Keywords: silver/metal iodide nanomaterials, optical-based sensors, plasmon resonance, environmental detection, pH detection, optical imaging, stability improvement

1. Introduction

Optical sensors have gained widespread use across numerous applications such as hydrology, medicine, chemical analysis, and industrial processes due to their high sensitivity, rapid response time, and ability to detect minute changes at the molecular level. They have a short response time and can sense changes at the molecular level. These sensors work based on the interaction of light with materials to measure particular characteristics or changes in the surroundings [1]. AgI with metals such as silver (Ag) or gold (Au) leads to the generation of localized surface plasmon resonance (LSPR), in that the free electrons within the metal nanoparticles oscillate collectively to the frequency of the applied light and thereby exhibit higher optical absorption and scattering. This type of plasmonic coupling enhances the spread of charge carriers and enhances the charge transfer rate in AgI, which helps in reducing the rate of electron-hole recombination and hence improves the sensitivity, signal-to-noise ratio, and stability of the optical sensors. One major trend observed in recent years has been growing interest in incorporating nanomaterials, which can offer increased interaction with light, mainly owing to the size of the material and interaction surface. Among the various parameters, the silver iodide (AgI) nanomaterials deserve attention because of their great optical performance and optimal photo-electrochemical properties [2]. Their tunable bandgap, broad spectral sensitivity, and compatibility with noble metals such as silver and gold make these nanomaterials highly suitable for the design and fabrication of advanced optical sensor technologies.

Highly localized photo-physical properties of AgI nanomaterials are among the most interesting features that potentially enhance the sensing capabilities. From this point of view, AgI has a direct bandgap (~2.8 eV), which enables it to absorb light in the ultraviolet (UV) region, and LSPR effects caused by a combination of metal nanoparticles, mainly silver and gold [3]. This interaction increases the density of the electromagnetic fields at the metal surface several times compared to the intensity of the optical response. The developed combinations offer better sensitivity to light and allow expanding the spectral field of operation of the nanosensors in the UV, visible, and near-infrared (NIR) ranges.

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These capabilities have put metal/AgI composites in a strategic hunting ground in the area of precision sensing and beyond academia and into practice [4].

It of course reveals the optical properties of silver iodide nanomaterials but exhausts its versatility. The intrinsic semiconductor nature of some metal oxides enables their high photoactivity, good charge separation, and transfer, which is obligatory for any photo-electrochemical sensor AgI nanostructures combined with metal enhance the photocatalytic properties of AgI, and they are sensitive to stimulation, for example, producing different results with changes in gas concentration, pH, or the presence of biomolecules [5]. "A scientist has discovered that these materials can be made flexible and have multiple functionalities that can include both optical and catalytic features, thus setting ingratiation for multi-sensor, pollutant sensing, biosensing, and medical diagnostics." Moreover, the tunability of sizes, morphology, and surface modifications of AgI nanomaterials allows the development of a more targeted strategy for certain sensing applications, expanding the functional range of these materials in various spheres [6].

However, when applied in optical sensing techniques, some obstacles need to be met while using AgI nanomaterials to achieve their full potential [7]. The environmental stability of AgI is a critical issue as this compound decomposes when exposed to light and moisture. Such a limitation calls for better stabilization techniques, for instance, using protective layers or incorporating stabilizing materials [8]. Also, the synthesis of metal/AgI composites is another key area that is actively investigated at present since the uniform and reproducible synthesis results are crucial for practical application. Addressing these difficulties will not only improve the efficiency and stability of AgI-based sensing devices but also expand their utilization area, promoting the development of optical sensors [9, 10].

The flowchart shown in Figure 1 visually represents the role and applications of silver iodide (AgI) nanomaterials in optical sensors. It begins with optical sensors, highlighting their sensitivity, fast response, and molecular-level detection capabilities, with applications in hydrology, medicine, and industry.

Next, it introduces the Role of Nanomaterials, emphasizing enhanced light interaction and increased sensitivity. The focus shifts to AgI nanomaterials, showcasing their key features: tunable bandgap (~2.8 eV), broad spectral sensitivity (UV–visible–IR), and LSPR synergy with metals like silver and gold. These properties enable multifunctional applications, including biosensing, pollutant detection, and medical diagnostics.

The Challenges section identifies environmental instability, such as decomposition in light and moisture, and synthesis difficulties in achieving uniform, reproducible composites. Finally, Solutions and Future Directions propose the use of protective layers, stabilizing materials, and improved methods to enhance stability and efficiency, ultimately expanding the application potential of AgI-based optical sensors [11].

