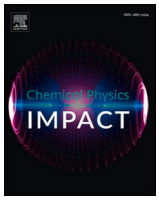
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Full Length Article

Lead-free halide double perovskites for sustainable environmental applications

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ABSTRACT

The development of renewable energy sources has become a crucial objective in today's world due to increasing environmental concerns and the depletion of fossil fuels. Solar energy has emerged as a promising alternative. In recent years, there has been a significant focus on perovskite solar cells due to their remarkable power conversion efficiencies and their ability to be produced in a cost-effective manner. These cells have attracted considerable attention from researchers and industry professionals alike. However, traditional perovskite materials often contain toxic lead, raising concerns about their environmental impact and long-term sustainability. This article highlights the environmental concerns associated with lead-based perovskite materials and explores the advantages, challenges, and potential of lead-free halide double perovskites as sustainable alternatives for achieving an enlightening and sustainable future in the field of photovoltaics. Lead-free halide perovskites have been an area of active research in the field of nanotechnology and material science due to their potential for various applications. We provide an overview of perovskite solar cells as a promising technology, discussing their material properties and device performance. Furthermore, we present a comparative analysis between lead-based and lead-free perovskites, emphasizing the challenges and future perspectives associated with the development and implementation of lead-free alternatives. Through this analysis, we aim to shed light on the potential of lead-free halide double perovskites and inspire further research in the quest for environmentally friendly materials for solar energy applications.

1. Introduction

1.1. Solar energy and the need for sustainable photovoltaics

In recent years, the rapid advancement of renewable energy technologies has brought solar energy to the forefront as a viable and sustainable alternative to traditional fossil fuels. Solar photovoltaics (PV) have emerged as a promising technology for harnessing solar energy and converting it into electricity. Lead-based halide perovskites have garnered considerable interest among various photovoltaic (PV) materials, primarily because of their exceptional performance in converting sunlight into electricity. Sustainable alternatives are required because these materials contain hazardous lead, which raises issues with regard to the environment and public health. Lead-free halide perovskites exhibit tremendous promise in diverse nanotechnological applications. Characterized by a distinct crystal structure, these materials possess compelling electronic, optical, and photovoltaic properties, rendering them highly attractive for employment in the field of nanotechnology [1].

Lead-free halide double perovskites have surfaced as a promising alternative to address the limitations of lead-based perovskite solar cells. These materials showcase comparable favorable optoelectronic characteristics to their lead-based counterparts but without the presence of toxic heavy metals. Consequently, they present a more ecologically sound and sustainable option for photovoltaic applications [2,3].

One of the key advantages of lead-free halide double perovskites is their abundance in the earth's crust, as they comprise earth-abundant elements such as tin, antimony, and bismuth. This addresses concerns

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regarding the scarcity and geopolitical issues associated with lead and other rare elements used in lead-based perovskites. The use of abundant and non-toxic materials ensures a more sustainable production and disposal cycle for solar panels, reducing the environmental impact [4].

In addition, halide double perovskites without lead demonstrate exceptional optoelectronic characteristics [5], such as significant light absorption, prolonged carrier lifetimes, and efficient charge transport. This makes them highly efficient in converting sunlight into electricity. Researchers have made significant progress in improving the power conversion efficiencies of lead-free perovskite solar cells, approaching the levels achieved by their lead-based counterparts. Lead-free halide perovskites face efficiency challenges due to limited light absorption in the visible to near-infrared spectrum. Liu et al. [6], in their study, reported the introduction of vanadium (V) with low-lying ground and excited-state energy levels to create two types of stable, lead-free V-based perovskite colloidal nanocrystals (Cs_2NaVCl_6 and Cs_3V2Cl_9). These nanocrystals exhibit strong light absorption spanning from the ultraviolet to the near-infrared region.

However, challenges still exist in the development of lead-free halide double perovskites for commercial-scale solar applications. Stability issues, such as moisture and thermal instability, remain a significant hurdle that needs to be addressed. Researchers are actively exploring various strategies, including interface engineering, compositional tuning, and device encapsulation techniques, to enhance the stability and reliability of lead-free perovskite solar cells [7,8]. While addressing these challenges, it is crucial to recognize the broader potential of lead-free halide perovskites in revolutionizing solar energy.

Solar energy is a promising avenue for sustainable power generation, and lead-free halide double perovskites offer a greener alternative to traditional lead-based perovskite materials. These materials possess excellent optoelectronic properties, while being composed of abundant and non-toxic elements. With further advancements in stability and efficiency, lead-free halide double perovskite solar cells have the potential to play a vital role in the transition towards a sustainable and clean energy future [9] .

1.2. Perovskite solar cells: an encouraging technology with great potential

Perovskite solar cells have become increasingly prominent in recent years as they offer a combination of high efficiency and potential for low-cost photovoltaic applications, attracting significant attention. Conventional perovskite solar cells usually consist of halide perovskite materials containing lead, like methylammonium lead iodide ($CH_3NH_3PbI_3$). Nonetheless, the inclusion of lead in these substances gives rise to apprehensions about their toxicity and potential environmental repercussions [10].

