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Perovskite Solar Cell Materials Development for Enhanced Efficiency and Stability

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Abstract

Solar photovoltaic (PV) technology has advanced due to climate change and energy security concerns. PV technologies like perovskite solar cells (PSCs) have advanced to over 25% power conversion efficiency. This analysis examines PSC evolution, concentrating on efficiency, stability, and cost-effective manufacture. Special materials, ABX3, where A and B are cations and X is an anion, are used to make PSCs. Their high light absorption coefficients, long carrier lifetimes, and programmable bandgaps make them intriguing photovoltaic options for the future generation. PSCs have advanced PCE, but long-term stability and scalable manufacture remain issues. Moisture, oxygen, UV radiation, and heat degrade PSCs. Laborious batch-based fabrication technologies reduce cost-effectiveness. This review addresses efficiency and stability techniques to overcome these issues. Doping, lattice strain relaxation, and encapsulation are key PSC performance enhancements. Finding lead-free perovskite compositions and different crystal structures lead to more stable materials. Roll-to-roll processing and spray coating are scalable and cost-effective fabrication processes with commercial potential. This article helps address these problems, but further research is needed to fully understand the intricacies of building scalable and cost-effective PSC fabrication processes. PSC efficiency, stability, and fabrication improvements offer hope for perovskite solar cell inclusion into renewable energy systems and a sustainable energy future.

Keywords: Perovskite Solar Cells, Efficiency, Stability, Scalability, Fabrication methods

INTRODUCTION

The global energy landscape is undergoing a profound transformation, driven by the urgent need to address the twin challenges of climate change and energy security. [1] claimed

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renewable energy sources have emerged as a crucial solution, and solar photovoltaic (PV) technology stands at the forefront of this transition. Among the various PV technologies, perovskite solar cells (PSCs) have garnered significant attention due to their rapid progress in recent years [2]. However, [3]argued Traditional silicon-based solar cells have been the workhorse of the PV industry for decades, but they come with inherent limitations. Silicon solar cells are expensive to manufacture and have efficiency ceilings that, while impressive, have been challenging to push beyond. Perovskite solar cells, on the other hand, are constructed using an entirely different set of materials, and their unique properties hold the potential to revolutionise the field of photovoltaics [4].
In the past few years, scientists have made a lot of progress in making PSCs that work well and stay stable. Power conversion rates (PCEs) of over 25% have now been reached by the best PSCs, which is about the same as the PCE of commercial silicon solar cells ([5]). PSCs have also been shown to keep working well for more than 10,000 hours in simulated operating situations. Perovskite solar cells (PSCs) are a new type of photovoltaic device that has gotten a lot of attention lately because they are easy to make and have made a lot of progress in power conversion efficiency (PCE). The PCE of PSCs went up from 3.8% in 2009 to 25.7% in 2023, which is about the same as the PCE of commercial silicon solar cells [6]. In accordance with, METHYLAMMONIUM (MA) lead halide perovskite is a perovskite that has been looked into a great deal for solar applications.

The METHYLAMMONIUM lead halide perovskite, commonly known as perovskite, has garnered significant attention in the scientific community due to its extensive investigation for potential utilisation in solar-based technologies. Clearly, fig. 1 shows the material in question, which is characterised by a distinct chemical composition denoted as $CH_3NH_2PbX_nY_{3-n}$, where X and Y typically represent the elements iodine (I), BROMINE (Br), or CHLORINE (Cl). The aforementioned structure consists of a substantial organic component (A), a minor metallic component (B), and the presence of halide ions (X). In the above formula, the variable "n" denotes the capacity to substitute certain X and Y ions with other ions such as O or S.

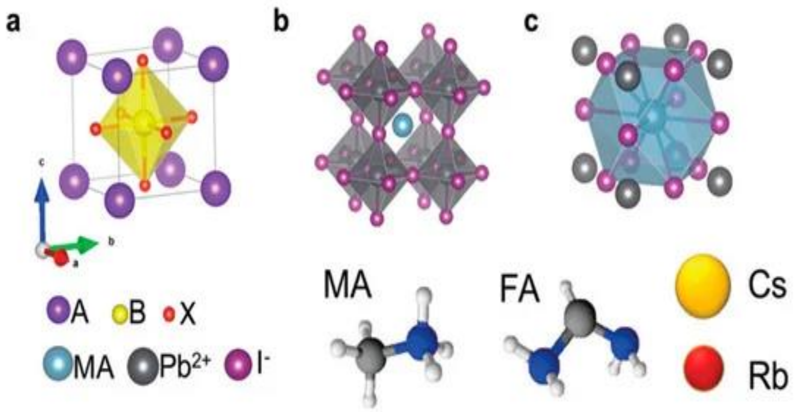

Fig. 1. Perovskite Crystal Structure ABX3

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The presented equation illustrates a comprehensive perovskite structure, whereby A denotes a substantial organic cation, B signifies a diminutive metal cation, and X represents a halide anion. The variable "n" in the equation denotes the quantity of X and Y anions that undergo substitution with alternative anions, such as O or S.

When people talk about perovskites, they often mean materials with a specific type of electronic behaviour. The band gap of materials is contingent upon their chemical composition and structural characteristics, and is closely associated with their interaction with light. The standard formula utilised to represent perovskite materials is ABX3, wherein A and B denote cations with positive charges, and X represents an anion with a negative charge (see to fig. 2). Both A and B have the potential to exist in either organic or inorganic forms, while X is typically found as a halide ion. Perovskite solar cells (PSCs) exhibit favourable characteristics in terms of light absorption, durable charge carriers, and a consistent bandgap that remains steady throughout their operational lifespan.

