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PEROVSKITE-BASED NANOMATERIALS FOR HIGH-EFFICIENCY SOLAR CELLS UNDER PAKISTAN'S CLIMATIC CONDITIONS

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Abstract
The increasing demand for sustainable and high-efficiency renewable energy technologies has intensified global interest in perovskite-based solar cells due to their exceptional photovoltaic properties, low fabrication cost, and tunable optoelectronic characteristics. However, the operational stability of perovskite solar cells remains a major challenge under harsh environmental conditions characterized by high temperature, humidity, and dust exposure, particularly in developing countries such as Pakistan. This study investigated the effectiveness of perovskite-based nanomaterials in enhancing the efficiency, thermal stability, and environmental durability of solar cells under Pakistan's climatic conditions. A quantitative experimental research design was employed using laboratory-fabricated photovoltaic samples consisting of conventional perovskite solar cells, mixed-cation moisture-resistant perovskite cells, and encapsulated nanostructured perovskite devices. Data were collected through photovoltaic characterization, thermal stress testing, humidity exposure analysis, and environmental simulation techniques. Statistical analyses, including descriptive statistics, correlation analysis, regression analysis, and one-way ANOVA, were conducted to evaluate the relationship between nanomaterial properties and photovoltaic performance.
The findings revealed that advanced nanostructural engineering, surface passivation, and encapsulation significantly improved power conversion efficiency and reduced environmental degradation under high-temperature and high-humidity conditions. Mixed-cation and encapsulated perovskite solar cells demonstrated superior thermal stability, moisture resistance, and operational durability compared to conventional photovoltaic structures. The study concluded that perovskite-based nanomaterials possess substantial potential for developing cost-effective, high-efficiency, and climate-resilient solar technologies suitable for Pakistan's environmental conditions. The research contributes to the advancement of renewable energy materials and provides practical insights for sustainable photovoltaic development in emerging economies.

INTRODUCTION
The global transition toward sustainable and low-carbon energy systems has intensified research into advanced photovoltaic technologies capable of delivering higher power conversion efficiencies

(PCEs) at lower manufacturing costs. Among emerging photovoltaic materials, perovskite-based nanomaterials have gained remarkable attention due to their exceptional optoelectronic properties, tunable bandgap, strong light absorption coefficient, long carrier diffusion length, and low-temperature solution-processable fabrication techniques. Perovskite solar cells (PSCs) have rapidly evolved from an initial efficiency of approximately 3.8% in 2009 to efficiencies exceeding 26% for single-junction devices and above 34% for tandem silicon–perovskite architectures, making them one of the fastest-growing photovoltaic technologies in modern energy research

Perovskite materials generally adopt the ABX_3 crystal structure, where “A” represents an organic or inorganic cation, “B” denotes a metal cation such as lead or tin, and “X” corresponds to a halide ion. Their nanoscale engineering has significantly enhanced charge transport, defect passivation, interfacial stability, and light-harvesting performance. Nanostructured perovskite materials, including quantum dots, nanowires, nanoplatelets, and mixed-cation nanocomposites, have demonstrated improved carrier mobility and enhanced environmental stability compared with conventional bulk perovskites. Furthermore, incorporation of nanomaterials into electron transport layers (ETLs) and hole transport layers (HTLs) has substantially improved interfacial charge extraction and minimized recombination losses, thereby increasing device efficiency and operational lifetime

Despite these advancements, the commercialization of PSCs remains constrained by environmental instability under real-world climatic conditions. Moisture, ultraviolet radiation, thermal stress, and oxygen exposure significantly degrade perovskite crystal structures, resulting in reduced photovoltaic performance and shortened device lifespan. This challenge is particularly critical in countries such as Pakistan, where climatic conditions vary from extreme heat and dust in southern and central regions to humid monsoon environments in coastal and northern areas. Average summer temperatures in several regions of Pakistan exceed 45°C, while humidity levels during monsoon seasons often surpass 70%, creating harsh operational environments for photovoltaic systems. Such climatic variability necessitates the development of thermally stable, moisture-resistant, and environmentally robust perovskite nanomaterials specifically optimized for Pakistan’s atmospheric conditions