To address these concerns, researchers have been actively exploring lead-free alternatives, and one promising class of materials is lead-free halide double perovskites. These materials have a crystal structure similar to the conventional perovskite materials but contain two different cations instead of one. By substituting lead (Pb) with less toxic elements, such as tin (Sn) or bismuth (Bi), researchers aim to develop environmentally friendly and sustainable perovskite solar cell technologies [11]. Lead-free halide double perovskites offer several advantages. First, they can achieve high power conversion efficiencies comparable to lead-based perovskites. Second, they exhibit improved stability and strength, addressing one of the tasks associated with traditional perovskite solar cells. Third, these materials have tunable optoelectronic properties, allowing for a wider range of applications [12].

Researchers have made significant progress in developing Pb-free halide double perovskite solar cells [13]. By carefully engineering the composition and crystal structure of these materials, they have achieved power conversion efficiencies exceeding 10 %. Additionally, stability tests have shown promising results, with some materials demonstrating improved resistance to moisture, heat, and light exposure. However, it's important to note that lead-free perovskite solar cells are still an active area of research, and there are challenges that need to be addressed. One challenge is reducing the defect density within the material, as defects can lead to reduced efficiency and stability. Another significant challenge revolves around achieving long-term stability under real-world operating conditions, as perovskite materials are susceptible to degradation over time, primarily due to exposure to environmental factors. So, lead-free halide double perovskites hold great promise as an alternative to lead-based perovskites in solar cell technology. Continuous research and development endeavors are directed towards enhancing the efficiency, stability, and scalability of these solar cells, with the goal of establishing them as a feasible choice for future photovoltaic applications [14,15].

2. Advantages and challenges of perovskite solar cells

Recent years have seen a lot of interest in perovskite solar cells because of their excellent efficiency and their potential for cost-effective manufacturing. Here are some advantages and challenges associated with perovskite solar cells:

Advantages:

Great Efficiency: Perovskite solar cells have made remarkable improvements in power conversion efficiency, surpassing the capabilities of traditional silicon solar cells. These innovative cells have demonstrated the ability to convert a higher percentage of sunlight into electricity, thereby offering the potential for increased energy generation [16].

Low-Cost Production: Perovskite solar cells can be manufactured using inexpensive materials and relatively simple fabrication processes, which can significantly reduce production costs compared to silicon-based solar cells. This makes perovskite solar cells attractive for large-scale deployment.

Versatility: Perovskite materials offer a wide range of composition possibilities, enabling the tuning of their electronic and optical properties. This versatility allows for the development of perovskite solar cells with different configurations and performance characteristics, making them suitable for various applications.

Lightweight and Flexibility: Perovskite solar cells possess the remarkable characteristic of being thin and flexible, enabling their seamless integration into diverse surfaces and adaptable form factors. This feature opens up possibilities for new applications, such as solar cells integrated into building facades, curved surfaces, or wearable devices [17]

Challenges:

Stability: Perovskite materials exhibit sensitivity to moisture, oxygen, and heat, leading to the degradation of their performance over time. Ensuring long-term stability and durability poses a significant challenge for perovskite solar cells. Scientists are currently engaged in ongoing research aimed at enhancing the stability of these materials. This involves exploring various encapsulation techniques and refining device designs to improve their overall resilience.

Scalability: While perovskite solar cells have shown promising results at the laboratory scale, scaling up the production process to commercial levels is challenging. Issues such as reproducibility, uniformity, and manufacturing yield need to be addressed to achieve large-scale production with consistent performance.

Performance in Real-World Conditions: The efficiency of perovskite solar cells is often measured under ideal laboratory conditions, which may not fully represent real-world scenarios. Factors like temperature variations, low light conditions, and partial shading can affect their performance. Developing strategies to improve the stability and efficiency of perovskite solar cells under diverse operating conditions is an ongoing research area.

Perovskite solar cells have enormous potential to make a significant impact in the realm of renewable energy, despite the obstacles they currently face. There are ongoing endeavors in research and development that strive to surmount these challenges and ultimately establish

perovskite solar cells as a commercially feasible and sustainable technology within the energy sector [18]

Toxicity: Researchers are actively investigating alternative materials and environmentally friendly manufacturing processes to address concerns regarding the environmental impact of certain perovskite materials that contain toxic elements like lead. The presence of these toxic elements raises apprehensions about their potential adverse effects during manufacturing, use, and disposal stages.

By exploring substitutes for these toxic lead containing materials and developing eco-friendly manufacturing techniques, researchers aim to minimize or eliminate the environmental concerns associated with perovskite technology [16,17].

3. The quest for lead-free alternatives

Lead-free alternatives refers to the ongoing efforts to find and develop substitutes for lead, particularly in various industrial and consumer applications. Lead has been widely used in various industries due to its desirable properties, such as high density, malleability, and resistance to corrosion. However, it is also a toxic substance that poses significant health and environmental risks.

3.1. Environmental impact of lead in perovskites

Lead in perovskite materials is a subject of concern and ongoing research due to its potential negative impacts on ecosystems and human health. Perovskite materials, which are used in solar cells and other electronic devices, have gained attention as a promising alternative to conventional silicon-based technology. Nonetheless, the existence of lead in these substances has raised worries about the possible emission of harmful substances into the environment. Perovskite solar cells have drawn a lot of interest in recent years as a promising technology because of their astounding efficiency and promise for low-cost manufacture. But a significant issue with most perovskite solar cells is the presence of lead, a hazardous heavy metal. Lead extraction and processing may have negative effects on the environment and human health. Ecosystems can become contaminated as a result of lead mining, endangering human health and contaminating soil and water. Additionally, the procedures used to make lead-based perovskite solar cells may leak lead compounds or particles into the air, adding to the pollution [19].