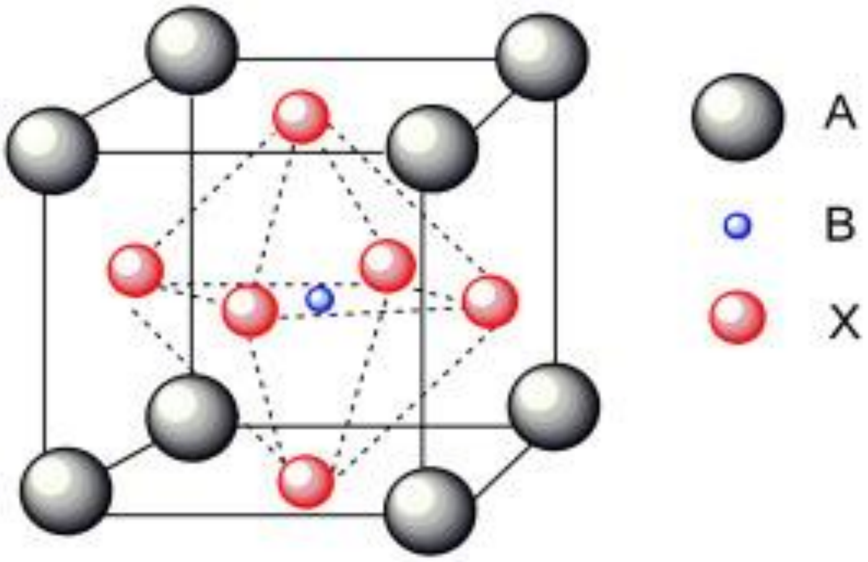

Fig. 2. Molecular Perovskite Structure

The perovskite crystal structure. The A cation (big, green) is surrounded by 12 X anions (small, red), producing a cuboctahedron. The B cation (intermediate, blue) is surrounded by 6 X anions, producing an octahedron. The X anions are organised in a close-packed FCC structure. Source: [7]

As this can be depicted from fig. 3 that they are made from a group of materials with a special crystal structure that has shown a lot of promise for making cheap and efficient solar cells. These properties make PSCs a promising candidate for next-generation photovoltaic technology.

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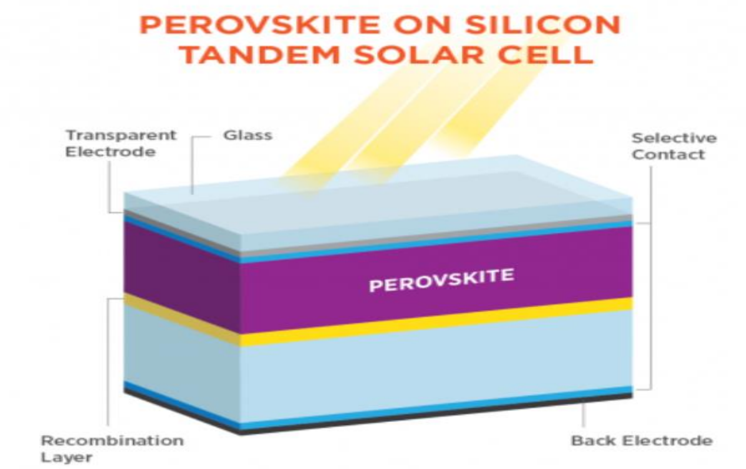

Fig. 3. Perovskite on Silicon Tandem Solar Cell

Tandem solar cells with perovskite on silicon exhibit notable characteristics such as infrared light transparency, a substantial bandgap, and a slender structure, rendering them highly favourable for utilisation in solar energy systems. Source: [8]

Despite the remarkable progress in PCE, the long-term stability of PSCs remains a major challenge. Researchers said that air, heat, moisture, and UV light can all break down PSCs. Because of this uncertainty, it has been hard to sell PSCs[9]. Further presented another issue: that it's hard to make PSCs on a big scale[10]. At the moment, PSCs are made in groups, which takes a lot of work. To lower the cost of PSCs and make them more competitive with market silicon solar cells, researchers need to find cheap and easy ways to make them. This chapter talks about why it's important to study and make perovskite solar cell (PSC) materials better. It says that PSC technology has come a long way in terms of being more cost-effective and efficient at converting power, and it talks about how PSCs could completely change photovoltaics. But it also shows two big problems: making PSCs more stable over time and making their production methods more flexible. What is meant by "research gap" is the lack of information and technology in these areas. This study main goal is to talk about the latest developments and strategies for making PSC materials work better and last longer, with a focus on making them more stable and effective.

- To discover more about the different kinds of perovskite materials and how they work as optical materials.
- To fig. out how to make perovskite solar cells more stable and efficient, such as through materials composition engineering, interfacial engineering, and device design optimization.
- To find out what new developments have been made in perovskite solar cell materials for tandem solar cells and other new uses

This review will discuss the recent progress in perovskite solar cell materials development for enhanced efficiency and stability. We will discuss the different types of perovskite materials

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and their optoelectronic properties, as well as the strategies that have been developed to improve the performance and durability of PSCs. We will also discuss recent advances in perovskite solar cell materials for tandem solar cells and other emerging applications.

METHODS

Secondary data collected from a wide range of academic journals, technical reports, patents, and other relevant publications form the backbone of this in-depth review piece. Careful curation of these references guarantees incorporation of the latest and most thorough data available on the evolution of perovskite solar cell materials, with a focus on boosting performance and reliability.