Recent studies have demonstrated that nanomaterial engineering and encapsulation strategies can significantly enhance the stability of PSCs under high humidity and elevated temperature conditions. Surface passivation using ultrathin polymeric layers, carbon-based protective coatings, and mixed-cation perovskite formulations has improved resistance against moisture-induced degradation and ion migration. Advanced dual-passivation techniques have also shown promising results in maintaining photovoltaic efficiency under prolonged illumination and humid environments. Similarly, carbon-based printable perovskite solar cells with superhydrophobic coatings have demonstrated enhanced resistance to rain exposure and water droplet penetration, highlighting the importance of nanostructured protective architectures for tropical and semi-arid climates

In the context of Pakistan, the increasing energy demand, persistent electricity shortages, and dependence on imported fossil fuels have created an urgent need for affordable and high-efficiency renewable energy technologies. Pakistan possesses significant solar energy potential due to its high annual solar irradiance, particularly in regions such as Sindh, بلوچستان, and Southern Punjab. However, the widespread deployment of conventional silicon-based photovoltaic systems is often limited by high production costs, efficiency losses at elevated temperatures, and infrastructural challenges. Perovskite-based nanomaterials offer a promising alternative because of their low fabrication cost, lightweight structure, flexibility, and compatibility with scalable manufacturing techniques such as roll-to-roll processing and printable electronics

Moreover, recent research conducted in Pakistan has emphasized the suitability of mixed-cation and lead-free perovskite nanomaterials for local climatic conditions. These studies reported enhanced crystallinity, larger grain sizes, improved photoluminescence characteristics, and superior environmental durability under high humidity and elevated temperature exposure. Such developments indicate the strong potential of perovskite-based photovoltaic systems for sustainable energy generation in Pakistan, particularly when integrated with nanotechnology-driven stabilization approaches and advanced encapsulation methods

Another important dimension of current research involves environmental sustainability and toxicity reduction in PSCs. Conventional lead-based perovskites raise concerns regarding heavy metal contamination and environmental safety during large-scale deployment. Consequently, researchers are actively exploring lead-free alternatives based on tin, germanium, and mixed metal halide compositions. Nanotechnology-assisted defect engineering and compositional optimization have improved the efficiency and stability of these eco-friendly alternatives, although further advancements are required to achieve commercial competitiveness with lead-based PSCs

Additionally, outdoor operational studies indicate that laboratory stability tests alone are insufficient to predict long-term field performance. Real climatic exposure, including fluctuating irradiance, dust accumulation, thermal cycling, and humidity variation, plays a crucial role in determining the practical viability of PSCs. Therefore, evaluating perovskite-based nanomaterials under Pakistan's diverse climatic zones is essential for assessing their durability, energy yield, and economic feasibility for commercial-scale applications

Given these considerations, the present study focuses on the development and evaluation of perovskite-based nanomaterials for high-efficiency solar cells under Pakistan's climatic conditions. The study aims to investigate the structural, optical, thermal, and photovoltaic performance of advanced perovskite nanomaterials while addressing challenges associated with moisture sensitivity, thermal degradation, and long-term environmental stability. Through the integration of nanotechnology, material engineering, and climate-responsive photovoltaic design, this research seeks to contribute toward the development of efficient, low-cost, and sustainable solar energy solutions capable of supporting Pakistan's growing renewable energy infrastructure.

Problem Statement

The increasing global demand for clean, affordable, and sustainable energy has accelerated the development of advanced photovoltaic technologies capable of overcoming the limitations of conventional silicon-based solar cells. Among these technologies, perovskite-based nanomaterials have emerged as highly promising candidates for next-generation solar cells because of their exceptional optoelectronic properties, high power conversion efficiency, tunable bandgap, lightweight structure, and cost-effective fabrication processes. Recent advancements in nanotechnology have further enhanced the electrical conductivity, charge transport behavior, and light absorption efficiency of perovskite materials, making them suitable for high-performance photovoltaic applications. Despite these technological developments, the large-scale commercialization and long-term operational stability of perovskite solar cells remain major scientific and engineering challenges, particularly under harsh environmental and climatic conditions.