One of the primary concerns associated with lead in perovskites is its potential for leaching. Perovskite solar cells are typically composed of layers that include lead-based materials. If these cells are damaged or disposed of improperly, there is a risk of lead leaching into the surrounding soil and water. This could result in soil and water contamination, posing risks to wildlife, aquatic organisms, and human populations.

Furthermore, the production and recycling processes of perovskite materials also pose environmental challenges. Lead is a key component in the synthesis of perovskite films, and its extraction and processing can lead to the release of harmful pollutants and emissions. Inadequate waste management practices during the manufacturing and disposal of perovskite-based devices can result in the release of lead-containing waste into the environment, further exacerbating the environmental risks associated with this material. Another concern is the potential for lead exposure to humans. Lead is widely recognized as a neurotoxin that can have harmful effects on human health, especially in children and pregnant women. Accidental ingestion or inhalation of lead-containing particles, either from the production or disposal of perovskite devices, can result in lead poisoning, which can lead to developmental delays, cognitive impairments, and other serious health issues.

To address these concerns, researchers are actively exploring lead-free alternatives for perovskite solar cells. These alternative materials aim to maintain the high efficiency and low-cost characteristics of perovskites while eliminating the use of toxic heavy metals like lead. The development of lead-free perovskites could significantly reduce the environmental impact associated with their production, use, and eventual disposal [20].

Efforts are being made to address these environmental concerns associated with lead in perovskites. Scientists are currently engaged in active research to find alternative materials that can substitute lead in perovskite solar cells, seeking to develop more environmentally friendly and sustainable options. Additionally, improved waste management practices and regulations are necessary to ensure the safe handling, recycling, and disposal of perovskite-based devices to minimize the risk of lead contamination [21]. While perovskite materials hold promise for clean energy applications, the presence of lead in these compounds raises significant environmental concerns. The potential for lead leaching, the environmental impact of manufacturing and disposal processes, and the risk of lead exposure to humans highlight the need for stringent regulations, responsible waste management, and ongoing research into safer alternatives. By addressing these concerns, the potential environmental benefits of perovskite technology can be realized while minimizing its negative impacts on ecosystems and human health.

3.2. Exploration of lead-free halide double perovskites

Lead halide perovskites, such as methylammonium lead iodide (MAPbI3), have shown exceptional performance in solar cells, light-emitting diodes, and other electronic devices. However, the toxicity and instability of lead have raised concerns about their widespread use. This has spurred research into finding lead-free alternatives, leading to the discovery and exploration of lead-free halide double perovskites [15, 22].

Lead-Free Halide Double Perovskites have garnered considerable interest in recent years as promising substitutes for lead-based perovskites across a range of optoelectronic applications [23]. These materials exhibit similar structural properties to lead halide perovskites but are composed of non-toxic elements, making them more environmentally friendly [22].

Halide double perovskites are a class of materials that belong to the perovskite family. Perovskites are compounds with a crystal structure characterized by a cubic arrangement of atoms. In halide double perovskites, two different halide ions (such as chloride, bromide, or iodide) are combined with two different metal cations to form the crystal lattice. These are characterized by a general chemical formula of A2BB'X6 [24]. In this formula, A and B represent cations, while X represents a halide anion shown in Fig. 1. Halide double perovskites have attracted significant attention in the field of optoelectronics and photovoltaics [23] due to their unique properties. They exhibit a variety of desirable properties, including tunable bandgaps, high carrier mobilities, long carrier lifetimes, and excellent optical absorption [25,26].

One of the most well-known lead free halide double perovskite materials is Cs2AgBiBr6, which has been extensively studied for its potential applications in solar cells. It has a direct bandgap suitable for absorbing sunlight and has shown promising photovoltaic performance [27].

Other lead free halide double perovskites, like Cs2AgInCl6, Cs2AgSbCl6, Cs2AgBiCl6, Cs2LiGaBr6 and Cs2NaGaBr6 have also been investigated for their optoelectronic properties and sustainable energy applications [28]. These materials exhibit different bandgaps, allowing for the possibility of bandgap engineering to optimize their performance for specific applications. The synthesis of halide double perovskites typically involves solution-based methods, such as chemical precipitation or solvent evaporation. By controlling the reaction conditions and precursor ratios, it is possible to tune the composition and properties of the resulting material. However, halide double perovskites also face some challenges. One significant issue is their stability, especially in the presence of moisture and heat. These materials can degrade over time, leading to a decrease in performance and reliability.

