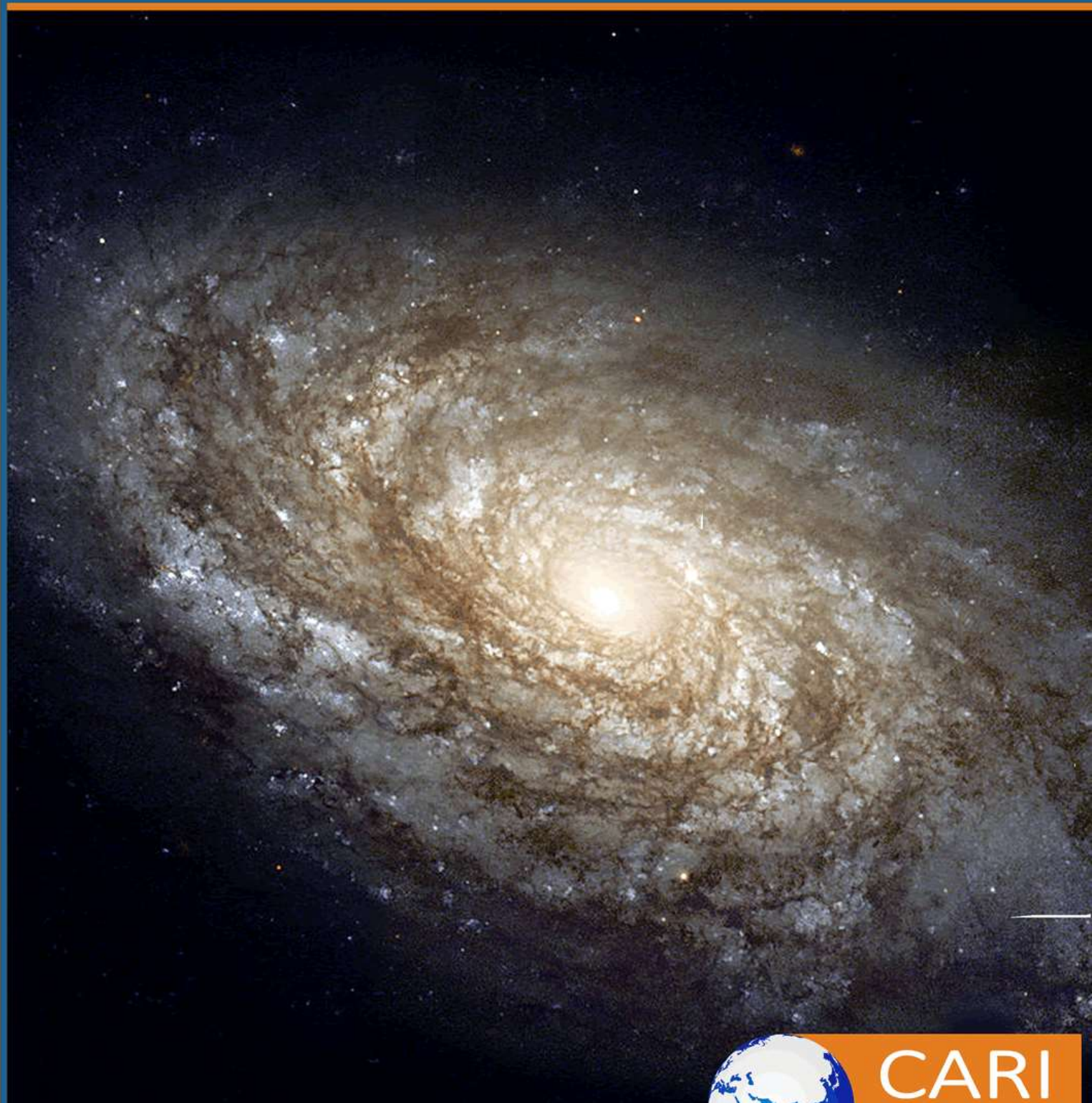


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**Nanostructured Surface Modifications and Solar Energy Conversion  
Efficiency in Perovskite Photovoltaic Cells in Japan**



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## Nanostructured Surface Modifications and Solar Energy Conversion Efficiency in Perovskite Photovoltaic Cells in Japan



Nanami Fujimoto  
Waseda University



### Abstract

**Purpose:** The aim of this study was to investigate the nanostructured surface modifications and solar energy conversion efficiency in perovskite photovoltaic cells in Japan.

**Methodology:** The study adopted a desktop research methodology. Desk research refers to secondary data or that which can be collected without fieldwork. Desk research is basically involved in collecting data from existing resources hence it is often considered a low-cost technique as compared to field research, as the main cost is involved in executive's time, telephone charges and directories. Thus, the study relied on already published studies, reports and statistics. This secondary data was easily accessed through the online journals and library.

