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Review

Emerging trends in manufacturing of micro and macro scale devices using metal iodide-based nanomaterials

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Abstract: A fresh interest has been accorded to metal iodides due to their fascinating physicochemical properties such as high ionic conductivity, variable optical properties, and high thermal stabilities in making micro and macro devices. Breakthroughs in cathodic preparation and metallization of metal iodides revealed new opportunities for using these compounds in various fields, especially in energy conversion and materials with luminescent and sensory properties. In energy storage metal iodides are being looked at due to their potential to enhance battery performance, in optoelectronics the property of the metal iodides is available to create efficient LEDs and solar cells. Further, their application in sensing devices, especially in environmental and medical monitoring has been quite mentioned due to their response towards environmental changes such as heat or light. Nevertheless, some challenges are still in question, including material stability, scale-up opportunities, and compatibility with other technologies. This work highlights the groundbreaking potential of metal iodide-based nanomaterials, emphasizing their transformative role in innovation and their promise for future advancements.

Keywords: metal iodides; ionic conductivity; optical characteristics; thermal stability; energy storage; optoelectronics

1. Introduction

The technological development of micro and macro devices has increased interest in metal iodide-based compounds since the materials have properties that fit well across multiple applications. Salts of iodide like silver iodide (AgI), copper iodide (CuI), and cesium iodide (CsI) are highly conductive ionic materials with good optical transmittance and high thermal stability that make them suitable for device applications. These materials are useful enablers of miniaturization, as shown in **Figure 1**, which means that producing devices that are smaller and more energy efficient can be done without compromising functioning. Flexible aggression and high efficiency coupled with miniaturization of components have been critical factors influencing compound adoption in microelectronic systems such as sensors, energy storage, and optoelectronic systems.

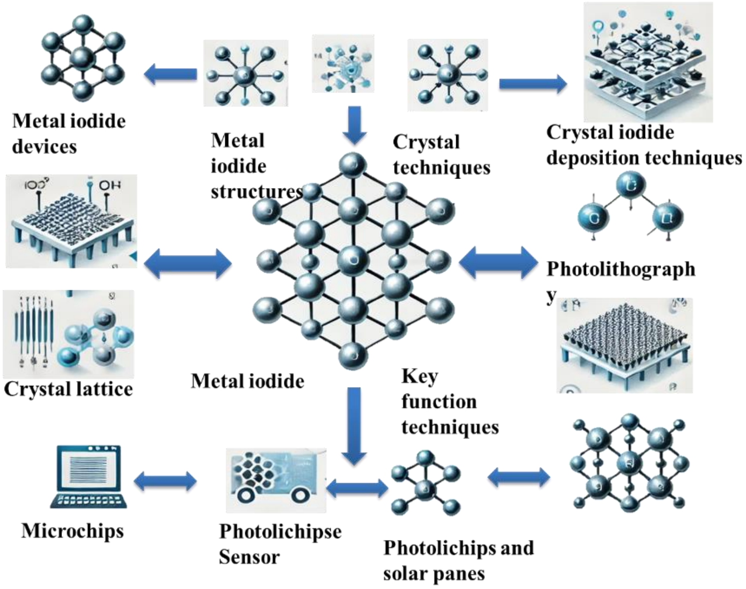

Figure 1. Represent the graphical abstract of this review.

The synthesis and processing of metal iodides have developed with improved fabrication techniques guaranteeing controlled micro- and nanoscale characteristics of the resulting materials. For instance, solution processes, Vapor deposition methods, and Chemical vapor deposition (CVD) techniques can be used, and each technique provides specific benefits depending on the goal of the metal iodide synthesis. These methods help specifically in the formation of thin films, nanoparticles, and nanowires which are compulsory for the Microfabrication of devices [1]. Furthermore, material science has given birth to hybrid forms of metal iodide which when combined with other materials such as polymers or graphene, will improve the efficiency and stability of the devices. These hybrid systems are especially advantageous in such applications as energy storage, where better charge maintenance and faster ion mobility are necessary [2].