Researchers are actively working to enhance the stability of lead free halide double perovskites through various strategies, such as interface

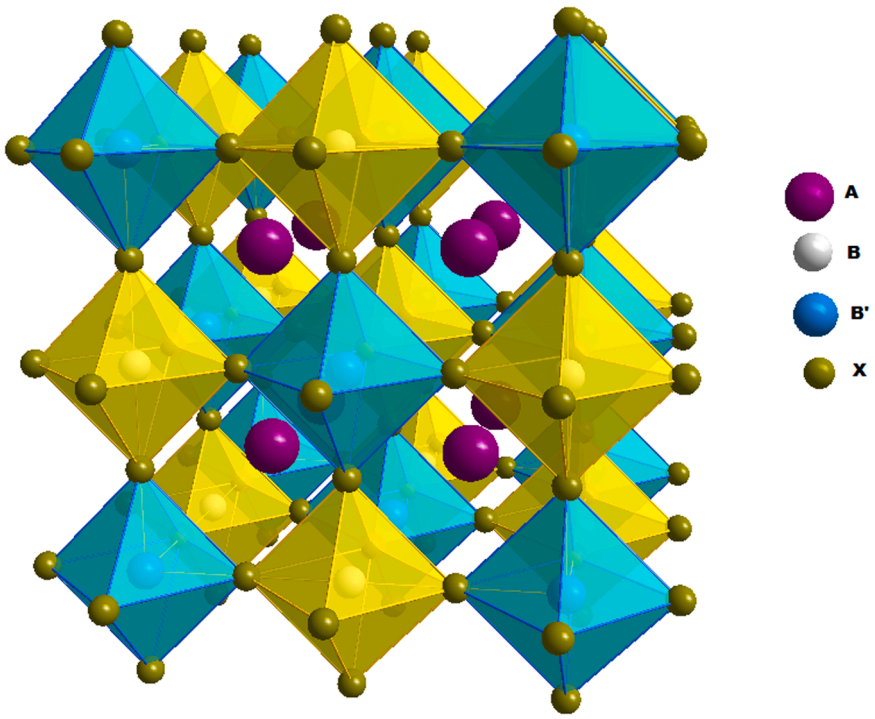


Fig. 1. Crystal Structure of Halide Double Perovskites.

engineering, encapsulation techniques, and compositional modifications [19,29]. The main challenge in lead-free variants lies in identifying suitable cations that can replicate both the structural and optoelectronic properties exhibited by lead-based perovskites [30]. To tackle this issue, researchers have investigated the utilization of various elements like tin (Sn), bismuth (Bi), antimony (Sb), and several others as potential replacements for lead [21,31].

Tin-based double perovskites are one of the potential lead-free double perovskite materials, commonly referred to as tin halide perovskites or tin-based hybrid perovskites. For example, the compound $Cs_2AgBiBr_6$, $Cs_2AgSbBr_6$ [32,33], Cs_2MGaBr_6 (M = Li, Na) has been explored as a lead-free alternative for solar cells and sustainable energy applications [28,34]. These materials exhibit decent optoelectronic properties, including suitable bandgaps for solar absorption and efficient charge carrier transport [34].

However, lead-free halide double perovskites face challenges in terms of stability and performance compared to their lead-based counterparts. The tin-based perovskites, in particular, have lower stability and tend to degrade more rapidly in the presence of moisture and oxygen. Researchers are actively working to improve their stability and efficiency through various strategies such as compositional engineering, surface passivation, and encapsulation techniques.

There is currently research being done on lead-free halide double perovskites, and scientists are continuously discovering new materials and improving their properties. These materials hold great promise for sustainable and environmentally friendly optoelectronic applications [35], and further advancements in their development may lead to their commercialization in the future [36].

3.3. Strategies for achieving lead-free halide double perovskites

Several strategies have emerged to develop lead-free alternatives while maintaining the desirable properties of perovskite materials.

One strategy involves exploring alternative cations to replace lead in the perovskite structure. Researchers have investigated various metal cations such as tin (Sn), germanium (Ge), bismuth (Bi), and antimony (Sb) as potential substitutes. These cations possess similar chemical characteristics to lead and can form stable double perovskite structures. By carefully selecting and optimizing the composition of these alternative cations, it is possible to achieve lead-free perovskite materials with comparable performance [37].

Another approach is to introduce hybrid organic-inorganic components into the perovskite structure [38]. By incorporating organic molecules into the crystal lattice, the stability and optoelectronic properties of the perovskite can be improved. For instance, the use of large organic cations such as guanidinium or phenethylammonium can help stabilize the perovskite structure and enhance its environmental stability [39].

Furthermore, researchers are exploring different anions to replace the halide ions in lead-based perovskites. Some promising alternatives include carbonate, azide, and thiocyanate ions. These anions can be incorporated into the perovskite lattice, altering its electronic structure and properties. In addition to compositional engineering, surface passivation techniques can be employed to enhance the stability and performance of lead-free halide double perovskites. Surface treatments with specific chemicals or coatings can reduce surface defects, suppress non-radiative recombination, and improve charge transport properties. This approach plays a crucial role in achieving high-efficiency and stable lead-free perovskite devices. Overall, a combination of exploring alternative cations, introducing organic-inorganic hybrids, utilizing different anions, and employing surface passivation techniques are key strategies in the pursuit of lead-free halide double perovskites. These strategies aim to develop environmentally friendly perovskite materials without compromising their optoelectronic properties, ultimately enabling their broader application in various optoelectronic devices [37].

4. Material properties and device performance

4.1. Optoelectronic properties of lead-free double perovskites

Lead-free double perovskites have emerged as a promising group of materials that have gained considerable attention in the realm of optoelectronics [40]. These materials possess fascinating optoelectronic characteristics, presenting them as potential substitutes for conventional lead-based perovskites, which have raised concerns due to their toxicity.

A key feature of lead-free double perovskites is their adjustable bandgap, which refers to the energy difference between the valence band and the conduction band and dictates the wavelengths of light the material can absorb and emit. The versatility to tune their bandgap over a wide range makes lead-free double perovskites suitable for diverse optoelectronic applications. This tunability is achieved by manipulating the material's chemical composition and structure, allowing researchers to tailor its properties to specific requirements [41].