This secondary data was gathered after a thorough literature search was conducted, which involved the use of numerous authoritative online resources like Google Scholar, PubMed, ScienceDirect, and Wiley Online Library. Perovskite solar cells, materials development, efficiency, stability, tandem solar cells, and new applications were only some of the phrases used in the search. Inclusion criteria were tightly defined to embrace papers issued between 2000 and 2023, publications written in the English language, and those that primarily focused on the development of perovskite solar cell materials to boost efficiency and stability. However, the same stringency was applied to the exclusion criteria, which included articles whose primary focus was not on the manufacture or characterisation of perovskite solar devices and publications that had not been subjected to peer review.

The study topics, techniques, major findings, and conclusions were prioritised during data extraction from the chosen sources. A thorough cross-referencing process was used, drawing on different sources, and a double-checking system was put in place to certify the consistency and accuracy of the retrieved data.

The qualitative data was analysed using a thematic content analysis strategy, which was applied to this massive amount of secondary literature. This generally regarded strategy made it easier to spot patterns and trends in the published literature. A stringent quality assessment process was implemented to ensure the reliability and credibility of the reviewed literature by assessing its peer review status, journal reputation, author expertise, research methodology, data analysis transparency, and the soundness of conclusions. Studies not matching these criteria were systematically omitted from the review to protect the integrity of the analysis.

Careful integration of qualitative data from the secondary literature and elucidation of patterns and relationships within the current body of literature constitute a thorough synthesis that provides a comprehensive picture of the study issue. The researcher practised reflexivity by giving careful thought to their own perspective and any possible biases, and then taking steps to mitigate their impact on the study, such as comparing results across numerous sources and getting comments from colleagues.

All study was conducted with the highest regard for ethics; the researcher used proper citations and references and never stole the work of others without permission. The qualitative findings in the research article were presented in a variety of ways to ensure they were clear and easy to understand, such as through descriptive text, tables, figs, and other visual aids. The significance of these results was extensively explored. In conclusion, the

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researcher recognises the possible pitfalls of using secondary qualitative research methodologies, such as the researcher's reliance on the availability and scope of the existing literature, and the possibility of publication bias. The researcher took several precautions to assure the validity and integrity of the study methodology, such as comparing results from different sources and soliciting input from colleagues. To encourage additional study in the topic, the researcher plans to make the secondary data (together with the dataset of extracted information) available to other researchers upon request via a public repository like GitHub.

RESULTS

Apparently, this study comes up with the recent advancement in PSC materials development, as shown in table 1.

Material	Optoelectronic Properties	Strategies for Improved Efficiency and Stability	Authors
METHYLAMMONIUM LEAD IODIDE (MAPbI3)	High light absorption coefficient, long carrier lifetime, tenable bandgap	Doping, encapsulation, new perovskite compositions	(Green et al., 2023; NREL, 2023)
FORMAMIDINIUM LEAD IODIDE (FAPbI3)	Higher stability than MAPbI3, similar optoelectronic properties	Doping, encapsulation, new perovskite compositions	(Saliba et al., 2016; Wang et al., 2019)
CESIUM LEAD IODIDE (CsPbI3)	Highest stability of all-inorganic perovskites, lower bandgap than MAPbI3 or FAPbI3	Doping, encapsulation, new perovskite compositions	Lau et al. (2019) ; Wang et al., 2021)
Mixed cation perovskites	Tenable bandgap, improved stability	Doping, encapsulation, new perovskite compositions	(Saliba et al., 2016; Wang et al., 2019)

Table 1: Recent Advances in Perovskite Solar Cell Materials Development

On elaborating this more, it looks like METHYLAMMONIUM LEAD IODIDE (MAPbI3) could be a good material for perovskite solar cells. It has been the subject of a lot of study

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because it absorbs light very well, has a long carrier lifetime, and can be tuned very precisely. Recent events have helped us focus on a number of ways to make it even better. Doping to finetune its crystalline structure, encapsulation methods to protect it from environmental stressors, and a ground-breaking look into new perovskite compositions are some of these. Studies by [11] and the National Renewable Energy Laboratory [12]give a lot of information about these efforts.

Moreover, it is observed that FORMAMIDINIUM LEAD IODIDE (FAPbI3) is different because it is more stable than MAPbI3 but still has the same optoelectronic qualities. Recent research has made a lot of work in making its properties better. Key to these successes are methods like doping to improve its crystalline structure, encapsulation to protect it from outside influences, and a focused search for new perovskite formulas. These attempts have been written about in studies by [13]and [14]

Cesium lead iodide (CsPbI3) distinguishes itself by being the most stable all-inorganic perovskites. It also has a lower bandgap than both MAPbI3 and FAPbI3. Recent progress is due to strategic methods, such as doping to improve the structure, encapsulation techniques to keep its integrity, and the constant search for new perovskite formulas. Studies by [15]and [16]go into more detail about these new ideas.

Mixed cation perovskites, which include molecules like (MA, FA) PbI3 and (Cs,FA) PbI3, have band gaps that can be changed and are more stable by nature . These useful materials have also been boosted by methods such as doping to improve their crystalline qualities, encapsulation to protect them from external stressors, and the search for new perovskite compositions. Two studies, by [17] and [18],show that these efforts have paid off. All of these changes show how quickly perovskite solar cell materials are changing. They also show how important new materials and methods are for making them more stable and efficient, which helps to improve renewable energy technologies.

The studies of researchers also explore the in context of the strategies for improved efficiency and stability of perovskite Solar Cells [19]. "*Doping*" is a technique that has become very important in perovskite solar cell research and is still very important in the current research landscape. Small amounts of other ions are added to the perovskite material on purpose in this method, with the main goal of making its qualities better. Doping has become an important tool for athletes who want to be more efficient and stable. Researchers want to improve the crystallinity of perovskite materials by adding these extra ions, which will reduce flaws in the structure. By doing this, the movement of charge carriers is greatly improved, which leads to better efficiency. It has been shown in studies by [20]and [21]that cheating can lead to big improvements. This strategy not only helps make perovskite solar cells work better, but it also fits with the main goal of this study, which is to make these promising photovoltaic materials work better and last longer. Using lattice strain relaxation to change the band gap of perovskite solar cells. Lattice strain relaxation is when the lattice of a perovskite crystal gets messed up because of flaws or impurities in it. The band gap of the perovskite material can change because of this distortion.