2. Preparation of Metal/Silver Iodide Nanomaterials

Silver iodide (AgI) nanomaterials synthesized using both chemical and physical approaches, and their size, shape, and structure can therefore be controlled. Of these techniques, chemical precipitation is one of the most extensively used techniques in which Ag^+ ions react with I^- ions to form AgI nanoparticles or thin films in an aqueous or organic solution [6]. It is found that temperature, the concentration of precursors, and stirring speed play a crucial role in the final shape and size of the AgI nanomaterials. Another method, hydrothermal synthesis, consists of the interaction of the precursors at high temperature and pressure in an autoclave. This technique offers not only the formation of high-purity AgI nanostructures but also the fabrication of a few shapes like nanorods and nanosheets to develop their optical and electrical behaviors [12]. Furthermore,

Figure 1
The AgI nanomaterials in optical sensors

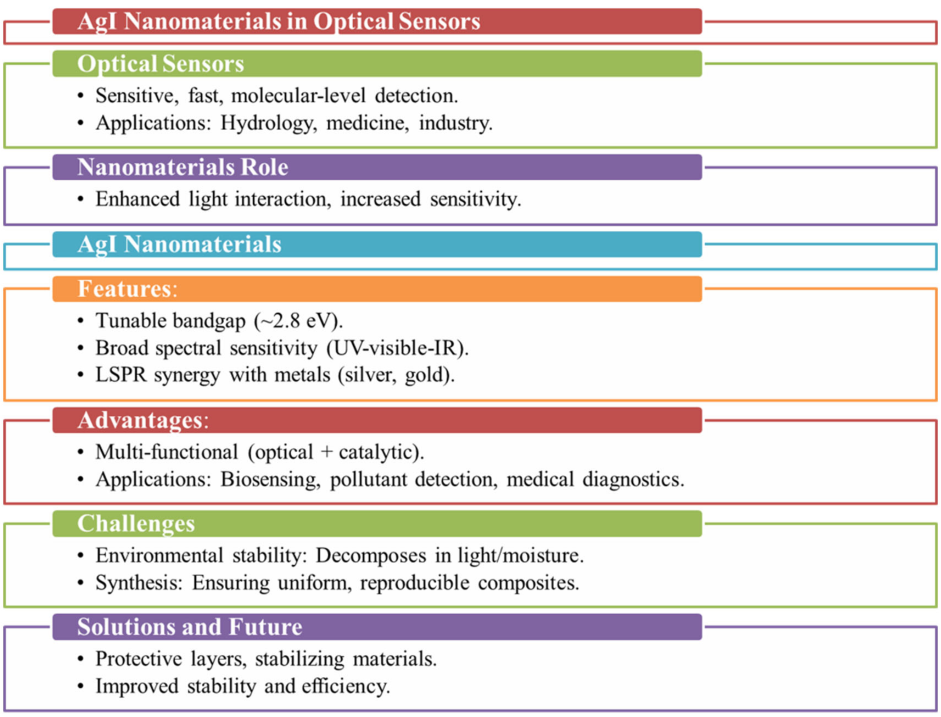
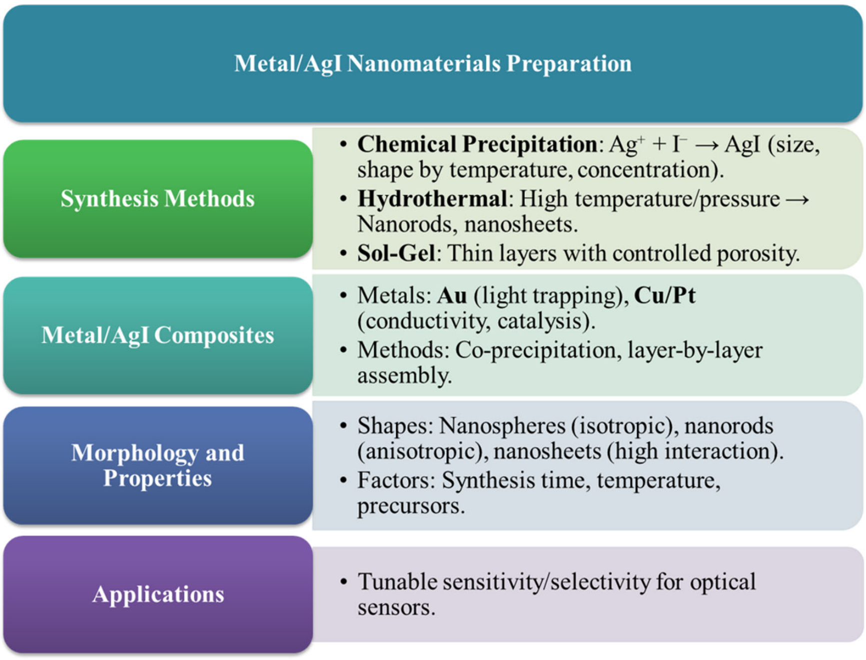


Figure 2
The AgI nanomaterials preparation



sol-gel techniques are the most suitable methods for the formation of a homogeneous AgI thin layer or composite material with pre-designed porosity for better performance of optical sensing [13].