Additionally, lead-free double perovskites exhibit efficient light absorption and charge carrier transport properties. These materials are capable of efficiently absorbing photons across a broad range of the electromagnetic spectrum, including visible and near-infrared light. The absorbed photons generate excited states, or electron-hole pairs, which can be effectively separated and contribute to the generation of electrical current. This efficient charge carrier generation and transport is crucial for the development of high-performance optoelectronic devices, such as solar cells and photodetectors. Moreover, lead-free double perovskites show excellent photoluminescence properties. When excited by light, these materials emit photons with specific energies, which depend on their bandgap. By carefully engineering the composition and structure of the perovskite, researchers can precisely control the emission wavelength, enabling the production of perovskite-based light-emitting devices with a wide color gamut. Furthermore, lead-free double perovskites exhibit good stability against moisture [42], heat, and light exposure, addressing one of the major challenges associated with lead-based perovskites. This stability is crucial for the long-term performance and reliability of optoelectronic devices, as it ensures that the material can withstand environmental conditions without degradation. So, lead-free double perovskites possess a range of desirable optoelectronic properties, including tunable bandgap, efficient light absorption and charge carrier transport, excellent photoluminescence, and improved stability [43]. These properties make them attractive candidates for various optoelectronic applications, such as solar cells, light-emitting diodes (LEDs) [44], photodetectors, and sensors as shown in Fig. 2. Continued research and development in this field hold the potential to unlock the full capabilities of lead-free double perovskites and pave the way for sustainable and high-performance optoelectronic technologies [41,45].

4.2. Stability and long-term performance

One crucial aspect in assessing the suitability of these Lead-free double perovskites materials is their stability and long-term performance. Stability is a fundamental requirement for any material used in practical applications. Lead-free double perovskites exhibit enhanced stability compared to their lead-based counterparts, which are known to be prone to degradation under environmental conditions such as moisture, heat, and light exposure. This increased stability is mainly attributed to the absence of toxic lead ions, which are highly reactive and susceptible to oxidation and other degradation processes.

The long-term performance of lead-free double perovskites is another critical factor in evaluating their viability. Extensive research efforts have focused on improving the intrinsic stability of these materials by optimizing their crystal structures, composition, and surface passivation techniques. These advancements have led to remarkable improvements in the device performance and long-term stability of lead-free double perovskite-based solar cells and LEDs.

Moreover, the introduction of alternative cations and anions in the perovskite structure has shown promising results in enhancing stability and reducing the impact of defects and structural instabilities. For example, by incorporating cesium (Cs) or rubidium (Rb) cations, researchers have achieved improved moisture stability and suppressed ion migration, leading to enhanced device lifetimes.

In addition to stability and long-term performance, lead-free double perovskites also offer advantages such as abundant and low-cost raw materials, tunable bandgaps, and favorable optoelectronic properties. These characteristics make them attractive candidates for sustainable and envionmentally friendly optoelectronic devices [46].

Overall, the stability and long-term performance of lead-free double perovskites have been significantly improved through innovative material engineering and device optimization strategies. Ongoing research in this field aims to further enhance their stability, scalability, and commercial viability, paving the way for their widespread adoption in various optoelectronic applications.

4.3. Efficiency challenges and strategies for improvement

The main efficiency challenges faced by lead-free double perovskites is their relatively low power conversion efficiency (PCE) compared to

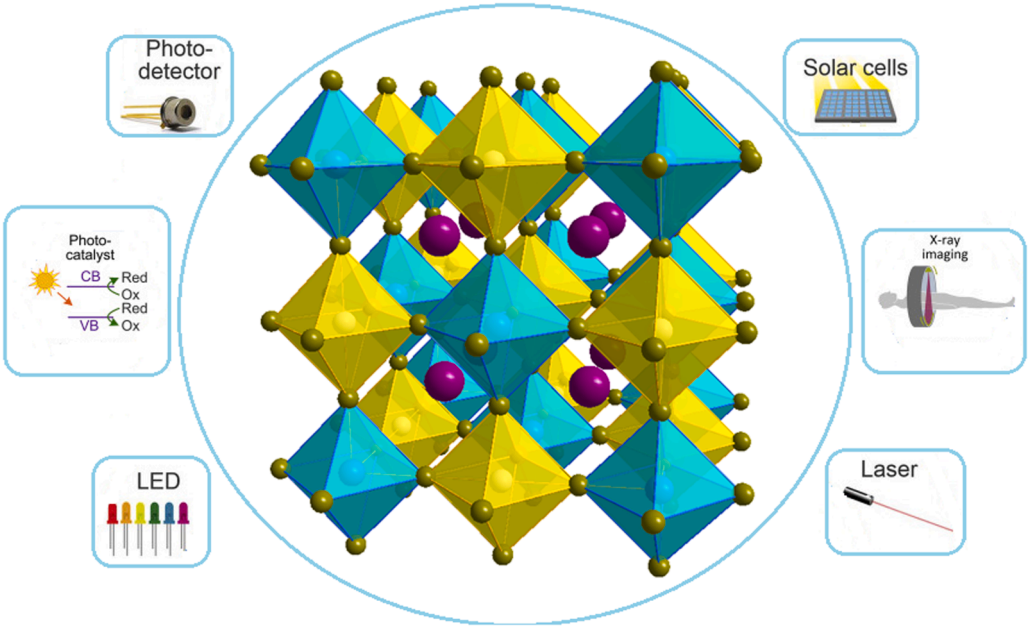


Fig. 2. Applications of Halide Double Perovskites.

lead-based counterparts. This is primarily due to their wider bandgaps, which limit their ability to absorb a broad range of solar spectrum. To address this challenge, researchers have been focusing on various strategies.