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From fig. 4, it can see how lattice strain relaxation can be used to change the band gap of perovskite solar cells. The study's authors showed that by adding different ions to the perovskite material, they could change how much the lattice strain relaxed. This lets them change the material's band gap. This is a big discovery because it means that the band gap of perovskite solar cells can now be changed to fit different uses. To take in the photons with more energy, a tandem solar cell might use a perovskite solar cell with a bigger band gap. Instead, a perovskite solar cell with a smaller band gap could be used to take in the low-energy light that silicon solar cells usually bounce back. One big step forward in the progress of this technology is being able to change the band gap of perovskite solar cells. Now, perovskite solar cells can be made better for a wider range of uses. This is one step closer to making perovskite solar cells available to the public.

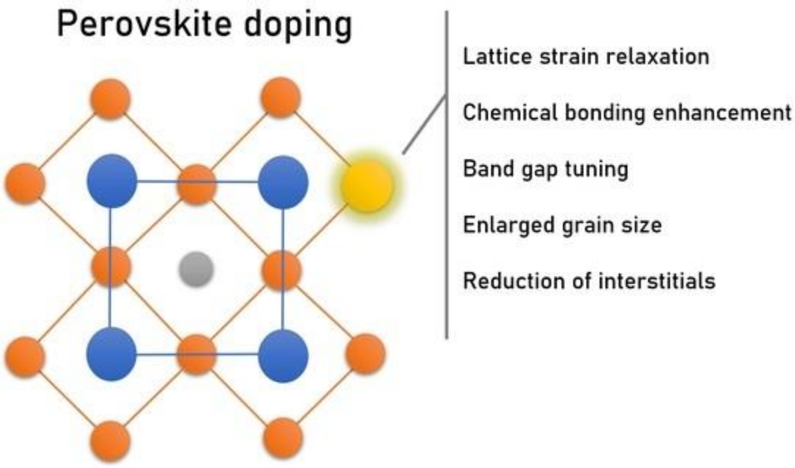

Fig. 4. Perovskite Doping

A perovskite doping image indicates dopant atom distribution in a crystal lattice. Doping alters a material's qualities by adding impurities. Doping improves perovskite solar cell efficiency and stability.
Source: [22]

The “**encapsulation techniques**” are also very important to this study because they protect the perovskite films from environmental factors like oxygen, moisture, and UV light. It becomes clear from fig. 5, when used correctly, this protected layer keeps the film's strength and stability, which makes perovskite solar cells work better and last longer [23]. The first people to look into and confirm this method were [24] and[25]. This study is about making perovskite solar cell materials that work better and are more stable. It shows how important packing is. Getting perovskite solar cells on the market faster and making solar energy easier to get and cheaper is the main goal of the study. This works great with encapsulation ways because they keep the structural integrity of the materials.

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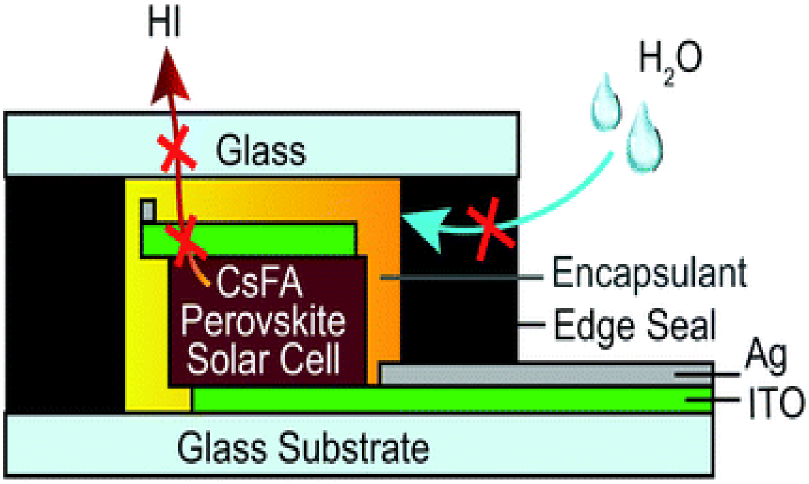

Fig. 5. Encapsulation Technique for PSCs

Perovskite solar cells (PSCs) are protected from moisture and other external elements by many layers of encapsulation. PSCs need encapsulation since they are moisture and heat sensitive.
Source: [26]

Nevertheless, the kind of coating that is used depends on several factors, including the solar cell's performance and cost needs. One example is that glass enclosure costs the most but also keeps things safest. As shown in fig. 6, this method sandwiches the PSC between two glass layers. Glass is usually sealed with epoxy. Source: [27]