The dispensability and applicability of AgI nanomaterials to optical sensing can be enhanced by incorporating other metal nanoparticles like gold (Au), copper (Cu), or platinum (Pt) to form hybrid or composite structures. These metal/AgI composites leverage the distinct advantages of both components: The analyzed factors include the strong LSPR and the wide bandgap and photoactivity of AgI [14]. For instance, incorporating gold nanoparticles into the AgI structure enhances light trapping and charge transfer properties, which are crucial for the development of highly sensitive optical sensors. Likewise, the integration of copper or platinum into the composite enhances its electronic conductivity and catalytic enhancement, thereby improving its applicability. Techniques, such as co-precipitation, layer-by-layer assembly, and so on, are used to uniformly incorporate metal nanoparticles into the AgI structure to guarantee identical and regular optical and electrical properties [15].

The size, morphology, and crystalline structure of the synthesized AgI are critical success factors that dictate the plasmonic behavior. Changes in synthesis conditions, such as synthesis time, synthesis temperature, and the concentration of precursors, will result in the production of different nanostructures including nanospheres, nanorods, nanowires, and nanosheets. These morphological differences induce drastic variations in the plasmonic and electronic characteristics of the materials. For instance, AgI nanorods can show anisotropic characteristic plasmon resonance, which can cause distinct transmission in one direction; conversely, nanospheres show isotropic response [16]. Furthermore, it is clear that nanosheets with large surface areas are still excellent for increasing the light–matter interaction properties, and therefore, it is suitable for optical sensor applications. The capacity to design and incorporate these features at the nanoscale levels makes metal/AgI nanomaterials suitable for enhanced sensing applications since their performance such as sensitivity and selectivity can fine-tune for different sensing applications [17].

Figure 2 illustrates the preparation of metal/silver iodide (AgI) nanomaterials for optical sensing applications. The process begins with synthesis methods, including chemical precipitation, hydrothermal techniques, and sol-gel methods. Chemical precipitation forms AgI nanoparticles or thin films by reacting Ag^{+} and I^{-} ions, influenced by temperature, precursor concentration, and stirring speed. Hydrothermal synthesis in an autoclave creates high-purity nanorods and nanosheets under high temperature and pressure. Sol-gel methods produce homogeneous AgI thin layers with pre-designed porosity [6].

Metal/AgI Composites are formed by incorporating gold, copper, or platinum nanoparticles to enhance properties such as light trapping, charge transfer, and catalytic activity. Techniques such as co-precipitation and layer-by-layer assembly facilitate the uniform incorporation of metal nanoparticles into the AgI matrix, thereby improving the consistency of optical and electronic properties.

The figure highlights the impact of morphology and properties, showing that synthesis conditions (time, temperature, precursor concentration) determine the shape (nanospheres, nanorods, nanosheets) and performance. These structures exhibit tunable sensitivity and selectivity, enhancing their application in optical sensors [18].

3. Optical and Electronic Characteristics of Metal/Silver Iodide Nanomaterials

Silver iodide (AgI) is characterized by unique optical constants mainly due to the material's large band gap of roughly 2.8 eV, thus permitting strong absorption of UV radiation. This property makes AgI a suitable candidate as a material for UV-sensitive devices. It has the optical properties of silver iodide and can greatly improve the optical performance through the plasmonic resonant effect when combined with metallic nanostructures such as silver or gold nanoparticles. Silver metal and other metallic nanoparticles show well-pronounced LSPRs because the conduction electrons of the metal resonate with the incident radiation at a defined frequency. This resonance increases the amplitude of the oscillating electromagnetic fields at the nanoparticle surface, which increases the coupling of light with matter [6, 17].

The combination of silver iodide with finite metallic nanoparticles leads to an unusual composite with excellent optical properties. Metal/AgI is a kind of semiconductor with a band gap of about 2.8–3.0 eV, which is sensitive to light and has a high ability in generating photo-induced charges, evidence of exciting effects, and a high refractive index so that it is appropriate material for applying in optical and plasmonic devices. One aspect raises the light adsorption and scattering ability of AgI, and the other provides the composite with stability and inherent photoactive character owing to the presence of silver iodide. In these materials, modifications often result in enhanced photosensitivity, significant shifts in plasmonic resonance frequencies, and improved charge transport properties. These enhancements are especially important for the creation of the new-generation optical sensors, photocatalytic systems, and photodetectors. The synergistic effects revealed between the LSPR and semiconducting AgI result in well-defined tunable optical performances, the discovery of which opens an exciting avenue toward the visualization of developing multifunctional materials with desired optical and electronic characteristics [19–21].