One strategy involves compositional engineering, where the chemical composition of the perovskite material is modified to enhance its light-absorbing properties. By incorporating different elements and adjusting their ratios, researchers aim to tailor the bandgap of the perovskite to better match the solar spectrum. This can be achieved by incorporating various elements such as tin, bismuth, antimony, and halides into the perovskite structure.

Another approach to improving efficiency is through interface engineering. The interfaces between different layers in the solar cell structure play a crucial role in charge transport and recombination processes. Optimizing the interface properties can help enhance charge collection efficiency and reduce energy losses. Strategies such as introducing interfacial layers, surface passivation, and improving the contact between the perovskite layer and the charge transport layers have shown promise in enhancing the overall device performance.

Furthermore, device architecture optimization is also being explored. This involves designing and engineering the overall structure of the solar cell to maximize light absorption, minimize charge recombination, and improve charge extraction. Strategies such as tandem cell configurations, nanostructured electrodes, and optimized device interfaces are being investigated to enhance the overall efficiency of lead-free double perovskite solar cells [18,36].

5. Comparative analysis of lead and lead-free perovskites

Perovskites, both lead and lead-free variants, have attracted considerable interest in solar cell research due to their outstanding photovoltaic properties. These materials, particularly lead-based perovskites, have demonstrated remarkable power conversion efficiencies (PCEs), fueling the potential to transform the solar energy industry. However, concerns have arisen regarding the toxicity and environmental impact associated with lead-based perovskites. Consequently, researchers have begun exploring lead-free alternatives in an effort to address these concerns. Let's compare lead and lead-free perovskites in detail:

Composition:

Lead Perovskites: The most commonly studied lead perovskite is methylammonium lead triiodide (CH3NH3PbI3). Other lead-based compositions include formamidinium lead triiodide (HC(NH2)2PbI3) and cesium lead triiodide (CsPbI3).

Lead-Free Perovskites: Lead-free perovskites typically consist of a combination of non-toxic elements such as tin (Sn), germanium (Ge), bismuth (Bi), or antimony (Sb). For example, tin-based perovskites, such as methylammonium tin iodide (CH3NH3SnI3), have been extensively studied as lead-free alternatives.

Optoelectronic Properties:

Lead Perovskites: Lead perovskites exhibit excellent optoelectronic properties, such as a high absorption coefficient, long charge carrier diffusion lengths, and high charge carrier mobilities. These properties contribute to their high photovoltaic performance.

Lead-Free Perovskites: Lead-free perovskites generally have lower absorption coefficients and shorter charge carrier diffusion lengths compared to lead perovskites. This results in lower PCEs for lead-free PSCs. However, continuous research and material engineering have shown promising improvements in the performance of lead-free alternatives .

Stability and Durability:

Lead Perovskites: Lead perovskites face significant challenges in terms of long-term stability and durability. Their performance tends to deteriorate over time due to their vulnerability to degradation when exposed to moisture, heat, and light. Efforts are being made to enhance their stability through encapsulation techniques and the use of protective layers.

Lead-Free Perovskites: Lead-free perovskites generally exhibit better stability compared to lead perovskites. They are less susceptible to moisture-induced degradation and have shown improved long-term stability under certain operating conditions. However, achieving comparable stability to lead perovskites remains a key area of research for lead-free alternatives.

Toxicity and Environmental Impact:

Lead Perovskites: Lead is a toxic heavy metal that poses environmental and health risks. The potential release of lead into the environment during the manufacturing, usage, and disposal of lead perovskite solar cells raises concerns. Proper handling, recycling, and disposal measures are necessary to mitigate these risks [47].

Lead-Free Perovskites: Lead-free perovskites offer a more environmentally friendly alternative, as they eliminate the use of toxic lead. This reduces the potential risks associated with toxicity and facilitates safer manufacturing processes. However, the environmental impact of lead-free alternatives should still be assessed for the full life cycle of the materials [22].

Lead perovskites have shown superior optoelectronic properties [48] and higher efficiencies in solar cell applications. However, the toxicity and environmental concerns associated with lead have stimulated research on lead-free alternatives. Lead-free perovskites, although currently lagging behind in performance, offer the advantage of reduced toxicity and improved environmental compatibility. Ongoing research aims to address the stability and efficiency challenges of lead-free perovskites to make them viable alternatives to lead perovskites in the future [49,50].

6. Applications of lead-free halide perovskites in nanotechnology

Lead-free halide perovskites, such as those based on tin (Sn), bismuth (Bi), or other metals, offer several advantages in nanotechnology applications

Quantum Dots: Lead-free perovskite quantum dots (nanoscale semiconductor particles) have been synthesized and studied for their potential use in nanotechnology, including applications in displays, sensors, and bioimaging.

Nanocatalysts: Lead-free perovskite nanomaterials have been investigated for their catalytic properties, making them potential candidates for various catalytic applications [51].