Specifically, metal iodides are being gradually applied in energy storage, particularly in lithium-ion batteries and sodium-ion batteries due to their great potential for enhancing battery performance. It mainly concerns the improvement of the charge transport throughout the battery thanks to the high ionic conductivity of metal iodides. Also, their thermal stability makes it possible to use the batteries safely in diverse circumstances [3]. Metal iodides are also being considered for supercapacitors applications in their ability to produce electrodes with increased surface areas, and improved charge storage capabilities. These enhancements are in line with the developing demands of compact storage that harness high power density storage systems for portable electronics, electric vehicles, and portable medical equipment [4,5].

It is for these reasons that metal iodides have become invaluable their chemical structures allow them to glow, and to absorb certain kinds of light. Metal iodides are employed in light-emitting diodes (LEDs), laser diodes, and photovoltaic cells where the conversion of electrical energy to light, or its converse, is highly effective [6,7]. The ability of the metal iodides to have continual variation in the frequency range of device operation also can be beneficial in practically any frequency range making the metal iodides ideal for a diverse range of uses, anywhere from simple electronics to medical equipment. Furthermore, the cost to realize metal iodide-based optoelectronic devices is significantly less than the cost to realize traditional materials like silicon or organics [8,9].

There are however several factors that hinder the use of metal iodides in commercial devices even though their use has the following benefits: Questions concerning the stability and applicability of such materials for long-term and large-scale applications need to be answered, especially where the devices are exposed to severe environmental conditions or where the devices are to be used continually [4,10]. Moreover, the toxicity of some metal iodides is high, and in particular their use in medical and environmental concerns like silver iodide. However, the still-growing efforts to develop more stable, biocompatible, and scalable metal iodide compounds, and advancement in fabrication technology should help address these problems. Metal iodides will become key components of next-generation micro and macro devices of higher performance in the advancement of the field [11,12].

2. Fabrication techniques

Multiple techniques exist for fabricating metal iodide materials allowing experts to modify their functional properties as well as structural characteristics shown in **Figure 2**. The fabrication process requires two main methods including sol-gel methods and hydrothermal synthesis for controlling structure and morphology. The production of thin films with left and right distributions depends on the Chemical vapor deposition (CVD) and spin coating methods. Efficient production of simple bulk materials happens through solution casting in combination with co-precipitation whereas precise material composition and thickness control is achieved using electrochemical deposition processes. Distinct benefits generated by these methods decide what application methods best suit electronics as well as optics and catalysis domains. The integration of these domains supports the role of fabrication methods in enhancing today’s technological advancement.

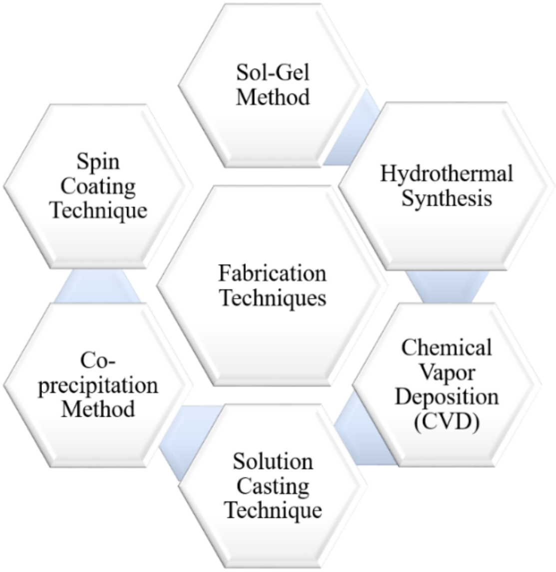

Figure 2. Represent the fabrication techniques of metal iodide-based materials.

2.1. Micro device manufacturing

Over the last few years, metal iodides have become promising candidates for integration into microdevices including sensors, photodetectors, and transistors because of their reliably turned electronic and optical attributes. The most significant benefit of metal iodides in microfabrication is that their bandgap can be tuned, and as such the electronic and optical properties of the material can be controlled. For example, CuI and AgI are preferred for high transmittance; a characteristic that is most crucial in optoelectronic applications [13]. Spin-coating and thermal evaporation are mostly used to incorporate metal iodides into micro-fabricated devices. Organometals can be created by depositing thin metal iodides and spin-coating and subsequent annealing provides the required morphology and thickness of the film [14]. Thermal evaporation, in contrast, provides a way of depositing very high-quality smooth and conformal films of metal iodides on different substrates; this is important for the optimization of the devices and scalability [15].