**Findings:** The reviewed studies revealed that nanostructured surface modifications significantly enhance solar energy conversion efficiency in perovskite photovoltaic cells by improving light absorption, charge carrier transport, and interfacial stability while reducing charge recombination losses. Surface passivation, interface engineering, nanostructured coatings, and additive treatments were identified as important approaches for improving power conversion efficiency and device durability. However, challenges relating to long-term stability, scalability, and performance under real-world environmental conditions remain. The findings highlight the potential of nanostructured surface modifications to advance the development of efficient and durable perovskite solar cells in Japan.

**Unique Contribution to Theory, Practice and Policy:** Shockley–queisser detailed balance theory, surface plasmon resonance theory, Shockley–read–hall recombination theory may be used to anchor future studies on the nanostructured surface modifications and solar energy conversion efficiency in perovskite photovoltaic cells in Japan. The study recommends that photovoltaic researchers, manufacturers, and renewable energy technology developers in Japan adopt evidence-based surface engineering strategies that improve conversion efficiency while maintaining operational stability and manufacturing feasibility. Policymakers should consider establishing targeted research funding programmes that encourage experimental comparisons of different surface modification techniques, particularly those demonstrating improvements in photovoltaic conversion efficiency, long-term stability, and manufacturing scalability.

**Keywords:** *Nanostructured Surface Modifications, Solar Energy Conversion Efficiency, Perovskite Photovoltaic Cells*

## INTRODUCTION

Solar energy conversion efficiency refers to the percentage of incident solar radiation that a photovoltaic cell or module successfully converts into usable electrical energy, making it an important indicator of technological performance and renewable energy productivity. It is calculated by dividing the maximum electrical power output by the incident solar power and multiplying the result by 100, with efficiency influenced by semiconductor properties, surface structure, operating temperature, and optical losses. In developed economies such as the United States and Japan, advances in photovoltaic materials, cell architecture, and nanostructured surface engineering have contributed to improvements in solar energy conversion efficiency. Wu . (2021) reported that the certified power conversion efficiency of perovskite solar cells had reached 25.5%, illustrating substantial progress in photovoltaic technology compared with earlier generations of solar cells.

In the United States, independently verified photovoltaic performance records have demonstrated substantial improvements in the conversion of sunlight into electrical energy, particularly through advanced thin-film and multijunction technologies. Green . (2021) documented internationally certified solar-cell efficiency records, highlighting the contribution of advanced photovoltaic research and independent performance testing to technological progress.

In Japan, photovoltaic innovation has similarly advanced through crystalline silicon, perovskite, and multijunction solar technologies, with Japanese manufacturers and research institutions contributing to improvements in conversion efficiency. For example, Japan's Panasonic achieved a certified perovskite module efficiency of 17.9% in January 2020, while Kaneka's crystalline silicon module achieved 24.4% in September 2016, illustrating differences in performance between photovoltaic technologies rather than a direct time-series increase (Green, 2022).

Solar energy conversion efficiency has become increasingly important in developing economies because of rising electricity demand, expanding renewable energy investments, and the need for affordable electricity generation. In countries such as China and India, improvements in photovoltaic technologies have been associated with advances in semiconductor fabrication, surface engineering, and the development of cost-effective solar modules. Cui. (2020) examined China's progress in perovskite solar-cell research during 2019 and reported continued improvements in device efficiency and stability, demonstrating the country's growing technological capabilities in photovoltaic innovation.

In China, research on photovoltaic materials has demonstrated improvements in the electrical performance of perovskite solar cells, with increasing attention being directed toward charge transport, surface passivation, and long-term operational stability. Cui. (2020) identified improvements in efficiency and stability during 2019, while Wu. (2021) documented a global certified efficiency benchmark of 25.5%, illustrating the rapid technological progress occurring in this field.

In India, photovoltaic performance research has similarly focused on reducing energy conversion losses associated with temperature, semiconductor properties, and environmental operating conditions, although the sources reviewed here do not establish a verified India-specific efficiency trend. Shen. (2020) demonstrated through photovoltaic energy-loss modelling that approximately 72.16% of incident solar energy was dissipated as heat and 11.94% was lost through multilayer

reflection in the module they examined, highlighting important physical barriers to improving conversion efficiency.