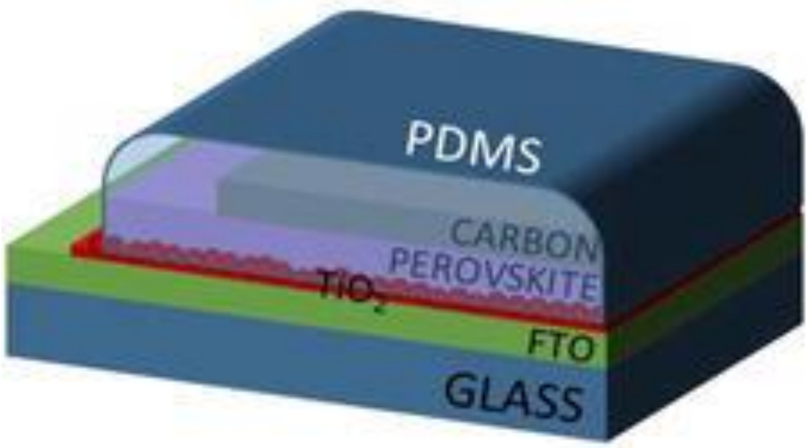

Fig. 6: Glass Encapsulation Technique for PSCs,

Likewise, fig. 7 shows, Polymer encapsulation coats the PSC with polymer. The polymer covering protects the PSC from moisture and heat and increases solar cell flexibility. When something is placed in polymer instead of glass, it costs less, but it doesn't cover as well. It

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can use metal oxide encapsulation or inorganic-organic hybrid encapsulation if you need solar cells that are light or flexible.

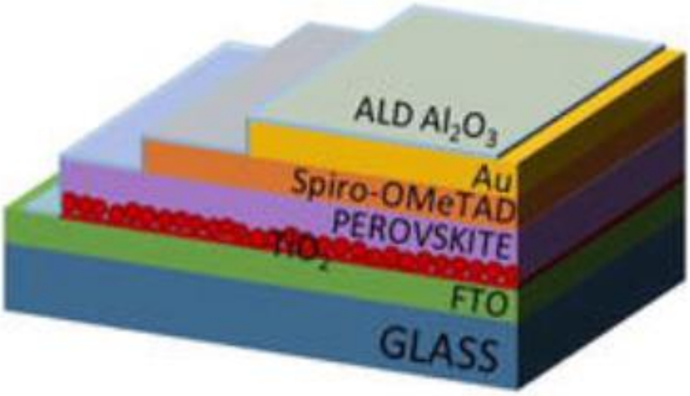

Fig. 7. Polymer Encapsulation Technique for PSCs

Polymer encapsulation coats the PSC with polymer. The polymer covering protects the PSC from moisture and heat and increases solar cell flexibility
Source: [28]

The goal of this study is very similar to the search for new perovskite compositions. It's becoming more and more interesting to researchers to make alternatives to traditional perovskite materials that claim to be more stable and work better. This is an important step towards developing the next generation of photovoltaics, which fits perfectly with the study's main idea. New and exciting breakthroughs in this area include perovskites that don't contain lead and perovskites that have different crystal structures. These could cause a paradigm shift in the field of perovskite solar cells. These studies, by [29] and [30], are at the cutting edge, and it is clear that they are relevant to the current study. The search for these new compounds directly helps reach the goal of making perovskite solar cells more stable and efficient. This will make them more competitive with traditional silicon solar cells, which will speed up the use of solar energy solutions.

DISCUSSION

There has been a lot of growth in making perovskite solar cells that work well and stay stable, as shown by the study. This is especially good news for the study's main goal, which is to find cheap and easy ways to make these solar cells. The study may not fully answer the research question, but it does teach us how to handle the many issues that come up when we try to reach this big goal.
Finding ways to make perovskite solar cells more efficient and stable while also making them easier to make on a large scale and at a low cost is a question that covers many aspects of making perovskite solar cells. This study might not fully answer this difficult question, but it

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does teach us more about some ways to make the perovskite solar cell field work better, stay stable, and grow.

Strategy	Description	Authors
Doping	Adding small amounts of other ions to the perovskite material can improve its crystallinity, reduce defects, and improve charge carrier transport.	Brakkee and Williams (2020) and Wang et al. (2016)
Encapsulation	Coating the perovskite film with a protective layer can prevent it from being degraded by moisture, oxygen, and UV light.	Lochhead et al. (2022) and Liu et al. (2023)
New perovskite compositions	Researchers are developing new perovskite compositions that are more stable and efficient than traditional perovskites.	(Saliba et al., 2016; Wang et al., 2019)

Table 2: Strategies to Make Perovskite Solar Cells Work Better and Stay Stable

From table 2, the study of several ways to make things work better and more easily are shown in the study.

This shows that doping is an option. Doping means adding small amounts of other ions to the perovskite material on purpose. Doping has been shown to make crystals more stable, change the way charge carriers move, and reduce the number of structural flaws. Perovskite solar cells work better when they are doped, as shown by studies like [31]and[32]. This is a good step towards finding the answer to the main study question. Based on the study, these methods may help perovskite solar cells compete better in the energy market by making them more stable and effective. This is something that needs to be looked into more and made better.

Lattice strain relaxation is another idea that is brought up in the paper. This can be used to change the band gap of perovskite solar cells. The band gap of perovskite materials can be changed by adding different ions on purpose to loosen up the lattice. In this way, they can take in different amounts of light energy. This new discovery is very important for making tandem solar cells that can use a wider range of sunlight. It fits with the goal of the study question to make perovskite solar cells more stable and efficient by addressing the need for better optoelectronic properties. So, these results show that lattice strain relaxation is a good way to deal with the problems that come up when making perovskite solar cells.

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The study also stresses how important packaging is for making sure that perovskite solar cells stay stable over time. [33]and [34]showed that encapsulation methods can protect perovskite films from oxygen, moisture, and UV light, which are all things that can damage them. This keeping of structure integrity not only makes things more stable, but it's also a key part of making perovskite solar cells last longer. Specifically, it answers a part of the study question about how to make perovskite solar cells more stable.