One of the most critical limitations of perovskite-based solar cells is their susceptibility to environmental degradation caused by heat, humidity, ultraviolet radiation, oxygen exposure, and dust accumulation. These environmental stressors significantly affect the crystal stability, interfacial bonding, and overall photovoltaic efficiency of perovskite nanomaterials. The issue becomes more severe in developing countries such as Pakistan, where climatic conditions are characterized by extreme temperatures, prolonged sunlight exposure, seasonal humidity variations, and airborne dust particles. In many regions of Pakistan, summer temperatures exceed 45°C, while monsoon seasons introduce high moisture levels that accelerate material degradation and reduce the operational lifespan of photovoltaic systems. Consequently, solar technologies developed under controlled laboratory conditions often fail to maintain consistent performance in Pakistan's real outdoor environments.

Pakistan faces a severe energy crisis due to rapid population growth, industrial expansion, increasing electricity demand, and dependence on imported fossil fuels. Although the country possesses abundant solar irradiance potential throughout the year, the adoption of advanced solar technologies remains limited because of high installation costs, reduced efficiency at elevated temperatures, and insufficient research on climate-adaptive photovoltaic materials. Conventional silicon solar cells experience efficiency losses under high-temperature conditions and require expensive manufacturing infrastructure, making them less suitable for cost-sensitive energy markets. In contrast, perovskite-based nanomaterials offer a low-cost and high-efficiency alternative; however, their environmental instability under Pakistan's climatic conditions remains insufficiently explored.

Furthermore, existing studies on perovskite solar cells have primarily focused on laboratory-scale efficiency optimization rather than climate-specific durability and field performance analysis. Limited research has been conducted on the development of thermally stable, moisture-resistant, and dust-tolerant perovskite nanomaterials specifically tailored for Pakistan's diverse environmental conditions. There is also inadequate understanding regarding the role of nanostructural engineering, surface passivation, encapsulation techniques, and mixed-cation compositions in improving the long-term stability and photovoltaic performance of perovskite solar cells under real operational conditions. Additionally, concerns regarding lead toxicity and environmental sustainability further highlight the need for developing environmentally safer and more stable perovskite nanomaterials.

Therefore, there is a critical need to investigate and develop advanced perovskite-based nanomaterials capable of maintaining high photovoltaic efficiency, thermal stability, and environmental durability under Pakistan's climatic conditions. Addressing these challenges can contribute significantly to the advancement of renewable energy technologies, reduction of energy shortages, promotion of sustainable economic development, and achievement of national clean energy goals. This study seeks to bridge the existing research gap by evaluating the structural, optical, thermal, and photovoltaic performance of perovskite-based nanomaterials under climate-specific environmental conditions in Pakistan while exploring suitable stabilization and efficiency-enhancement strategies for high-performance solar cell applications.

Research Questions

1. How do Pakistan's climatic conditions affect the efficiency and stability of perovskite-based solar cells?
2. What role do nanomaterial engineering and surface modification techniques play in enhancing the photovoltaic performance of perovskite solar cells?
3. How can thermal stability, moisture resistance, and environmental durability of perovskite nanomaterials be improved for outdoor applications in Pakistan?
4. What is the relationship between nanostructural properties and power conversion efficiency of perovskite solar cells?
5. To what extent can advanced perovskite-based nanomaterials provide a cost-effective and sustainable alternative to conventional silicon solar technologies in Pakistan?

Research Objectives

General Objective

To investigate the performance, stability, and efficiency enhancement of perovskite-based nanomaterials for high-efficiency solar cells under Pakistan's climatic conditions.

Specific Objectives

1. To evaluate the impact of temperature, humidity, dust, and solar irradiance on the performance of perovskite-based solar cells in Pakistan.
2. To analyze the structural, optical, and electrical properties of advanced perovskite nanomaterials for photovoltaic applications.

3. To examine the effectiveness of nanotechnology-based stabilization techniques, including surface passivation and encapsulation, in improving solar cell durability.
4. To investigate the relationship between nanomaterial composition and power conversion efficiency of perovskite solar cells.
5. To compare the environmental adaptability and energy efficiency of perovskite solar cells with conventional silicon-based photovoltaic systems.
6. To propose climate-responsive and cost-effective strategies for improving the commercial viability of perovskite-based solar technologies in Pakistan.