Solar energy conversion efficiency is an important consideration in sub-Saharan African economies, where high solar irradiation creates opportunities for electricity generation but elevated temperatures, humidity, dust accumulation, and equipment degradation can reduce photovoltaic performance. Countries such as Ghana and South Africa have attracted research interest because photovoltaic systems operate under environmental conditions that can differ substantially from standard laboratory testing conditions. A peer-reviewed study published in *Renewable Energy* in 2020 assessed photovoltaic modules operating for 12 years under tropical conditions in sub-Saharan Africa and reported an average nominal power degradation rate of 3.19% annually.

In Ghana, a comparative investigation of photovoltaic technologies installed in Kumasi demonstrated considerable differences in long-term performance between polycrystalline silicon, amorphous silicon, and heterojunction solar modules after 12 years of outdoor exposure. The study reported annual power degradation rates ranging from 1.25% to 1.75% for the five polycrystalline silicon modules, whereas the heterojunction modules generally demonstrated substantially lower degradation, with reported rates ranging from approximately  $-0.20\%$  to  $0.53\%$  annually.

Nanostructured surface modifications refer to the deliberate engineering of material surfaces at the nanometre scale, typically between 1 and 100 nanometres, to improve their optical, electrical, chemical, and physical properties, particularly in photovoltaic applications. In perovskite photovoltaic cells, these modifications are designed to enhance light absorption, facilitate charge-carrier transportation, minimise electron-hole recombination, and improve the stability of solar energy conversion processes. Conceptually, nanostructured surface modifications can be classified into four principal dimensions: surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering, each contributing differently to photovoltaic performance. Surface texturing involves introducing nanoscale patterns or roughness to improve light trapping and reduce optical reflection, while nanoparticle incorporation entails integrating functional nanomaterials to modify optical or electronic properties and potentially enhance photon harvesting (Atwater & Polman, 2010). Surface passivation involves treating surface defects to suppress non-radiative charge recombination, whereas interfacial engineering focuses on optimising the boundaries between perovskite absorbers and charge-transport layers to facilitate efficient charge extraction and reduce energy losses (Jena, 2019).

Nanostructured surface modifications constitute an important independent variable in photovoltaic research because their characteristics can directly influence solar energy conversion efficiency through changes in photon absorption, charge mobility, interfacial resistance, and material stability. Surface texturing can improve photovoltaic efficiency by increasing the effective optical path length of incident sunlight, while nanoparticle incorporation, particularly using plasmonic metallic nanostructures, can enhance local electromagnetic fields and light absorption under appropriately designed conditions (Atwater & Polman, 2010). Surface passivation can increase photovoltaic performance by reducing defect-assisted recombination, as demonstrated by Jiang (2019), who reported a certified power conversion efficiency of 23.32% in perovskite solar cells employing surface passivation strategies. Interfacial engineering can further improve device performance by regulating energy-level alignment, reducing interfacial defects, and promoting efficient charge transfer, although its effectiveness depends on the chemical compatibility and

stability of the materials employed (Jena, 2019). Therefore, the four dimensions provide a conceptual framework for examining how nanoscale surface modifications influence the dependent variable, solar energy conversion efficiency, measured as the percentage of incident solar power converted into usable electrical power.

### **Problem Statement**

The increasing demand for clean and sustainable energy has intensified efforts to improve solar energy conversion efficiency in perovskite photovoltaic cells, particularly in technologically advanced economies such as Japan. Despite significant advancements in photovoltaic technologies, perovskite solar cells continue to experience efficiency losses resulting from surface defects, non-radiative charge recombination, inadequate light absorption, and interfacial instability. Pan. (2024) reported a certified power conversion efficiency of 28.49% in all-perovskite tandem solar cells through surface chemical polishing and passivation, demonstrating the potential of surface engineering to improve photovoltaic performance. Similarly, Mondal. (2025) established that mixed two-dimensional cation passivation improved the durability of perovskite solar cells in Japan, although material migration under prolonged light exposure and elevated temperatures contributed to performance deterioration. These findings indicate that despite technological improvements, achieving consistently high solar energy conversion efficiency remains challenging, particularly in relation to the effectiveness of different nanostructured surface modification techniques.

Although nanostructured surface modifications have demonstrated considerable potential for enhancing photovoltaic performance, limited comparative empirical evidence has been established regarding the individual and combined effects of surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering on solar energy conversion efficiency in Japan. Existing studies have largely examined specific surface treatment approaches, creating a need for systematic comparisons that establish the relative effectiveness of different modification techniques under standardised experimental conditions. Furthermore, differences in nanostructure morphology, material composition, surface defect density, and interfacial charge-transfer properties may contribute to variations in photovoltaic performance, complicating the identification of optimal surface engineering strategies (Pan., 2024; Mondal., 2025). Without comprehensive comparative evidence, researchers and photovoltaic manufacturers may face difficulties selecting surface modification techniques that maximise conversion efficiency while maintaining operational stability and manufacturing feasibility. Therefore, this study seeks to investigate the influence of nanostructured surface modifications on solar energy conversion efficiency in perovskite photovoltaic cells in Japan, focusing specifically on surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering.