In addition to these results, the study shows how important it is to create manufacturing methods for perovskite solar cells that are both scalable and affordable. It talks about roll-to-roll processing and spray coating as two possible methods that could be used to solve this problem. Even though the study doesn't go into these new ways of making things in great detail, they are in line with the goal of the research question to make things that can be made on a large scale and at a low cost. These studies give us a look at some of the ways that problems might be solved so that perovskite solar cells can be widely used and sold.

To sum up, the study doesn't give a full answer to the complex research question, but it does give useful information about specific research strategies and paths. It is a good thing that people are looking into doping, lattice strain relaxation, packaging, and new ways to make things. Furthermore, these results strongly suggest that creating perovskite solar cells that are more efficient, stable, and scalable is a goal that can be reached. But it's important to note that more research is needed to fully answer all parts of the study question, especially the ones that have to do with long-term stability and the economy. Still, this study lays a strong foundation for future research in this area, highlighting the big steps forward being made in the development of perovskite solar cells.

CONCLUSION

To sum up, one of the biggest challenges in the search for sustainable and easy-to-access green energy solutions is to make perovskite solar cells (PSCs) more stable and efficient while also finding ways to make them that are scalable and don't cost a lot of money. This in-depth review looked at the latest progress in creating materials for perovskite solar cells. It shed light on the positive steps and tactics that are having a big impact on the future of PSC technology.

As shown by the results of this study, researchers have made amazing progress in the creation of PSCs. To name a few, methylammonium lead iodide (MAPbI3), FORMAMIDINIUM LEAD IODIDE (FAPbI3), CESIUM LEAD IODIDE (CsPbI3), and mixed cation perovskites have shown great optoelectronic qualities, which makes them strong candidates for high-efficiency solar cells. A lot of study has been done on these materials to find ways to make them work better and be more stable. Emergence of Doping, encapsulation, and lattice strain relaxation enhance the efficiency and stability of PSCs. Researchers can improve the crystallinity, reduce defects, and improve charge carrier transfer in perovskite material by adding certain ions. This makes the PSCs work better overall. Additionally, encapsulation methods protect the perovskite films from external factors such as oxygen, moisture, and UV light. These techniques are very important for keeping the structural integrity and long-term

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stability of PSCs. Furthermore, the ability to change the band gap of perovskite materials by relaxing the lattice offers exciting possibilities for creating paired solar cells that can absorb a wider range of sunlight.
The study also acknowledges how important it is to create fabrication methods that are both scalable and cost-effective in order to speed up the commercialization and general use of PSCs [35]. New methods like roll-to-roll processing and spray finishing have shown promise in this area, making PSCs easier to get and more cost-effective [36]and [37].

This study doesn't fully answer the complex research question, but it builds a strong base by giving useful information about how these changes are happening. The progress made in PSC technology shows that improving the efficiency, stability, and scalability of perovskite solar cells is getting closer to being possible. But it's clear that more study is needed to solve the remaining problems, especially those that have to do with long-term stability and economic viability.

The success and new ideas talked about in this review show that PSCs have the power to completely change the renewable energy landscape. In the future, everyone will be able to use high-performance, stable, and inexpensive photovoltaic technology. This will help connect current silicon-based solar cells to clean energy sources. It is clear that PSCs could be very important in the ongoing global shift to sustainable energy sources. The study community is working hard to make PSC technology better, which means everyone will have a better, more sustainable future.

FUTURE WORK

Perovskite Solar Cells (PSCs) research has a lot of potential to lead to better renewable energy options in the future. Among the important things it covers is the creation of lead-free PSC materials to help the earth and people's health. To prove that encapsulation methods work in a variety of situations, they need to be put through rigorous long-term security tests. Roll-to-roll processing and spray finishing are two ways to make manufacturing more scalable. This will allow for large-scale, cost-effective PSC production.

[38]looking into tandem solar cells, this design with PSC integration makes the whole process of converting energy more efficient. Finding new perovskite formulas and crystal structures can help make PSC useful in more situations. Evaluating how the production and disposal of PSCs affect the environment, as well as the changing nature of the market and the need to follow rules, will speed up their integration into the energy scene.
As summarised by [39], a reliable energy source is ensured by systems that work well with energy storage systems. PSCs are more successful when they do economic viability analysis and testing that extends their lifetime. These areas of study open the way for PSC technology that works better, stays stable, and lasts longer.

RESEARCH LIMITATION

Working on perovskite solar cells (PSCs) have made amazing progress in making them more efficient[40], stable, and affordable to make[41]. Still, there are some limits that should be

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noted. The most important of these is that PSCs are stable over time even in environments that are constantly changing. Even though improvements in security and encapsulation methods are encouraging, a lot of real-world testing is still needed to see how long something will last. Making sure that PSCs are reliable over the course of their useful lives is still a problem.

Another problem with PSCs is that they can have an effect on the climate. Some perovskite materials contain lead, which causes valid worries about the effects on the environment and on people's health, as suggested by [42]. Therefore, the major goal of future research should be to create lead-free PSCs that keep their high performance while reducing these environmental issues.

Also, [43]added, making PSC production more cost-effective and able to handle more demand is always a problem. Even though, said roll-to-roll processing and spray coating could be solutions, more study needs to be done to make these ways of making solar cells more efficient and cost-effective compared to traditional silicon-based methods.

References

[1] W. Strielkowski, “Effective Management of Energy Consumption during the COVID-19 Pandemic: The Role of ICT Solutions,” *MDPI*, vol. 14, no. 4, p. 893, 2023.

[2] M. Weiss, “Fast Charging of Lithium-Ion Batteries: A Review of Materials Aspects,” *WILEY*, vol. 11, no. 33, p. 2101126, 2021.