These fabrication techniques provide high levels of accuracy, and the devices made by these techniques are microscale and possess excellent electrical optical, and mechanical behaviors. In the course of designing sensors, it is important for the electronic properties of metal iodides to be tailored to increase sensitivity to gases, ions, or light [16]. Due to their high charge carrier mobility, metal iodides are used also in photodetectors and transistors, essential in communication systems and medical diagnostics. These microdevices have low defect densities, and by closely controlling the material’s structure at the time of fabrication, their performance and reliability are enhanced. Due to the growing need for the miniaturization of electronic devices and high efficiency, the application of metal iodides will continue to be significant within microelectronics necessary for the demands of technologies of the following generations [17,18].

The micro device manufacturing industry establishes precise tiny components to work at microscale dimensions. The production process contains several vital characteristics involving minimal power consumption together with miniature product manufacturing along with superb dimensional standards and very small-sized light-weight components. Micro device technologies operate best for applications that require accurate small-scale structures thanks to their combined features. Micro device production enables the production of intricate components with precise details while using rawest materials. The production of uniform precise parts depends on a process that combines micro-milling with micro-electromechanical systems fabrication and laser machining and lithography methods. The components reach enhanced reliability and performance due to both excellent tolerance standards and high-quality surfaces they achieve. Many high-tech business operations depend on micro device manufacturing for their functioning. In electronics production semiconductor chips and microprocessors emerge from this technology while the manufacturing of small dimensional sensors also takes place. Medical implants gain useful assistance through microfabrication methods that also support precision surgical tools and lab-on-a-chip devices in healthcare applications. Aerospace companies enhance flying systems and spacecraft capabilities through weight reduction components while working with reduced sizes. Manufacturing of micro devices will increase in significance as technology advances because it allows future inventions to create performance transformations within industries through effective compact tools. **Figure 3** illustrates these key characteristics.

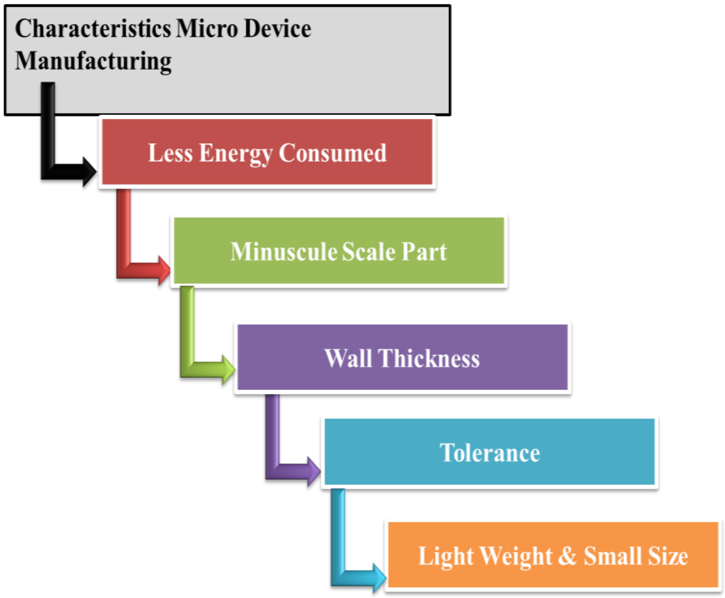

Figure 3. Characteristics of microdevices manufacturing.

2.2. Macro device manufacturing

The production of large-scale high-precision durable components relies on multiple fabrication procedures which fall under macro device fabrication. The fabrication of macro devices utilizes several techniques including machine operations (milling, turning and drilling) as well as injection molding for plastic parts quantity production and casting for complex metal form generation along with 3D printing for prototype development and specific manufacturing. According to the application different methods such as welding, forging and extrusion are employed to transform materials and make them joinable. Technical methods get chosen for production based on properties of materials and design complexity as well as production volume and cost-efficiency.