The research of light–matter interactions with nanostructured materials in nano-optics receives growing interest because it improves optical sensor performance. Metal/silver iodide nanomaterials showcase exceptional optical properties because they integrate AgI semiconducting behavior with noble metal nanoparticle LSPR effects using silver (Ag) and gold (Au) additives [17, 19]. Light causes metal nanoparticles to exhibit LSPR by making electrons at their surface collectively oscillate at select wavelength excitations. Submitted to the nanoparticle interface, this enhancement results in magnified electromagnetic fields, which raise light absorption and scattering capabilities, thereby enhancing optical device sensitivity [20, 22].

Nano-optical enhancement occurs when researchers embed metallic nanoparticles into AgI structures. The optical absorption capacity of AgI spanning from UV to visible wavelengths becomes improvable through its interaction with metal nanoparticles due to the adjustable wide bandgap of ~2.8–3.0 eV [6, 19]. The creation of heterojunctions between AgI and metallic components into a single unit sustains the separation between charges and minimizes electrical recombination along with enhancing both photocatalytic performance and sensing responsiveness [21]. Through controlled alteration of metallic nanoparticle dimension and material selection and shape design, the optical performance spectrum gets modified across UV through visible light into NIR wavelengths [17, 23].

Nanostructure design stands as a fundamental factor to determine their plasmonic characteristics. The fundamental shape characteristics of nanorods enable direction-dependent LSPR effects, while nanosheets maximize their light interaction area [16]. Core-shell and Janus-type advanced nanostructures make it possible to develop asymmetric field distributions suitable for building multifunctional detection platforms [24]. Fibercasting beyond co-precipitation plus layer-by-layer assembly enables manufacturers to achieve uniform metal nanoparticle placement as well as better optical repeatability within the AgI matrix [15, 18].

Plasmon-enhanced features from nanocomposite materials led to substantial advancements throughout sensor technology development. The LSPR effect in surface-enhanced Raman spectroscopy (SERS) amplifies weak signals so researchers can identify proteins and nucleic acids and pathogens at trace-level concentrations [25–27]. Light absorption and strong scattering of metal/AgI composites increase image contrast and resolution, making them beneficial for biomedical diagnostics [28–31]. Plasmonic sensors that work by detecting environmental index changes exhibit optimal sensitivity for real-time label-free monitoring because they can identify tiny changes in their environment [32, 33]. Metal/AgI nanomaterials gain high-performance multifunctionality as optical sensors when combined with nano-optical principles and plasmonic enhancements. The advancements in this field strengthen the ongoing research in diagnostic and environmental monitoring systems that use nanoscale technologies [34, 35].

Figure 3 illustrates the optical and electronic characteristics of metal/silver iodide (AgI) nanomaterials and their significance in advanced applications. It begins with the optical properties of AgI, highlighting its large bandgap (~2.8 eV) that facilitates strong UV absorption, making it ideal for UV-sensitive devices [23].

Next, it emphasizes plasmonic enhancement, where LSPRs of metallic nanoparticles like silver or gold enhance the light–matter interaction. This occurs due to the resonance of conduction electrons with incident light, amplifying electromagnetic fields at the nanoparticle surface.

The formation of metal/AgI composites integrates these effects, resulting in enhanced light absorption, improved photosensitivity, and increased stability. These synergistic properties combine the LSPR effects of metals with the semiconducting nature of AgI [22].

Finally, the figure highlights applications, showcasing how these composites enable tunable optical and electronic characteristics for optical sensors, photodetectors, and photocatalytic systems, driving the development of multifunctional materials [17, 19].

4. Investigations of Metal/Silver Iodide Nanomaterials for Optical Sensor System

Due to the sol growth of metal nanoparticles in AgI, better nanomaterials are developed, which exhibit good optical performance for optical sensing. Due to the plasmon resonance along the metal nanoparticle including silver or gold and the semiconductor aspect of AgI, certain of the improved sensitized selectivities and stabilities of the developed sensors have been observed. In the subsequent subtopic, a review of the various inventions considered is done [16, 36].