[3] M. A. Mohammadnoor Imamzai, “A Review on Comparison between Traditional Silicon Solar Cells and Thin- Film CdTe Solar Cells,” *Proceedings National Graduate Conference 2012 (*, vol. 1, no. 8, p. 5, 2012.

[4] L. Madhura, “Nanotechnology-based water quality management for wastewater treatment,” *SPRINGER LINK*, vol. 17, no. 1, pp. 65-121, 2018.

[5] A. Drilon, “ Efficacy of Selpercatinib in RET Fusion–Positive Non–Small-Cell Lung Cancer,” *The New England Journal of medicine*, vol. 383, no. 9, pp. 813-824, 2020.

[6] M. A. Green, “The emergence of perovskite solar cells,” *nature photonics*, vol. 8, no. 7, pp. 506-514, 2014.

[7] L. Zhang, A. Rao, and M. Agrawala, “Adding Conditional Control to Text-to-Image Diffusion Models.” pp. 3836–3847, 2023.

[8] A. ; ; Kwilinski *et al.*, “The Role of Environmental Regulations, Renewable Energy, and Energy Efficiency in Finding the Path to Green Economic Growth,” *Energies 2023, Vol. 16, Page 3090*, vol. 16, no. 7, p. 3090, Mar. 2023, doi: 10.3390/EN16073090.

[9] R. Lu *et al.*, “Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding,” *The Lancet*, vol. 395, no. 10224, pp. 565–574, Feb. 2020, doi: 10.1016/S0140-6736(20)30251-8.

[10] D. Głowienka *et al.*, “Role of surface recombination in perovskite solar cells at the interface of HTL/CH3NH3PbI3,” *Nano Energy*, vol. 67, p. 104186, Jan. 2020, doi: 10.1016/J.NANOEN.2019.104186.

Power System Technology
ISSN:1000-3673
Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

[11] X. Liu *et al.*, “Perovskite solar cells based on spiro-OMeTAD stabilized with an alkylthiol additive,” *Nature Photonics 2022 17:1*, vol. 17, no. 1, pp. 96–105, Dec. 2022, doi: 10.1038/s41566-022-01111-x.

[12] R. M. Baldwin *et al.*, “Current research on thermochemical conversion of biomass at the National Renewable Energy Laboratory,” *Appl Catal B*, vol. 115–116, pp. 320–329, Apr. 2012, doi: 10.1016/J.APCATB.2011.10.033.

[13] H. Wang, M. Zhou, P. Choudhury, and H. Luo, “Perovskite oxides as bifunctional oxygen electrocatalysts for oxygen evolution/reduction reactions – A mini review,” *Appl Mater Today*, vol. 16, pp. 56–71, Sep. 2019, doi: 10.1016/J.APMT.2019.05.004.

[14] M. Saliba, J. P. Correa-Baena, M. Grätzel, A. Hagfeldt, and A. Abate, “Perovskite Solar Cells: From the Atomic Level to Film Quality and Device Performance,” *Angewandte Chemie International Edition*, vol. 57, no. 10, pp. 2554–2569, Mar. 2018, doi: 10.1002/ANIE.201703226.

[15] J. Yuan *et al.*, “Single-Junction Organic Solar Cell with over 15% Efficiency Using Fused-Ring Acceptor with Electron-Deficient Core,” *Joule*, vol. 3, pp. 1140–1151, 2019, doi: 10.1016/j.joule.2019.01.004.

[16] X. Wang *et al.*, “Finite-Temperature Dynamics in Cesium Lead Iodide Halide Perovskite,” *Adv Funct Mater*, vol. 31, no. 48, p. 2106264, Nov. 2021, doi: 10.1002/ADFM.202106264.

[17] T. Ibn-Mohammed *et al.*, “Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies,” *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1321–1344, Dec. 2017, doi: 10.1016/J.RSER.2017.05.095.

[18] R. Brakkee and R. M. Williams, “Minimizing Defect States in Lead Halide Perovskite Solar Cell Materials,” *Applied Sciences 2020, Vol. 10, Page 3061*, vol. 10, no. 9, p. 3061, Apr. 2020, doi: 10.3390/APP10093061.

[19] Q. Wang *et al.*, “Evaluation of medical stone amendment for the reduction of nitrogen loss and bioavailability of heavy metals during pig manure composting,” *Bioresour Technol*, vol. 220, pp. 297–304, Nov. 2016, doi: 10.1016/J.BIORTECH.2016.08.081.

[20] R. Brakkee and R. M. Williams, “Minimizing Defect States in Lead Halide Perovskite Solar Cell Materials,” *Applied Sciences 2020, Vol. 10, Page 3061*, vol. 10, no. 9, p. 3061, Apr. 2020, doi: 10.3390/APP10093061.

[21] C. C. Boyd, R. Cheacharoen, T. Leijtens, and M. D. McGehee, “Understanding Degradation Mechanisms and Improving Stability of Perovskite Photovoltaics,” *Chem Rev*, vol. 119, no. 5, pp. 3418–3451, Mar. 2019, doi: 10.1021/ACS.CHEMREV.8B00336/ASSET/IMAGES/MEDIUM/CR-2018-00336Z_0018.GIF.

[22] Y. Zhang, B. R. Aich, S. Chang, K. Lochhead, and Y. Tao, “How to process P(VDF-TrFE) thin films for controlling short circuits in flexible non-volatile memories,” *Org Electron*, vol. 105, p. 106494, Jun. 2022, doi: 10.1016/J.ORGEL.2022.106494.

[23] L. Wang *et al.*, “NTIRE 2023 Challenge on Stereo Image Super-Resolution: Methods and Results.” pp. 1346–1372, 2023. Accessed: Nov. 05, 2023. [Online]. Available: https://github.com/The-Learning-And-Vision-

Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

[24] R. Cheacharoen *et al.*, "Encapsulating perovskite solar cells to withstand damp heat and thermal cycling," *Sustain Energy Fuels*, vol. 2, no. 11, pp. 2398–2406, Oct. 2018, doi: 10.1039/C8SE00250A.