Nano-Optics and Nanophotonics: Lead-free perovskites have unique optical properties that make them suitable for nanophotonic and nano-optical devices, such as waveguides, nano-lasers, and nano-antennas.

Scientists are working to improve the stability, efficiency, and scalability of lead-free perovskite-based nanotechnologies. While they offer promising solutions for various applications, challenges related to material stability, toxicity, and device lifetime still need to be addressed to make them commercially viable and competitive with other existing technologies. Fig. 3 represent the traits of Lead halide perovskites and the consequences for the pursuit of lead-free halide perovskite alternatives.

6. Challenges and future perspectives

6.1. Scalability and manufacturing challenges of lead-free perovskites

Inspite of significant attention of Lead-free perovskites as a promising alternative to traditional lead-based perovskites in various applications, including solar cells and optoelectronic devices [52], their scalability and manufacturing challenges pose significant hurdles that need to be addressed for widespread commercialization .

One of the primary scalability challenges of lead-free perovskites lies in their complex and sensitive composition. Unlike lead-based

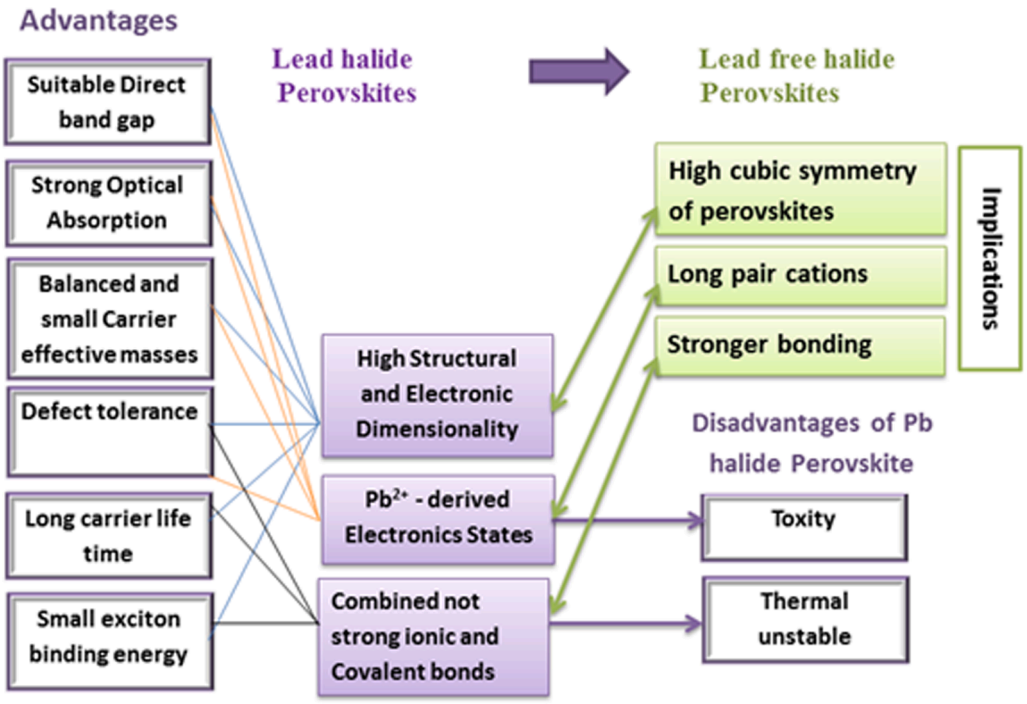


Fig. 3. Traits of Pb Halide Perovskites and Consequences for the pursuit of lead-free halide perovskite alternatives.

perovskites, which have a well-established and optimized fabrication process, lead-free perovskites often exhibit a broader compositional space, which makes it challenging to achieve consistent and reproducible properties. The precise stoichiometry and elemental composition of lead-free perovskites need to be controlled during manufacturing to obtain the desired properties, such as bandgap and stability. Achieving large-scale production with uniform quality becomes a significant challenge due to the inherent variability associated with the composition of lead-free perovskites.

Another critical aspect that affects scalability is the stability of lead-free perovskite materials. Many lead-free perovskites exhibit reduced stability compared to their lead-based counterparts. They are more prone to degradation due to moisture, heat, or light exposure. This instability hinders the long-term performance and reliability of devices based on lead-free perovskites. Developing robust manufacturing processes that can produce stable lead-free perovskite materials and devices is essential to ensure their scalability and commercial viability.

Furthermore, the manufacturing techniques used for lead-free perovskites often require precise control over the deposition and crystallization processes. Various methods such as solution processing, vapor deposition, and printing techniques have been explored for manufacturing lead-free perovskite films. However, achieving uniform film quality and controlling the grain size and orientation at large scales remain significant challenges. The manufacturing process must be optimized to ensure high throughput, cost-effectiveness, and reproducibility while maintaining the desired film properties.

Additionally, the integration of lead-free perovskites into existing device architectures poses compatibility challenges. Many lead-free perovskite materials have different electronic properties and energy level alignment compared to lead-based perovskites. This necessitates the development of new device designs and engineering strategies to ensure efficient charge extraction and transport within the devices. Achieving seamless integration of lead-free perovskites into existing manufacturing processes and device architectures requires extensive research and development efforts .