4.1. Gas sensing

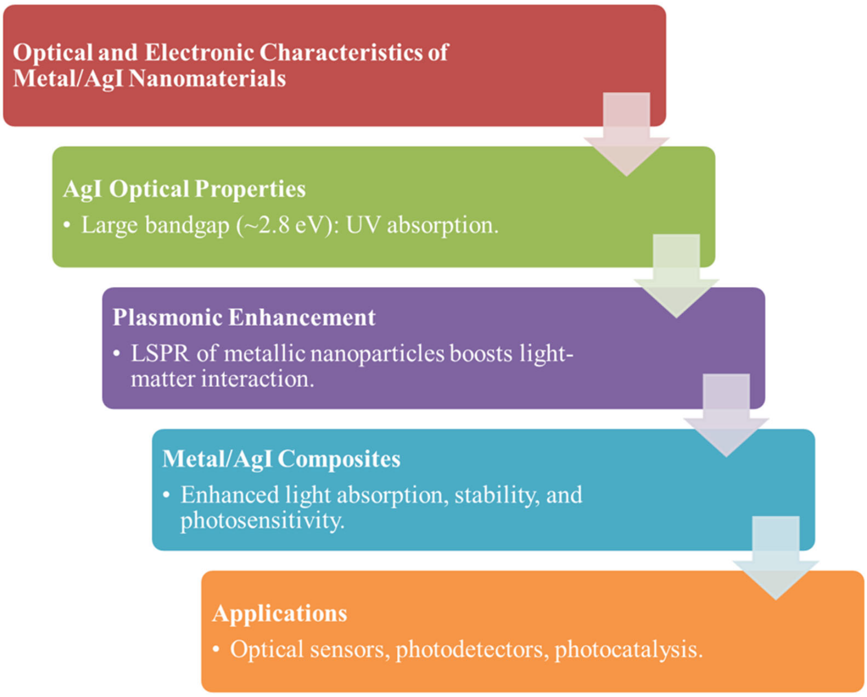
Gas sensing is a broad area of the multipurpose metal/AgI nanomaterials because of the possibility of identification of the gases and the concentration of the same owing to the formation of nanomaterials. On this note, silver iodide is as sensitive as various gases, such as ammonia (NH_3), nitrogen dioxide (NO_2), and hydrogen (H_2). This sensitivity is also enhanced once integrated with metal nanoparticles via the LSPR properties [37].

The plasmon resonance of metal nanoparticles is characterized by strong interaction with the environment: Physicochemical modifications, including variations in the refractive index of the local environment or the extent of adsorption of the gas molecules to the nanoparticle surface, cause an observable change in the optical frequency. For instance, there is an alteration of the absorbance, reflectance, or fluorescence property of the nanomaterial upon exposure of the nanomaterial to the target gas. These changes, when properly controlled, can be utilized to measure the concentration of the gas. This feature is very useful for industrial safety instrumentation, health diagnostic instruments, breath analyzers, and, above all, risky gas surveillance of the environment [16, 22].

4.2. Biological sensing

Metal/AgI nanomaterial is comprised primarily of metal and silver iodide nanocrystals, and these nanomaterials carry the

Figure 3
The optical and electronic characteristics of AgI nanomaterials



change agent potential of the biosensing platform, resulting from increased photochemical response integrated with selective molecular recognition. The sensitivities and specificities reported in the literature, and those achieved with these nanomaterials when conjugated with biorecognition components such as antibodies, enzymes, or DNA probes, are remarkable [25, 26].

One specific implementation is in SERS, where the plasmonic properties of metal nanoparticles amplify Raman signals from biomolecules immobilized on their surfaces. This allows for the detection of analytes at very low concentrations, including proteins, pathogens, and nucleic acids. Likewise, related sensing based on fluorescence expands the positive impact of the metal/AgI composites on emission enhancement to create a stable sensing line for biomarkers in biological systems [27].

These nanomaterials can be functionalized for selective recognition in the event of antigens, tumor markers, or pathogens at high sensitivity levels. For instance, the resulting multiplex complex of metal/AgI nanomaterials with immobilized DNA aptamers can selectively hybridize with the target DNA/RNA sequences while exhibiting an optical readout. Such capability has immense potential for charting out several possible futures in areas of diagnostic medicine, molecular medicine, and diagnostics on the go [32, 38].

4.3. pH sensing

Because metal/AgI nanomaterials have been touted to have optical properties, the technique can be used for pH detection in any environment. However, it should be remembered that modification in terms of the proton concentration (pH) does affect the electronic characteristics of AgI, and this can be easily observed from the plasmonic resonance or the optical absorption spectra. For example, when the sensor touches an acidic or basic fluid, the protons in the solution interact with the AgI component and result in a change of the refractive index or light scattering property of the composite [39]. Such variations can be quantified using spectroscopy, which is an actual pH difference measurement at best. Such sensors are particularly useful in:

Biomedical applications: In essence, any test that calls for the quantification of simple substances in body fluids like blood, saliva, urine, or sweat involves pH [32].