In the macro device generation, metal iodides are mainly used for their high ionic conductivity and thermal stability; they are used in solar cells and light-emitting diodes (LEDs). In the field of solar energy, the iodides based on hybrid perovskite have become more popular, especially for methyl ammonium lead iodide ($MAPbI_3$) owned to record high power conversion efficiencies [19]. These materials provide a high charge carrier mobility, meaning that efficient charge transport in photovoltaic devices enhances the energy conversion potential [20]. These perovskite iodides demonstrate high stability and have high process ability coupled with thin-film formation capability that makes them favorable as optoelectronic materials for cost-efficient, large-area photovoltaic applications [21].

In the field of LEDs, metal iodides are prized for their characteristics as they can release light in a broad area of the electromagnetic spectrum, which includes visible light and infrared. In the case of metal iodides, the high ionic conductivity is most advantageous for achieving efficient injection of charges and low energy loss in LED devices [22]. Their stability at high operational temperatures also means durability, thus suitable for commercial and industrial applications such as lighting. In addition, new hybrid iodide materials like perovskite have been well demonstrated to boost the efficiency and wavelength of light emission of LEDs. As the studies of the metals iodide-oriented materials are being extended prospects of these compounds are expected to become more profound in creating high-performance macro-devices, especially in renewable energy and optoelectronics [23].

Any design or system creation process includes diverse essential components according to **Figure 4** illustrated below. Project objectives together with boundaries get defined first in the development process. The Generic Requirements apply generic standard criteria to multiple domains yet Specific Requirements handle project-specific demands. Graphical notation represents the system through visual images which the Language Specification defines accurately while graphical notation supplies easy interpretation of these images. The modeling tools help designers create visual elements of system components which align with project objectives through design and visualization processes. System accuracy alongside functionality and external readiness receives constant refinement through successive improvements during the Refinement stage.

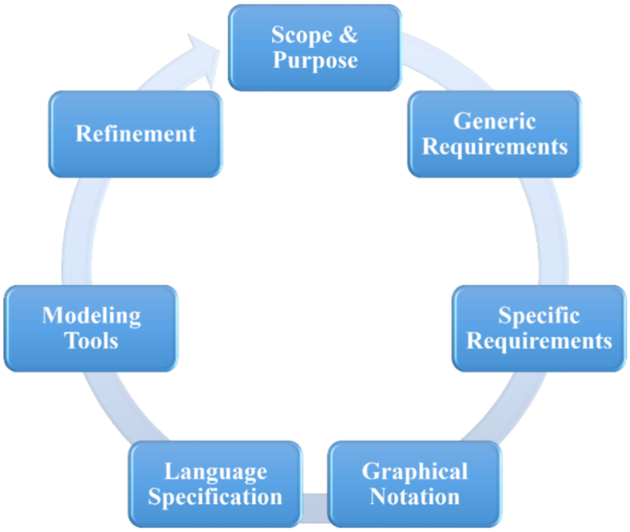

Figure 4. Represent the schematic scheme of macro manufacturing techniques.

2.3. Energy devices

Metal iodide materials as well as perovskites have shown high efficiency in energy applications, especially in solar cells and batteries. Concerning solar cells, metal iodide perovskites such as $MAPbI_3$ have offered significantly high power conversion efficiencies that have all but overshadowed traditional silicon-based photovoltaic solar cells [24]. These materials have the advantage of using easily scalable, low-cost deposition techniques such as solutions processing, which include spin coating or ink-jetting, and are hence preferred for large-scale fabrication. These perovskites have high ionic conductivity, whereby charge carrier transport is efficient for energy harvesting applications, and tunable optical characteristics for tailoring light absorption efficiency, a key factor in improving the efficiency of solar panels. Thus, metal iodide perovskites are identified as one of the top materials for future solar devices with further work dedicated to the enhancement of perovskite solar cells stability and progress towards big-scale manufacturing [14,25].

In batteries, the metal iodides are also being studied for use as solid electrolytes, because of their high ionic conductivity. Some common metal iodide salts include lithium iodide (LiI) and Sodium iodide (NaI), which are incorporated in solid-state batteries as an improvement of the use of liquid electrolytes due to the safety and stability offered in the application. These solid electrolytes also allow for overcoming several problems of lithium-ion batteries, including leakage, corrosion, and flammability. Furthermore, the solid-state electrolytes based on metal iodide show high ionic conductivity that is higher than 10 µs/cm allowing for a higher rate capability which increases the rate of charge and discharge of batteries [26]. Their application in next-generation energy storage materials is already under investigation for practical use in solid-state batteries and supercapacitors promising a new generation of batteries that may boast high energy densities, long cycle life, and improved operational safety [27].