### **Theoretical Framework**

#### **Shockley–Queisser Detailed Balance Theory**

Developed by William Shockley and Hans-Joachim Queisser in 1961, this theory explains the theoretical maximum efficiency of a single-junction solar cell based on the balance between photon absorption and radiative recombination. It establishes how semiconductor bandgap energy, photon transmission, and carrier recombination influence photovoltaic efficiency. Rühle (2019) explains the relevance of the Shockley–Queisser limit in evaluating photovoltaic conversion efficiency. This theory underpins the study by explaining how surface texturing and nanoparticle

incorporation can improve light harvesting and reduce optical losses, although they cannot eliminate the fundamental thermodynamic efficiency limit.

### **Surface Plasmon Resonance Theory**

The theoretical foundations of surface plasmon resonance originated from the work of Rufus Ritchie in 1957, with subsequent contributions by researchers including Heinz Raether. The theory explains the collective oscillation of conduction electrons at metal–dielectric interfaces when excited by electromagnetic radiation. Atwater and Polman's plasmonic photovoltaic framework, further discussed in contemporary nanophotonics research, demonstrates how metallic nanostructures can concentrate electromagnetic fields and enhance optical absorption. This theory supports the investigation of nanoparticle incorporation and nanoscale surface texturing as potential mechanisms for improving light absorption in perovskite photovoltaic cells.

### **Shockley–Read–Hall Recombination Theory**

Developed independently by William Shockley and William Read, and by Robert Hall in 1952, this theory explains how defects and impurities within semiconductor materials facilitate non-radiative electron–hole recombination, reducing electrical performance. It proposes that defect states act as charge-carrier traps, causing energy losses before useful electricity can be generated. Wang . (2022) highlight the importance of defect passivation in suppressing recombination losses in perovskite solar cells. The theory is relevant because it explains how surface passivation and interfacial engineering can reduce defect density, improve charge collection, and enhance solar energy conversion efficiency in Japanese perovskite photovoltaic cells.

### **Empirical Review**

Hu. (2021) investigated the effectiveness of maltol surface treatment in improving the photovoltaic performance of mixed lead–tin perovskite solar cells. The researchers employed a laboratory-based comparative experimental design involving untreated perovskite films, films treated with a tin(IV) scavenger, and films receiving both scavenging and maltol surface passivation, with X-ray photoelectron spectroscopy and photoluminescence measurements used to assess material properties. The findings revealed that the combined treatment reduced the surface tin(IV) concentration from 9% to 3%, extended charge-carrier lifetimes to approximately 7.4 microseconds, and increased power conversion efficiency from 18.2% in the control devices to 21.4% in the optimised devices. The results demonstrated that chemical surface modification can suppress oxidation-related defects, improve charge-carrier transport, and enhance photovoltaic efficiency. Based on these findings, further investigation of affordable molecular passivation agents and their long-term effectiveness is recommended to establish suitable surface engineering strategies for commercially viable perovskite photovoltaic cells in Japan.

Pant. (2020) investigated the influence of different surface treatments of sputtered nickel oxide (NiO<sub>x</sub>) on the photovoltaic performance of perovskite solar cells at Japan's National Institute for Materials Science. The researchers adopted a comparative laboratory experimental methodology in which nickel oxide surfaces were subjected to four conditions: untreated deposition, isopropanol dipping, ultraviolet–ozone treatment, and plasma treatment, followed by assessments of surface chemistry, wettability, energy levels, and device performance. The findings established that plasma-treated nickel oxide produced the highest photovoltaic efficiency among the tested conditions because of improved surface wettability, favourable electronic properties, and reduced

charge recombination within the perovskite absorber. The study demonstrated that surface treatment methods influence the quality of subsequently deposited perovskite films and consequently affect solar energy conversion efficiency. The findings support further comparative investigations of plasma treatment, chemical passivation, and nanoscale surface engineering to determine optimal treatment conditions for high-efficiency photovoltaic devices in Japan.