Industrial processes: For example, the regulation of the direction of acidity or alkalinity of the chemicals in the manufacture, storage, or transportation of chemical commodities and articles, foods and food products, or water processing equipment and organs [16, 40].

Environmental studies: Some are related to tracking increases and decreases in pH levels within the water body and other body systems due to the health of ecosystems like lakes or ponds or even ocean ecosystems or soil-supported ecosystems.

They are thus appropriate for a vast array of uses since they afford precise determination of stress as it occurs – a condition that is further enhanced by the parameter's tunability [33].

4.4. Environmental monitoring

This specific targeting of various environmental monitoring, especially toxins, employs the aid of an optical sensor, which consists of the metal/AgI nanocomposite materials. These materials exhibit high sensitivity to a variety of contaminants, including [32]:

Heavy metals: For example, Pb^{2+} ions, Hg^{2+} ions, and Cd^{2+} ions, as well as CH_3Hg^+ and NH_4^+ [41].

Organic pollutants: The following types of chemical residues were identified: pesticide residues, dyes and coloring matters, and other pharmaceutical product residues.

It changes the optical characteristic of the AgI nanomaterial by either the adsorption of the pollutants onto the surface of the nanomaterial or by the repositioning of the positioned absorption or emission peaks. The positive aspect of enhancement by metal nanoparticles is that clients can ascertain the presence of undesirable substances in an inconceivably small measure. This capability is used to preserve the standard of air, water, and soil quality in industrial fields, agricultural fields, and urban areas [42, 43].

For instance, the quite advanced sensor, which has been proposed in this study using metal/AgI nanomaterials, might be mounted on the water supply system to assess the levels of pollution as water flows through it. They said that the material shows stability and performance potential at conditions and temperatures, which would make it eligible to accommodate long-term environmental sensing instruments [44–46].

4.5. Optical imaging

Such reversible transformations of the properties of metal/AgI nanomaterials allowed their use in optical imaging in biological and materials sciences. All these materials can be used as fluorescence or/ scattering contrast agents that can improve the spatial resolution and/ or sensitivity of the measurements. In biological imaging, metal/AgI composites have the function of staining the targeted cell, tissue, or biomolecule [28]. Due to the structures, some of them can function selectively with lights to frequencies; this covers the part of increasing contrast and high definition when visualizing biological systems. For instance [29]:

Fluorescence imaging: The fluorescent characteristics of the metal nanoparticles enhance the sensitivity of the AgI to allow for the identification of trace levels of a target from samples of tissue or cells [30].

Photoacoustic imaging: The metal/AgI composites demonstrated here provide high light absorption at specific frequencies for generating sound waves that can effectively resolve 7 mm of biological tissues [31].

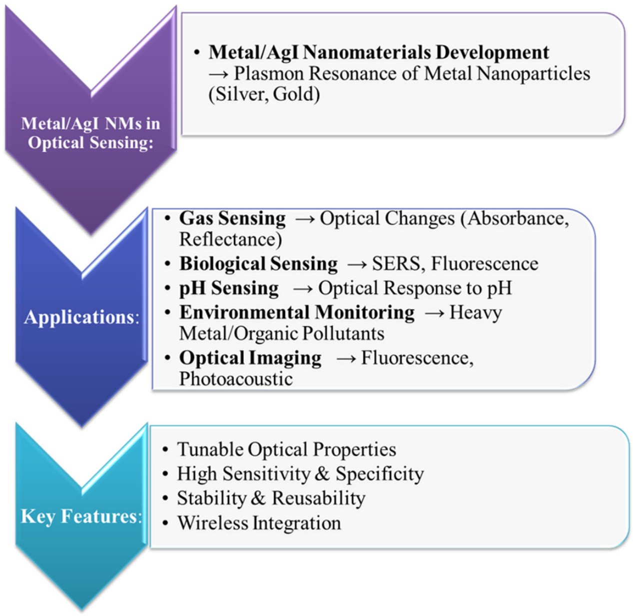
Besides biological imaging, they are also used in arteriography, where optical characteristics of the material are used in establishing the structure and constitution of the material at a sub-micron or nanoscale. In this more or less extensive subpart, we shall outline some specific features of the processes of innovation and several possible further developments of this notion. The combination of metal nanoparticles with AgI offers several innovative features that expand the potential applications of these nanomaterials in optical sensing [47]:

Tunable optical properties: Metal/AgI nanocomposites, especially nano-optics and enhanced plasmonic properties, are essential in determining the functionality of the metal/AgI nano-adhesives for optical sensing. The enhancement of the incident light field happens near the metal nanoparticles interface when AgI is mixed with noble metals; the noble metals include Ag or Au – this leads to an LSPR with resultant improved light–matter interaction as well as increased light absorption. This indeed enhances the sensitivity, spectral selectivity, and fluorescence intensity of the material, making them suitable for activities such as SERS, biosensing, and environmental sensing. Moreover, enhanced plasmon-exciting coupling in these nanocomposites improves photocatalytic activity and charge transfer rates, making them promising for optoelectronic and sensing applications. If certain sizes, shapes, and metal compositions are attained, then the plasmon resonance frequency and the optical absorption of the metal nanoparticles could be tuned to specific use wavelengths [24].

High sensitivity and specificity: Both the metal cation and its interaction with AgI enhance the response of packed sensors and improve selectivity toward specific analytes [48].

Stability and reusability: To achieve growth in unfavorable conditions, the stability of the material through the incorporation of AgI is beneficial for the object to be multifunctional. Some of

Figure 4
The processes and applications of metal/AgI nanomaterials in optical sensing systems



the opportunities that may accrue from integrating these sensors with wireless communication and analysis tools include the use of the sensors in smart sensing networks, health care, conservation and environmental management, industries, and many more. These optical and electronic properties of the metal/AgI nanocomposite materials give hope that the optical sensing and imaging technique will be enhanced to a high level and solve various scientific and practical problems [34, 35, 49].

Figure 4 highlights the role of metal/AgI nanomaterials in optical sensing, focusing on their development, applications, and key features. These nanomaterials are engineered to leverage the plasmon resonance of metallic nanoparticles, such as silver and gold, for enhanced optical detection. Their applications span various fields, including gas sensing (e.g., NH_3, NO_2) through optical changes in absorbance and reflectance, biological sensing for proteins and pathogens using SERS and fluorescence, pH sensing for biomedical and environmental monitoring, and environmental monitoring to detect heavy metals and organic pollutants. Additionally, they are utilized in optical imaging techniques, such as fluorescence and photoacoustic methods, for tissue and cell visualization. Key features of these materials include tunable optical properties, high sensitivity and specificity, stability and reusability, and potential for wireless integration, making them versatile and effective in a range of optical sensing applications [35].

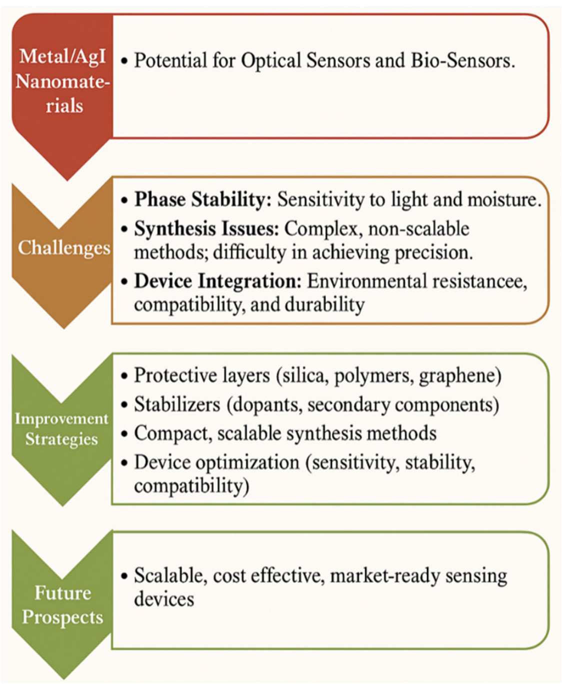
5. Issues and Prospects

Indeed, metal/silver iodide (AgI) nanomaterials exhibit significant potential as optical sensors and/or biosensors, but there are several secondary issues that need to be resolved to enhance these applications. One major concern is the phase stability of silver iodide in normal environments. AgI however is sensitive to color change, especially in the presence of light and moisture, which may alter the reliability of sensors. To address this, researchers are exploring strategies such as coating the AgI layer with protective materials like silica, polymers, or graphene or incorporating stabilizing agents such as dopants or other secondary components. These approaches are designed to improve the stability and keep up the functional characteristics of the nanomaterials for long periods. One of the problems is the formation of well-defined and highly reproducible metal/AgI nanostructured materials with the desired size, shape, and composition. It is desirable to have tight tolerances meeting the required precision in these properties to produce the desired, consistent optical effects. However, the majority of the synthesis methods employed today are lengthy, tedious, or not amenable to scaling up [50, 51].