The scalability and manufacturing challenges of lead-free perovskites revolve around the complexity of their composition, the need for stability enhancement, control over manufacturing processes, and compatibility with existing device architectures. Overcoming these challenges requires interdisciplinary collaborations between materials scientists, device engineers, and manufacturing experts to develop robust and scalable fabrication techniques for lead-free perovskite-based devices. Addressing these challenges will be crucial for realizing the full potential of lead-free perovskites in various applications [36].

6.2. *Integration of lead-free perovskites in commercial solar technologies*

The integration of lead-free perovskites in commercial solar technologies has garnered significant attention and holds great potential for advancing the renewable energy sector.

One area where lead-free perovskites are being integrated is in the development of photovoltaic cells. These cells are an essential component of solar panels, responsible for converting sunlight into electricity. Traditional solar cells often rely on lead-based perovskites, which pose environmental and health risks. However, the emergence of lead-free perovskites offers a safer and more sustainable alternative. Researchers and engineers have been working towards optimizing the performance and steadiness of lead-free perovskite solar cells to meet the requirements of commercial applications. Remarkable advancements have been achieved in improving the efficiency of power conversion and durability of these solar cells [53], leading to their growing competitiveness in comparison to conventional solar technologies . The integration of lead-free perovskites is not limited to photovoltaic cells alone. They are also being explored in other solar technologies, such as solar water heaters and solar concentrators [54,55]. By incorporating lead-free perovskite materials into these systems, their overall efficiency and performance can be significantly improved, leading to higher energy yields and cost savings. Furthermore, the production and manufacturing processes for lead-free perovskite solar technologies are becoming more scalable and economically viable. This scalability is crucial for commercial deployment, as it allows for mass production and widespread adoption of lead-free perovskite-based solar devices [56].

6.3. Outlook for the future: advancements and opportunities

Lead-free perovskites are offering significant advancements and opportunities for the future. These new materials exhibit comparable optoelectronic properties, such as high efficiency and excellent light absorption, while addressing the environmental and health concerns associated with lead. One of the main advantages of lead-free perovskites is their potential for commercialization and widespread adoption. With increasing regulations and consumer demand for eco-friendly technologies, lead-free perovskites offer a compelling choice for a range of applications, encompassing solar cells, light-emitting diodes (LEDs), and photodetectors. This opens up new avenues for research, development, and market penetration, leading to a sustainable and cleaner energy future [57,58].

Moreover, lead-free perovskites offer opportunities for enhancing device stability and longevity. Lead-based perovskites often suffer from instability issues, such as moisture sensitivity and thermal degradation, which limit their practical applications. By exploring lead-free alternatives, researchers can overcome these challenges and develop more robust and reliable devices. This increased stability will not only improve the performance and durability of solar cells and other optoelectronic devices but also reduce maintenance and replacement costs, making them more economically viable. Furthermore, lead-free perovskites foster collaborations among scientists, engineers, and industries worldwide. The development and optimization of these materials require multidisciplinary approaches, involving material synthesis, device fabrication, and characterization techniques. As a result, research collaborations and knowledge exchange become crucial for advancing the field. The growing interest in lead-free perovskites has already sparked collaborations across academic and industrial sectors, leading to accelerated progress and innovation.

So, the outlook for lead-free perovskites is promising, with a plethora of advancements and opportunities on the horizon. These materials offer comparable optoelectronic properties to lead-based perovskites while addressing environmental concerns [59]. Their commercial viability, improved stability, and fostering of collaborations make lead-free perovskites a key player in the future of renewable energy and sustainable optoelectronics. Continued research and development in this field will undoubtedly unlock new breakthroughs and accelerate the transition towards a greener and cleaner future [46,56] .

7. Conclusions

In conclusion, the development and utilization of lead-free halide double perovskites hold great significance in the field of optoelectronics and solar energy. Their environmental friendliness, excellent optoelectronic properties, and improved thermal stability make them a viable and attractive alternative to lead-based perovskites. By harnessing their potential, researchers and engineers can contribute to the advancement of sustainable and efficient technologies while addressing the concerns associated with lead toxicity and environmental impact.

The future of lead-free halide double perovskites holds great promise. Continued research efforts will focus on overcoming stability challenges, developing novel synthesis methods, and optimizing device architectures. Collaboration between material scientists, device engineers, and industry partners is essential to bridge the gap between lab-scale research and commercialization

The objective of this article is to present a detailed and inclusive analysis of lead-free halide double perovskites as promising substitutes for conventional perovskite materials in the realm of solar cell applications. It covers the fundamentals of perovskite solar cells, the environmental concerns associated with lead, and the exploration of lead-free alternatives. The synthesis and characterization techniques for lead-free double perovskites are discussed, along with the material properties and device performance. The environmental impact and sustainability aspects are addressed, considering toxicity, life cycle assessment, and end-of-life management. Furthermore, challenges and future perspectives in the field are presented to highlight the current state and the potential advancements that can shape a more enlightening and sustainable future for photovoltaics.

CRediT authorship contribution statement

Ruby Jindal: Writing – original draft, Project administration, Methodology, Formal analysis, Conceptualization. **Archana Tripathi:** Methodology, Formal analysis, Data curation, Conceptualization. **Chandra Mohan:** Formal analysis, Data curation, Conceptualization. **Alka Garg:** Resources, Investigation, Formal analysis, Conceptualization. **Rajender S. Varma:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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