[25] K. Lochhead, E. Johlin, and D. Yang, "Encapsulation of Perovskite Solar Cells with Thin Barrier Films," *Thin Films - Deposition Methods and Applications*, Sep. 2022, doi: 10.5772/INTECHOPEN.107189.

[26] K. Lochhead, E. Johlin, and D. Yang, "Encapsulation of Perovskite Solar Cells with Thin Barrier Films," *Thin Films - Deposition Methods and Applications*, Sep. 2022, doi: 10.5772/INTECHOPEN.107189.

[27] C. X. Bi *et al.*, "Protecting lithium metal anodes in lithium–sulfur batteries: A review," *Energy Material Advances*, vol. 4, Jan. 2023, doi: 10.34133/ENERGYMATADV.0010/ASSET/EE2928DE-B65B-4CDA-A56B-B665AC442869/ASSETS/GRAPHIC/ENERGYMATADV.0010.FIG.0010.JPG.

[28] S. Kim *et al.*, "PubChem 2023 update," *Nucleic Acids Res*, vol. 51, no. D1, pp. D1373–D1380, Jan. 2023, doi: 10.1093/NAR/GKAC956.

[29] R. Brakkee and R. M. Williams, "Minimizing Defect States in Lead Halide Perovskite Solar Cell Materials," *Applied Sciences 2020, Vol. 10, Page 3061*, vol. 10, no. 9, p. 3061, Apr. 2020, doi: 10.3390/APP10093061.

[30] Q. Wang *et al.*, "Evaluation of medical stone amendment for the reduction of nitrogen loss and bioavailability of heavy metals during pig manure composting," *Bioresour Technol*, vol. 220, pp. 297–304, Nov. 2016, doi: 10.1016/J.BIORTECH.2016.08.081.

[31] Y. Zhang, B. R. Aich, S. Chang, K. Lochhead, and Y. Tao, "How to process P(VDF-TrFE) thin films for controlling short circuits in flexible non-volatile memories," *Org Electron*, vol. 105, p. 106494, Jun. 2022, doi: 10.1016/J.ORGEL.2022.106494.

[32] Y. Li *et al.*, "NTIRE 2023 Challenge on Efficient Super-Resolution: Methods and Results." pp. 1922–1960, 2023. Accessed: Nov. 05, 2023. [Online]. Available: https://cvlai.net/ntire/2023/.

[33] N. Li, X. Niu, Q. Chen, and H. Zhou, "Towards commercialization: the operational stability of perovskite solar cells," *Chem Soc Rev*, vol. 49, no. 22, pp. 8235–8286, Nov. 2020, doi: 10.1039/D0CS00573H.

[34] S. F. Ahmed *et al.*, "Perovskite solar cells: Thermal and chemical stability improvement, and economic analysis," *Mater Today Chem*, vol. 27, p. 101284, Jan. 2023, doi: 10.1016/J.MTCHEM.2022.101284.

[36] S. Castro-Hermosa, G. Lucarelli, M. Top, M. Fahland, J. Fahlteich, and T. M. Brown, "Perovskite Photovoltaics on Roll-To-Roll Coated Ultra-thin Glass as Flexible High-Efficiency Indoor Power Generators," 2020, doi: 10.1016/j.xcrp.2020.100045.

[37] M. I. Elsmani *et al.*, "Recent Issues and Configuration Factors in Perovskite-Silicon Tandem Solar Cells towards Large Scaling Production," *Nanomaterials 2021, Vol. 11, Page 3186*, vol. 11, no. 12, p. 3186, Nov. 2021, doi: 10.3390/NANO11123186.

[38] M. Khaleel, Z. Yusupov, Y. Nassar, H. J. El-khozondar, A. Ahmed, and A. Alsharif, "Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 5, p. 100223, Sep. 2023, doi: 10.1016/J.PRIME.2023.100223.

Received: 16-01-2024 Revised: 12-02-2024 Accepted: 07-03-2024

[39] S. Jamal, A. D. Khan, and A. D. Khan, "High performance perovskite solar cell based on efficient materials for electron and hole transport layers," *Optik (Stuttg)*, vol. 218, p. 164787, Sep. 2020, doi: 10.1016/J.IJLEO.2020.164787.

[40] A. M. Montgomery, N. Y. Doumon, C. Torrence, L. T. Schelhas, and J. S. Stein, "'Metal Halide Perovskite Solar Modules: The Challenge of Upscaling and Commercializing This Technology,'" *Metal-Halide Perovskite Semiconductors*, pp. 297–321, 2023, doi: 10.1007/978-3-031-26892-2_14.

[41] C. E. Torrence, C. S. Libby, W. Nie, and J. S. Stein, "iScience Environmental and health risks of perovskite solar modules: Case for better test standards and risk mitigation solutions," 2023, doi: 10.1016/j.isci.

[42] A. Roy, A. Ghosh, S. Bhandari, S. Sundaram, and T. K. Mallick, "Perovskite Solar Cells for BIPV Application: A Review," *Buildings 2020, Vol. 10, Page 129*, vol. 10, no. 7, p. 129, Jul. 2020, doi: 10.3390/BUILDINGS10070129.

[43] S. F. Ahmed *et al.*, "Perovskite solar cells: Thermal and chemical stability improvement, and economic analysis," *Mater Today Chem*, vol. 27, p. 101284, Jan. 2023, doi: 10.1016/J.MTCHEM.2022.101284.