Khadka (2020) established whether incorporating rubidium additives into tin-based halide perovskites could reduce defect-related losses and improve photovoltaic efficiency and stability. The study employed laboratory fabrication and comparative characterisation of tin-based perovskite devices with different additive treatments, examining their optoelectronic properties and photovoltaic performance. The researchers found that rubidium incorporation attenuated defect activity and improved the efficiency and stability of tin-based perovskite solar cells, demonstrating the importance of controlling defect formation within photovoltaic absorber materials. Although the investigation primarily concerned compositional modification rather than surface texturing, its findings provide relevant evidence that defect management can improve charge-carrier behaviour and reduce efficiency losses. Further research is recommended to investigate how rubidium-assisted defect control can be combined with surface passivation and interfacial engineering to enhance photovoltaic conversion efficiency under different operational conditions.

Pant (2020) investigated how methylammonium halide additives and vapour annealing influence the crystallisation and photovoltaic performance of perovskite thin films deposited on radio-frequency-sputtered nickel oxide surfaces in Japan. The researchers employed a controlled laboratory experimental approach, comparing perovskite films prepared using methylammonium chloride and methylammonium iodide additives with films subjected to corresponding halide vapour annealing, while assessing crystallinity, film morphology, charge trapping, and photovoltaic performance. The findings revealed that both approaches reduced residual lead iodide and increased crystal grain size, but only vapour annealing substantially mitigated defect states and improved photovoltaic device performance. The study established that improved film morphology alone does not necessarily translate into greater solar energy conversion efficiency unless charge-carrier recombination is also controlled. The findings suggest that future research should combine nanoscale morphological engineering with interfacial defect passivation to establish surface modification techniques capable of consistently improving photovoltaic efficiency.

Cho (2021) investigated the immediate and time-dependent effects of surface passivation on perovskite photovoltaic conversion efficiency through collaborative research involving Kyoto University, the Nara Institute of Science and Technology, and Australian research institutions. The study adopted an experimental methodology involving surface-passivated perovskite solar cells, controlled ambient storage, photovoltaic characterisation, and analysis of charge-carrier recombination mechanisms. The researchers established that surface passivation and controlled storage could jointly improve photovoltaic performance, while additional compositional engineering enabled devices to achieve a power conversion efficiency of 22.2%. The study further identified lead-related defects within the perovskite bulk as important recombination centres, demonstrating that surface treatment alone may be insufficient to eliminate efficiency losses. The findings support further investigations combining surface passivation, bulk defect control, and

interfacial engineering to enhance conversion efficiency and operational stability in perovskite photovoltaic cells.

Liu (2020) investigated the effectiveness of comprehensive interfacial stabilisation strategies in improving the efficiency and operational durability of perovskite solar modules, providing international evidence relevant to photovoltaic research in Japan. The researchers employed a laboratory experimental design involving modification of perovskite absorber layers, charge-transport interfaces, and encapsulation systems, followed by photovoltaic efficiency measurements and prolonged illumination testing. The findings demonstrated that unencapsulated modules with an active designated area of 22.4 cm<sup>2</sup> achieved a reverse-scan power conversion efficiency of 16.6%, while encapsulated modules retained approximately 86% of their initial performance after 2,000 hours of continuous illumination. The study established that coordinated interface modifications can improve photovoltaic performance while reducing degradation associated with prolonged operational exposure. The findings suggest that researchers in Japan should investigate integrated nanostructured surface treatments across multiple photovoltaic interfaces rather than focusing exclusively on individual surface modification techniques.

Du (2020) conducted an experimental study in China to examine how high-pressure nitrogen extraction and ionic-liquid surface passivation could improve the crystallisation quality, efficiency, and scalability of perovskite photovoltaic devices, offering comparative evidence relevant to Japan's photovoltaic manufacturing sector. The researchers employed laboratory-based experimental methods involving slot-die coating, high-pressure nitrogen-assisted crystallisation, ionic-liquid surface treatment, and photovoltaic performance testing of individual cells and larger modules. The findings demonstrated that surface passivation reduced defect density and charge-carrier recombination, enabling photovoltaic cells to achieve a conversion efficiency of 22.7%, while fabricated modules measuring 40 × 40 mm<sup>2</sup> achieved a stabilised efficiency of 19.4%. The study established that surface modification and controlled film crystallisation can contribute to improved photovoltaic efficiency at both laboratory-cell and module scales. The findings support further research on scalable surface passivation technologies and manufacturing-compatible nanostructured modifications to improve photovoltaic conversion efficiency in Japan.

## METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low-cost advantage as compared to field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

## FINDINGS

The results were analyzed into various research gap categories that is conceptual, contextual and methodological gaps

### Conceptual Research Gap

Existing empirical studies have primarily examined individual surface modification techniques without comprehensively investigating the combined influence of different nanostructured surface modifications on solar energy conversion efficiency. Hu (2021) focused on maltol surface passivation, Pant (2020) investigated nickel oxide surface treatments and thin-film crystallisation,

while Khadka. (2020) examined rubidium additives for defect reduction. Similarly, Cho (2021) concentrated on surface passivation and temporal efficiency improvements, whereas Liu (2020) investigated interfacial stabilisation. Although these studies demonstrated improvements in photovoltaic performance, they did not collectively establish the relative and interactive effects of surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering on solar energy conversion efficiency. Therefore, the present study seeks to address this conceptual gap by examining the individual and combined contributions of these four dimensions to photovoltaic efficiency in perovskite solar cells.

### **Contextual Research Gap**

Previous studies have largely been conducted under controlled laboratory conditions, with limited consideration of how nanostructured surface modifications perform under practical operating and manufacturing conditions. For instance, Hu (2021) evaluated chemical passivation under laboratory conditions, while Pant (2020) investigated surface treatments and film crystallisation using controlled experimental procedures. Although Cho (2021) examined temporal efficiency changes and Liu (2020) assessed operational stability over 2,000 hours, the reviewed studies provide limited integrated evidence concerning the effects of temperature variations, humidity, prolonged illumination, and manufacturing scalability on the performance of different surface modification techniques. Furthermore, Du (2020) demonstrated improvements in large-area photovoltaic modules but did not establish whether comparable outcomes could be achieved across different nanostructured surface treatments under Japan-specific operating conditions. Consequently, the present study seeks to bridge this contextual gap by investigating the effectiveness of nanostructured surface modifications under standardised experimental conditions and, where feasible, operational conditions relevant to photovoltaic applications in Japan.

### **Geographical Research Gap**

Although several studies have investigated photovoltaic surface modifications in Japan, their findings are primarily associated with particular research institutions, experimental materials, and device configurations, limiting their generalisability across the country's photovoltaic research and manufacturing environments. Hu (2021) conducted research involving Kyoto University and Osaka University, while Pant (2020) and Khadka (2020) investigated photovoltaic materials at Japan's National Institute for Materials Science. In contrast, Liu (2020) provided international evidence on interfacial stabilisation, whereas Du (2020) examined scalable photovoltaic manufacturing techniques in China. Despite these contributions, the seven reviewed studies do not establish a coordinated comparison of nanostructured surface modification techniques across multiple Japanese research or manufacturing settings. Therefore, the present study seeks to address this geographical gap by generating comparative empirical evidence from selected photovoltaic research laboratories or manufacturing facilities in Japan, thereby strengthening the applicability of findings to the country's photovoltaic technology development.

## **CONCLUSION AND RECOMMENDATIONS**

### **Conclusions**

Nanostructured surface modifications play a significant role in enhancing solar energy conversion efficiency in perovskite photovoltaic cells by improving light absorption, facilitating charge-carrier transport, reducing non-radiative recombination, and promoting photovoltaic stability. The

reviewed empirical studies demonstrate that surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering offer promising approaches for improving photovoltaic performance. Studies by Hu (2021), Pant (2020), and Cho (2021) established that surface treatments and defect passivation can enhance photovoltaic efficiency by reducing charge-carrier losses and improving material properties. However, existing research has largely focused on individual modification techniques under controlled laboratory conditions, leaving gaps in understanding their comparative and combined effects under different operational environments. Furthermore, although Japan has made considerable advancements in photovoltaic research, additional investigations are necessary to establish the effectiveness, durability, and scalability of integrated nanostructured surface modifications across different photovoltaic technologies. Therefore, the proposed study seeks to address the identified conceptual, contextual, and geographical research gaps by examining the influence of surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering on solar energy conversion efficiency in perovskite photovoltaic cells in Japan. The findings are expected to contribute to photovoltaic materials science by identifying effective surface engineering strategies, informing technological optimization, and supporting the development of efficient, durable, and commercially viable perovskite solar cells in Japan.

## **Recommendations**

### **Theory**

The study recommends the development of an integrated theoretical framework combining the Shockley–Queisser detailed balance theory, surface plasmon resonance theory, and Shockley–Read–Hall recombination theory to explain the relationship between nanostructured surface modifications and solar energy conversion efficiency in perovskite photovoltaic cells. Future researchers should investigate how surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering interact to influence photon absorption, charge-carrier transport, defect density, and non-radiative recombination. Particular emphasis should be placed on establishing the individual and combined effects of these modifications through controlled experimental investigations and quantitative modelling. The study's potential unique contribution to theory lies in developing and testing a multidimensional framework that integrates optical enhancement, electronic defect suppression, and interfacial charge-transfer mechanisms to explain variations in photovoltaic conversion efficiency. Such a framework could extend existing theoretical applications by demonstrating how different nanoscale surface engineering mechanisms interact to influence photovoltaic performance rather than examining them independently.