The possibility of engineering compact, low-cost syntheses for the creation of highly efficient metal/AgI nano-hybrid materials will be imperative to move these materials from the laboratory onto the market. However, integration into practical sensing devices creates further challenges. The incorporation of metal/AgI nanomaterials into the devices must also be optimized to attain the combination of sensitivity and stability in the device that is resistant to environmental factors. Implemented challenges concerning compatibility with existing systems, long-run steady working, and convenience must be considered as well [52].

The flowchart of Figure 5 illustrates the key challenges and improvement strategies associated with the development of metal/AgI nanomaterials for optical and biosensing applications. It begins by highlighting the significant potential of these nanomaterials in sensing technologies, emphasizing their versatility and functional advantages. However, several challenges impede their practical application, including phase stability issues caused by sensitivity to light and moisture, the complexity of synthesis methods, and difficulties in achieving precise, reproducible nanostructures. Additionally, challenges in device integration, such as environmental resistance, compatibility with existing systems, and long-term durability, are outlined. To address these issues, improvement strategies are proposed, including the use of protective layers (e.g., silica, polymers, graphene), stabilizing agents (e.g., dopants), and the development of compact, scalable synthesis methods. The flowchart concludes with prospects for scalable, cost-effective production and the creation of durable, market-ready devices that combine high sensitivity and stability [53].

Figure 5
The AgI nanomaterials challenges and future prospects



5.1. Emerging enhanced approaches

Current studies are working on improving ways to use silver iodide (AgI) nanomaterials and boost their optical sensor abilities because of their current limitations. Scientists develop such approaches to enhance stability and increase sensitivity and scalability alongside increasing multifunctionality for practical implementation. Scientists focus heavily on designing innovative protective coatings as their main research priority. AgI stability against photo-degradation and moisture impact improves through encapsulation processes that use protective materials including silica as well as graphene oxide and conductive polymers, which guard AgI while preserving its optical performance [34]. Such protective layers simultaneously boost the material stability and provide better conditions for charge transfers and light absorption. Researchers improve AgI by combining it with other semiconductors or precious metals using different structural designs like core–shell, Z-scheme, and Janus heterojunction. The designs enable better electron–hole separation along with expanded light absorption rates and amplified plasmonic field interactions through efficient electromagnetic field connecting [20, 24].

AgI nanostructures serve applications that need quick response together with high discrimination capability, especially in biological sensors and pollutant detectors. Green synthesis approaches are now more popular since they provide both environmental sustainability and large-scale production capabilities. The production of nanocomposites with precise morphology and diminished toxicity becomes possible through research on plant materials, biopolymers, or microwave-assisted processes [21, 39]. The future direction of sensor development includes integrating AgI nanomaterials into smart platforms that include wearable devices, lab-on-chip structures, and wireless network systems. These systems combine AgI nanocomposite sensitivity with features of real-time tracking, miniaturized design, and remote access to deliver essential characteristics for upcoming sensing systems [48]. New sensor systems are showing great potential toward practical, efficient, and sustainable operation through emerging technological approaches. Future research in these domains will boost AgI nanomaterials' capabilities to suit multiple application sectors while improving their operational performance.

6. Conclusion

Metal/silver iodide nanomaterials consisting of such particles with specific optical, electronic, and photoactive properties can be very useful in designing advanced optical sensors. It has been proven that those materials possess very high sensitivity in gas recognition, biomolecule identification, pH level determination, pollutant detection, and other environmental conditions. These applications hold a prospect in different spheres such as environmental observation, healthcare detection, and industrial security. As research in metal/AgI nanomaterials progresses, several key challenges must be addressed, including improving environmental stability, increasing synthesis yield, and enhancing integration efficiency for device applications. Future developments in protective measures, large-scale deposition approaches, and new structures of the sensing devices will open the way for this metal/AgI nanomaterial to be used in actual sensing systems. More to this, these nanomaterials are seen to occupy a special position in the development of the next generation of optical sensors with superior performance and flexibility for increased use.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Nazia Nusrat: Conceptualization, Investigation, Writing – original draft. **Humaira Aslam:** Methodology, Validation, Investigation, Writing – review & editing. **Ali Umar:** Methodology, Formal analysis, Visualization. **Jehanzaib Sohail:** Software, Formal analysis, Data curation, Visualization. **Aman Ullah:** Methodology, Software. **Shumaila Ayuab:** Validation, Writing – original draft. **Ayesha Siddiq:** Investigation, Data curation. **Shehla Honey:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration. **Misbah Ullah Khan:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration.

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