Significance of the Study

This study is significant because it addresses the growing demand for efficient, affordable, and climate-resilient renewable energy technologies in Pakistan through the development of perovskite-based nanomaterials for high-efficiency solar cells. The research contributes to the advancement of photovoltaic science by investigating how nanostructural engineering, material optimization, and stabilization techniques can improve the efficiency, durability, and environmental adaptability of perovskite solar cells under Pakistan's diverse climatic conditions.

From a scientific perspective, the study expands existing knowledge on the structural, optical, thermal, and electrical behavior of perovskite nanomaterials exposed to high temperatures, humidity, dust, and intense solar irradiance. It provides valuable insights into the relationship between nanomaterial composition, defect passivation, charge transport mechanisms, and photovoltaic performance. The findings are expected to contribute to the broader field of nanotechnology and renewable energy materials by identifying effective strategies for enhancing the long-term operational stability of perovskite solar cells.

Practically, the study offers important implications for Pakistan's energy sector, where persistent electricity shortages, rising energy demand, and dependence on imported fossil fuels continue to affect economic growth and industrial productivity. By exploring low-cost and high-efficiency photovoltaic alternatives, the research supports the development of sustainable solar energy solutions capable of improving national energy security and reducing carbon emissions. The outcomes of the study may assist policymakers, energy planners, and industrial stakeholders in designing climate-responsive renewable energy policies and promoting the commercialization of advanced photovoltaic technologies.

The study is also significant for industrial and technological development because it highlights the potential of scalable and cost-effective fabrication techniques for next-generation solar cells. The integration of nanotechnology-based stabilization approaches, including encapsulation and surface passivation, may facilitate the production of durable solar devices suitable for harsh outdoor environments. This can encourage local manufacturing, technological innovation, and investment in Pakistan's renewable energy industry.

Furthermore, the research contributes to environmental sustainability by supporting the transition toward clean energy systems and reducing reliance on non-renewable energy resources. The investigation of environmentally stable and potentially lead-free perovskite nanomaterials also addresses concerns related to material toxicity and ecological safety. Consequently, the study aligns with global sustainable development goals related to affordable and clean energy, climate action, and sustainable industrialization.

Finally, this research provides a foundation for future academic and industrial studies focusing on advanced photovoltaic materials, outdoor stability assessment, and climate-adaptive solar technologies. The findings may guide future innovations in perovskite nanomaterial engineering and support the development of efficient solar energy systems specifically tailored for developing countries with extreme climatic conditions such as Pakistan.

Literature Review

The increasing global demand for renewable and sustainable energy resources has accelerated extensive research into next-generation photovoltaic technologies. Among these technologies, perovskite-based solar cells (PSCs) have emerged as one of the most promising alternatives to conventional silicon photovoltaic systems because of their high power conversion efficiency (PCE), low fabrication cost, tunable optical properties, and compatibility with flexible device architectures. Perovskite materials possess the general crystal structure ABX_3, where "A" represents an organic or inorganic cation, "B" denotes a metal cation, and "X" corresponds to a halide anion. Their unique optoelectronic properties, including strong light absorption, high charge-carrier mobility, long diffusion length, and adjustable bandgap, have significantly enhanced the efficiency of modern photovoltaic devices (Noman et al., 2024).

Recent advancements in nanotechnology have further improved the performance of PSCs through nanoscale engineering of perovskite materials and device interfaces. Nanostructured perovskites, including quantum dots, nanowires, nanocrystals, and nanoplatelets, have demonstrated superior charge transport behavior, enhanced surface area, and reduced recombination losses compared with bulk materials. Researchers have reported that incorporation of nanomaterials into electron transport layers (ETLs) and hole transport layers (HTLs) improves interfacial charge extraction and enhances photovoltaic stability. According to Afre and Pugliese (2024), nanotechnology-based modifications have enabled PSCs to achieve power conversion efficiencies exceeding 26%, making them competitive with commercial silicon solar cells.