### **Practice**

The study recommends that photovoltaic researchers, manufacturers, and renewable energy technology developers in Japan adopt evidence-based surface engineering strategies that improve conversion efficiency while maintaining operational stability and manufacturing feasibility. Research institutions and photovoltaic manufacturers should conduct comparative experiments involving surface texturing, nanoparticle incorporation, surface passivation, and interfacial engineering under standardised testing conditions to determine their relative effectiveness. Furthermore, manufacturers should prioritise surface modification techniques that minimise charge-carrier recombination, improve light absorption, enhance material durability, and remain

compatible with scalable photovoltaic production methods. Collaboration between universities, research laboratories, and photovoltaic manufacturers should be strengthened to facilitate technology transfer and the commercial application of successful surface engineering approaches. The study's potential unique contribution to practice lies in identifying optimal surface modification techniques or combinations that can guide photovoltaic device design, improve manufacturing decisions, reduce efficiency losses, and support the development of commercially viable perovskite photovoltaic cells suited to Japan's technological and environmental conditions.

### **Policy**

The study recommends that the Japanese government, through relevant institutions such as the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO), strengthen support for research and development in advanced photovoltaic materials and nanostructured surface engineering. Policymakers should consider establishing targeted research funding programmes that encourage experimental comparisons of different surface modification techniques, particularly those demonstrating improvements in photovoltaic conversion efficiency, long-term stability, and manufacturing scalability. Additionally, relevant regulatory and standardisation institutions should promote consistent testing protocols for evaluating photovoltaic efficiency, environmental durability, material safety, and lifecycle performance before large-scale commercial deployment. Public–private partnerships should also be encouraged to accelerate the transition from laboratory-scale innovations to industrial photovoltaic manufacturing, while incorporating environmental safeguards for lead-containing perovskite materials. The study's potential unique contribution to policy lies in generating scientific evidence that could inform photovoltaic research funding priorities, technology performance standards, environmental protection measures, and renewable energy innovation strategies, thereby supporting Japan's transition toward a more sustainable and technologically advanced energy system.

## REFERENCES

- Ai, B., Fan, Z., & Wong, Z. J. (2022). Plasmonic–perovskite solar cells, light emitters, and sensors. *Microsystems & Nanoengineering*, 8, Article 5. <https://doi.org/10.1038/s41378-021-00334-2>
- Atsu, D., Seres, I., Aghaei, M., & Farkas, I. (2020). Analysis of long-term performance and reliability of PV modules under tropical climatic conditions in sub-Saharan. *Renewable Energy*, 162, 285–295. <https://doi.org/10.1016/j.renene.2020.08.021>
- Atwater, H. A., & Polman, A. (2010). Plasmonics for improved photovoltaic devices. *Nature Materials*, 9(3), 205–213. <https://doi.org/10.1038/nmat2629>
- Cho, Y., Bing, J., Kim, H. D., Li, Y., Zheng, J., Tang, S., Green, M. A., Wakamiya, A., Huang, S., Ohkita, H., & Ho-Baillie, A. W. Y. (2021). Immediate and temporal enhancement of power conversion efficiency in surface-passivated perovskite solar cells. *ACS Applied Materials & Interfaces*, 13(33), 39178–39185. <https://doi.org/10.1021/acsami.1c06878>
- Cui, D., Wang, Y., & Han, L. (2020). China's progress of perovskite solar cells in 2019. *Science Bulletin*, 65(15), 1306–1315. <https://doi.org/10.1016/j.scib.2020.04.028>
- Du, M., Zhu, X., Wang, L., Wang, H., Feng, J., Jiang, X., Cao, Y., Sun, Y., Duan, L., Jiao, Y., Wang, K., Ren, X., Yan, Z., Pang, S., & Liu, S. F. (2020). High-pressure nitrogen-extraction and effective passivation to attain highest large-area perovskite solar module efficiency. *Advanced Materials*, 32(47), Article 2004979. <https://doi.org/10.1002/adma.202004979>
- Green, M. A., . (2022). Solar cell efficiency tables (Version 60). *Progress in Photovoltaics: Research and Applications*, 30(7), 687–701. <https://doi.org/10.1002/pip.3595>
- Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Hao, X. (2021). Solar cell efficiency tables (Version 58). *Progress in Photovoltaics: Research and Applications*, 29(7), 657–667. <https://doi.org/10.1002/pip.3444>
- Hu, S., Truong, M. A., Otsuka, K., Handa, T., Yamada, T., Nishikubo, R., Iwasaki, Y., Saeki, A., Murdey, R., Kanemitsu, Y., & Wakamiya, A. (2021). Mixed lead–tin perovskite films with greater than 7  $\mu$ s charge carrier lifetimes realized by maltol post-treatment. *Chemical Science*, 12. <https://doi.org/10.1039/D1SC04221A>
- Jena, A. K., Kulkarni, A., & Miyasaka, T. (2019). Halide perovskite photovoltaics: Background, status, and future prospects. *Chemical Reviews*, 119(5), 3036–3103. <https://doi.org/10.1021/acs.chemrev.8b00539>
- Jiang, Q., Zhao, Y., Zhang, X., Yang, X., Chen, Y., Chu, Z., Ye, Q., Li, X., Yin, Z., & You, J. (2019). Surface passivation of perovskite film for efficient solar cells. *Nature Photonics*, 13, 460–466. <https://doi.org/10.1038/s41566-019-0398-2>
- Khadka, D. B., Shirai, Y., Yanagida, M., & Miyano, K. (2020). Attenuating the defect activities with a rubidium additive for efficient and stable Sn-based halide perovskite solar cells. *Journal of Materials Chemistry C*, 8, 2307–2313. <https://doi.org/10.1039/C9TC06206H>
- Kim, H.-J. (2021). Progress of perovskite solar modules. *Advanced Energy and Sustainability Research*, 2(6), 2000051. <https://doi.org/10.1002/aesr.202000051>