Metal iodide nanomaterials have many uses in energy devices because of their properties such as high ionic conductivity, thermal stability, and good optoelectronic properties shown in **Figure 5**. These materials are comprehensively used in solar cells, especially in perovskite, as a solar material for in-v solar technologies; and energy conversion efficiency. They also demonstrate their importance in batteries by either being the solid electrolyte or the cathode in new-generation lithium-ion and sodium-ion systems. Moreover, metal iodide nanomaterials help to increase the efficiency of fuel cells and ion transport depending on the conditions. These components when incorporated into supercapacitors enhance the capacity of charge storage and in LED, they are crucial in developing energy-efficient illumination. All these applications support the recognition of their importance for the development of new-generation energy solutions.

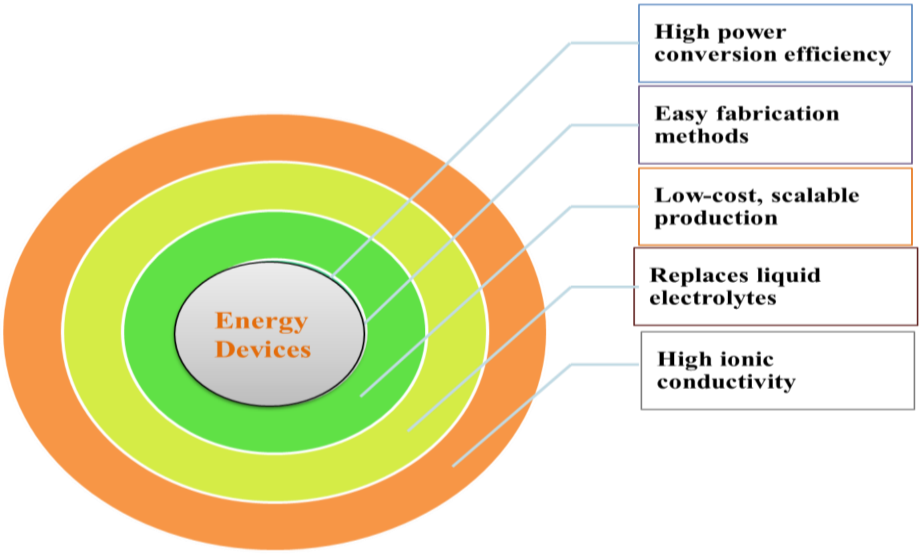

Figure 5. Some applications of metal iodide nanomaterials in energy devices.

2.4. Optoelectronics

Metal iodides are of great essence in optoelectronics because they exhibit variable optical characteristics that enhance light absorption and emission. For example, in light-emitting diodes (LEDs), metal iodides are intermediates that favor the conversion of electrical energy to light. One key advantage of metal iodides is the great control possible in the tunability of bandgap to obtain the desired emission wavelength, from [28] displays to communication systems. Besides, metal iodides play important roles in designing photodetectors that are relevant in areas such as imaging, sensing, telecommunications, and other applications. Catchability and stability, and the fact that the metal iodides are photosensitive, and can be easily precipitated have placed them among the promising materials for the new generation optoelectronic components. For example, infrared and ultraviolet photodetectors, such as AgI metal iodides also provide the best performance owing to their broad absorption spectra [29].

The electrical and optical properties of metal iodides also render this compound ideal for inclusion into other optoelectronic devices such as sunlight-catching cells, lasers, and photoelectric sensors. One of the features differentiating these materials is their ability to resonate to the various wavelengths of light which is the major reason why they will continue to be used across numerous industries including consumer electronics, environment monitoring, and even in medical fields [30]. Given the increasing demand for more energy-efficient and higher-performing optoelectronic devices, metal iodides are predicted to be the essential building block in satisfying the requirements of modern technologies within this segment [31].