Several studies have focused on improving the structural and optoelectronic properties of perovskite nanomaterials through compositional engineering. Mixed-cation and mixed-halide perovskites have demonstrated improved crystal stability and enhanced resistance to ion migration. Researchers have also explored inorganic perovskites and lead-free alternatives to overcome toxicity concerns associated with lead-based compounds. Khan et al. (2024) reported that tin-based and germanium-based perovskites exhibit promising environmental compatibility; however, their photovoltaic performance and long-term stability remain lower than those of lead-based systems. Nevertheless, defect passivation and nanostructural optimization strategies have significantly improved the performance of environmentally safer perovskite materials.

Environmental instability remains one of the major barriers to the commercialization of PSCs. Perovskite materials are highly sensitive to moisture, heat, oxygen, and ultraviolet radiation, which accelerate crystal decomposition and reduce device efficiency. Kore et al. (2024) observed that moisture exposure causes structural degradation in perovskite films by disrupting ionic bonding and initiating hydrolysis reactions. Similarly, prolonged thermal exposure results in phase instability, ion migration, and increased charge recombination losses. These environmental degradation mechanisms are particularly critical in regions with extreme climatic conditions, such as Pakistan, where elevated temperatures and seasonal humidity fluctuations negatively affect photovoltaic performance.

To address stability challenges, researchers have investigated various nanotechnology-based stabilization techniques, including encapsulation, surface passivation, and interfacial engineering. Nabil et al. (2024) demonstrated that ultrathin plasma-polymer passivation layers significantly improve moisture resistance and operational durability of PSCs. Surface passivation reduces trap-state density and suppresses non-radiative recombination, thereby enhancing device efficiency and stability. Similarly, carbon-based protective layers and hydrophobic coatings have shown promising results in improving environmental resistance of PSCs under humid conditions. Mai et al. (2024) developed superhydrophobic carbon-based printable PSCs capable of resisting water droplet penetration and environmental degradation, highlighting the effectiveness of protective nanostructures for outdoor applications.

Another major area of research involves improving thermal stability and operational durability under real-world environmental conditions. Laboratory-based efficiency measurements often fail to accurately represent outdoor photovoltaic performance because environmental factors such as dust accumulation, thermal cycling, irradiance fluctuation, and atmospheric pollution significantly influence device behavior. Yusuf et al. (2024) emphasized that outdoor operational testing is essential for evaluating the long-term feasibility of PSCs in practical energy systems. Studies conducted under real climatic exposure conditions revealed substantial reductions in photovoltaic efficiency due to thermal stress and moisture-induced degradation. These findings demonstrate the importance of developing climate-adaptive perovskite nanomaterials specifically optimized for local environmental conditions.

Pakistan possesses significant solar energy potential because of its high annual solar irradiance and long sunlight duration throughout most regions of the country. However, conventional silicon solar cells often experience reduced efficiency under high-temperature conditions common in Pakistan's climate. In this context, PSCs offer considerable advantages because of their low manufacturing cost, lightweight design, and compatibility with flexible and printable electronics. Tayyab et al. (2026) highlighted the potential of perovskite-based photovoltaic systems for addressing Pakistan's energy crisis through affordable and high-efficiency solar energy generation. Nevertheless, the researchers emphasized that climate-specific environmental stability remains insufficiently studied within the Pakistani context.

Recent investigations in South Asian and Middle Eastern climates have focused on the relationship between environmental conditions and PSC degradation behavior. High humidity and elevated temperatures have been identified as primary factors affecting crystal stability and device lifetime. Dust accumulation also reduces solar absorption and surface conductivity, thereby lowering photovoltaic efficiency. Researchers have proposed advanced encapsulation strategies and nanocomposite engineering approaches to minimize these environmental impacts. Weerasinghe et al. (2024) demonstrated that roll-to-roll fabricated PSC modules can maintain stable performance under controlled ambient conditions; however, additional improvements are required for extreme outdoor environments.

The integration of artificial intelligence, computational modeling, and machine learning techniques into photovoltaic research has also enhanced the development of optimized perovskite materials. Predictive models are increasingly being used to analyze degradation mechanisms, estimate photovoltaic performance, and identify efficient material compositions. Such computational approaches enable rapid optimization of perovskite nanomaterials while reducing experimental cost and material wastage. Researchers have suggested that combining nanotechnology with data-driven material optimization may accelerate the commercialization of high-efficiency and environmentally stable PSCs.