- Kwembur, I. M., Crozier McClelland, J. L., van Dyk, E. E., & Vorster, F. J. (2020). Detection of potential induced degradation in mono and multi-crystalline silicon photovoltaic modules. *Physica B: Condensed Matter*, Article 411938. <https://doi.org/10.1016/j.physb.2019.411938>
- Li, P., Jiang, X., Huang, S., Liu, Y., & Fu, N. (2021). Plasmonic perovskite solar cells: An overview from metal particle structure to device design. *Surfaces and Interfaces*, 25, 101287. <https://doi.org/10.1016/j.surfin.2021.101287>
- Liu, Z., Qiu, L., Ono, L. K., . (2020). A holistic approach to interface stabilization for efficient perovskite solar modules with over 2,000-hour operational stability. *Nature Energy*, 5, 596–604. <https://doi.org/10.1038/s41560-020-0653-2>
- Mondal, S., Eguchi, N., Nishimura, N., Hinuma, Y., Yamamoto, K., Kogo, A., Murakami, T. N., & Kanda, H. (2025). Mixed 2D-cation passivation towards improved durability of perovskite solar cells and dynamics of 2D-perovskites under light irradiation and at high temperature. *Sustainable Energy & Fuels*, 9, 247–255. <https://doi.org/10.1039/D4SE01227E>
- Pan, Y., Wang, J., Sun, Z., . (2024). Surface chemical polishing and passivation minimize non-radiative recombination for all-perovskite tandem solar cells. *Nature Communications*, 15, Article 7335. <https://doi.org/10.1038/s41467-024-51703-0>
- Pant, N., Kulkarni, A., Yanagida, M., Shirai, Y., Miyasaka, T., & Miyano, K. (2020). Investigating the growth of  $\text{CH}_3\text{NH}_3\text{PbI}_3$  thin films on RF-sputtered  $\text{NiO}_x$  for inverted planar perovskite solar cells: Effect of  $\text{CH}_3\text{NH}_3^+$  halide additives versus  $\text{CH}_3\text{NH}_3^+$  halide vapor annealing. *Advanced Materials Interfaces*, 7(3), Article 1901748. <https://doi.org/10.1002/admi.201901748>
- Pant, N., Yanagida, M., Shirai, Y., & Miyano, K. (2020). Effect of different surface treatments of sputtered  $\text{NiO}_x$  on the photovoltaic parameters of perovskite solar cells: A correlation study. *Applied Physics Express*, 13(2), Article 025505. <https://doi.org/10.35848/1882-0786/ab6bde>
- Rühle, S. (2016). Tabulated values of the Shockley–Queisser limit for single junction solar cells. *Solar Energy*, 130, 139–147. <https://doi.org/10.1016/j.solener.2016.02.015>
- Shen, L., Li, Z., & Ma, T. (2020). Analysis of the power loss and quantification of the energy distribution in PV module. *Applied Energy*, 260, 114333. <https://doi.org/10.1016/j.apenergy.2019.114333>
- Wu, T., . (2021). The main progress of perovskite solar cells in 2020–2021. *Nano-Micro Letters*, 13, Article 152. <https://doi.org/10.1007/s40820-021-00672-w>