Metal iodide nanomaterials have taken the optoelectronics world by storm with their ability to revolutionize new-age device-making by enhancing the performance and efficiency of the devices. Thus, they have been widely used in light-emitting diodes (LEDs), due to their high brightness, tunable wavelengths, and better energy efficiency. In photodetectors, they improve the efficiency by which light is collected and captured and the sensitivity which is important for high-speed communications and imaging devices. Metal iodides are also at the forefront of lasers with stable and coherent light sources for health, productivity, and communication. Furthermore, their incorporation into displays offers possibilities for the development of rich, high-resolution, and flexible screens in contemporary electronics. Combining scalable data with high performance, metal iodides are opening the door to efficient future solutions to optoelectronics, some of which are listed below in **Figure 6**.

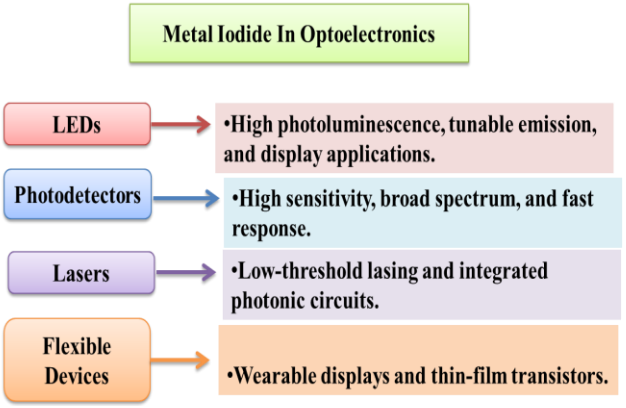

Figure 6. Application of metal iodide in optoelectronics.

2.5. Sensing technologies

There is much interest in metal iodides in the field of sensing solutions, especially for gases, ions as well as biomolecules. Metal iodides possess distinct characteristics including high ionic mobility and chemical stability, and due to these two noble characteristics, metal iodides are ideal for use in chemical and biological sensors [32]. For instance, metal iodides can be incorporated into electrochemical sensors for measuring certain ions or gases or responding selectively to CO_2, NH_3, or NO_2. The flexible nature of metal iodides makes them suitable for use within optical sensors, whereby any changes in the absorption or emission of light can be measured to determine the presence of different materials [33]. Due to this flexibility, metal iodides are especially sought after for uses in environmental sensing, clinical detection, and even for industrial uses [34].

Nanoscale metal iodide has recently become the subject of great interest due to its potential applications in sensing systems because of its ability to respond quickly, selectively, and electronically. These materials are widely employed in chemical sensors owing to their high electrical conductivity and surface activity that allows analyzing oxygen, nitrogen dioxide, and ammonia, for example. Metal iodides are involved in the analysis of biomolecules and, due to this ability, biosensors are used in medicine for the detection of glucose, DNA, and proteins. Moreover, they find use in the optical sensors for exploiting their ability of photoluminescence, which offers precise and quick response to light or alteration in the environment. They assert the potential of MI-based materials in the development of state-of-the-art sensing systems for environmental, health, and industrial monitoring, some of which are listed in **Figure 7**.

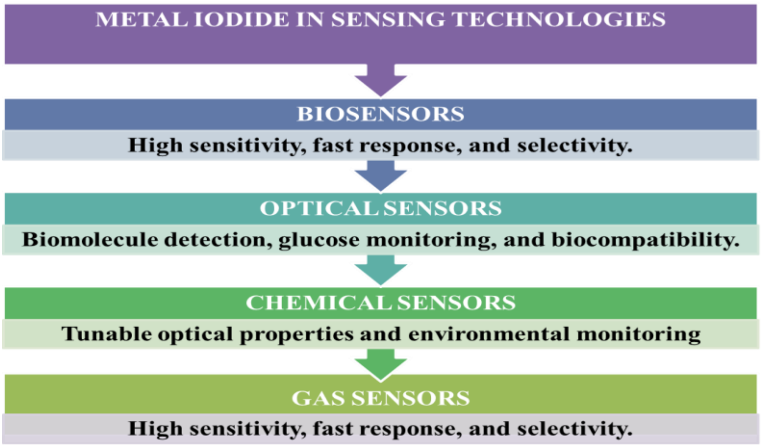

Figure 7. Application of metal iodide in sensing technologies.

Convenient and rapid methods based on metal iodide sensors were designed for the identification of biomolecules, glucose, DNA, pathogens, etc. The selective control of size and properties of metal iodides means that it is possible to engineer the affinity between the sensor and certain biomolecules which is important in point-of-care diagnostic applications [35]. Another advantage of the selected metal iodides is that they are relatively stable under different working conditions thus the sensors can work for a long time hence suitability for practical use. The development of higher demand for precise, transportable, and non-lethal sensing systems will be defined by the new use and incorporation of Metal iodides into these apps in the areas of human health and environmental control [36].

3. Challenges and future directions

The prospects for using metal iodide-based materials in devices appear solid yet the path to full practical implementation requires resolution of various vital technical obstacles. Environmental stability issues represent the primary technical challenge to adopting metal iodides in practical applications. The chemical decomposition of multiple metal iodide compounds begins immediately after they come into contact with moisture and experience both oxygen exposure and light exposure especially when lead compounds form their base. Device longevity together with operational performance decreases when targeted devices are exposed to exterior usage conditions or need strong reliability guarantees [37]. A variety of solutions are currently studied by researchers to enhance resistivity in metal iodide-based materials. Protective layers composed of metal oxides polymers and hydrophobic act as blocking elements which guard metal iodides against water and oxygen to increase operational timespan. The combination of dopants along with environmental-friendly elements in alloyed form stabilizes materials against environmental degradation. Switching lead substances with tin or bismuth produces material enhancement. The creation of nanostructured core-shell nanoparticles and layered heterostructures provides two layers of protection against destructive agents and improves mechanical strength and provides chemical stability. Thin protective layers made from graphene materials and atomic layer deposition (ALD)-grown oxides form exceptional barriers to block oxygen and moisture from entering the system.

Producing top-quality metal iodide films and nanomaterials encounters crucial challenges during the process of creating large-scale uniform products at cost-effective levels [32]. Current research involves multiple optimization methods for fabrication to address this manufacturing difficulty. The production of uniform metal iodide films on a large scale becomes feasible through continuous roll-to-roll processing since it enables creation of consistent large areas alongside high-quality devices. Flexible electronics together with extensive area solutions benefit from low-cost solution processing methods through spin coating and dip coating and inkjet printing for scalable fabrication. The film thickness control along with compositional accuracy can be achieved through vapor deposition methods which include both chemical vapor deposition (CVD) and physical vapor deposition (PVD).

When metal iodides are used for electronic applications, their environmental safety becomes challenging due to lead-containing substances that affect stability and scalability. Lead’s dangerous nature poses critical challenges for waste management operations because it puts the environment at severe risk [38]. Tin-based and bismuth-based and antimony-based iodides stand as research-based material alternatives for electronic applications because they match optoelectronic properties while reducing environmental harm during application. The production process becomes environmentally beneficial by incorporating environmentally friendly solvents and reducing agents with alternative synthesis techniques. Waste device material recovery through solvent extraction methods together with mechanical recycling and thermal recovery allows researchers to minimize environmental hazards along with lower waste output. Achieving sustainable material development requires combining environmental regulations with lifecycle assessment testing to make the process possible.

Research by multiple fields of science stands as a fundamental requirement to convert metal iodide-based materials suitable for future applications while addressing their existing obstacles. The modern materials will transition from experimental materials to practical components in healthcare systems and aerospace technology and renewable energy generation when properly scaled manufacturing takes place alongside environmental improvement efforts and stability enhancements [39,40].

4. Conclusion

Due to the specific properties of metal iodide-based materials, they play a major role in the advancement of micro and macro techniques making a notable contribution to many fields. Because of their high ionic conductivity tunable optical properties and high thermal stability, researchers have employed them in energy devices, Optoelectronics, and sensing devices proving their applicability. These materials are further expected to assume even a larger role in the design of newer devices as research goes on, in areas such as renewable energy, health care, and communication. Nevertheless, the future of metal iodides depends on ongoing research and development improvements in material synthesis, integrating these materials into devices, and scaling up their production. In addition, care for environmental issues for instance through the use of environmentally friendly processing and disposal will form part of their sustainable use. The metal iodides will most undoubtedly be a significant component in the future of numerous present-day technologies as James has fully focused on overcoming all the challenges noting that efficiency with a characteristic of environmental friendliness of a material is the key focus.

Conflict of interest: The authors declare no conflict of interest.

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