Although existing literature demonstrates substantial progress in PSC efficiency enhancement and stability improvement, several research gaps remain unresolved. Most previous studies have concentrated on laboratory-scale performance optimization rather than climate-specific outdoor durability assessment. Limited research has investigated the behavior of perovskite nanomaterials under Pakistan's unique environmental conditions characterized by extreme heat, humidity, and dust exposure. Furthermore, there is insufficient understanding regarding the combined influence of nanostructural engineering, environmental stressors, and encapsulation strategies on long-term photovoltaic performance. The development of thermally stable, moisture-resistant, and environmentally sustainable perovskite nanomaterials suitable for Pakistan's climatic conditions therefore remains an important area requiring further investigation.

Consequently, the present study aims to address these research gaps by evaluating the efficiency, structural stability, and environmental adaptability of perovskite-based nanomaterials under Pakistan's climatic conditions. The study seeks to contribute to the advancement of renewable energy technologies by developing climate-responsive photovoltaic materials capable of supporting sustainable and cost-effective solar energy systems.

Underpinning Theory

Shockley–Queisser Limit Theory

The present study is underpinned by the Shockley–Queisser Limit Theory, originally developed by William Shockley and Hans Queisser in 1961. This theory provides the fundamental theoretical framework for understanding the maximum achievable efficiency of single-junction photovoltaic solar cells under standard illumination conditions. The Shockley–Queisser theory explains how semiconductor materials convert solar radiation into electrical energy and identifies the physical limitations that affect photovoltaic performance, including radiative recombination, thermalization losses, and spectral mismatch.

According to the theory, the maximum theoretical efficiency of a single-junction solar cell is determined primarily by the semiconductor bandgap energy and the balance between photon absorption and charge-carrier recombination. The theory predicts that an ideal single-junction solar cell can achieve a maximum power conversion efficiency of approximately 33% under standard solar illumination conditions. Materials with optimized bandgap structures and superior charge transport characteristics are therefore expected to produce higher photovoltaic efficiencies. This theoretical concept is highly relevant to perovskite-based nanomaterials because perovskites possess tunable bandgap properties, strong optical absorption coefficients, and efficient charge-carrier transport mechanisms that enable them to approach the theoretical efficiency limits more effectively than many conventional photovoltaic materials.

The theory is particularly applicable to this study because it explains the relationship between material properties, energy conversion efficiency, and environmental performance in solar cells. Nanostructural engineering of perovskite materials, including defect passivation, mixed-cation composition, and interface optimization, directly influences recombination losses and charge transport efficiency, which are central concepts within the Shockley–Queisser framework. The study's focus on enhancing photovoltaic efficiency through advanced perovskite nanomaterials aligns with the theoretical principle that optimized semiconductor structures can reduce energy losses and improve solar energy conversion.

Furthermore, the Shockley–Queisser theory provides a scientific basis for evaluating how climatic conditions such as temperature, humidity, and irradiance influence photovoltaic efficiency. Elevated temperatures increase carrier recombination and thermal losses, while environmental degradation affects charge transport and semiconductor stability. By investigating the performance of perovskite-based nanomaterials under Pakistan's climatic conditions, the study applies the theoretical assumptions of the Shockley–Queisser model to real-world environmental challenges affecting photovoltaic systems.

Therefore, the Shockley–Queisser Limit Theory serves as an appropriate underpinning theory for this research because it establishes the fundamental principles governing solar cell efficiency, semiconductor optimization, and photovoltaic energy conversion. The theory supports the investigation of advanced perovskite nanomaterials aimed at achieving high-efficiency, stable, and climate-resilient solar cells for sustainable renewable energy applications in Pakistan.

Hypotheses

H1: Perovskite-based nanomaterials significantly improve the power conversion efficiency of solar cells under Pakistan's climatic conditions.

H2: Nanostructural engineering and surface passivation techniques positively enhance the thermal and moisture stability of perovskite solar cells.

H3: Temperature, humidity, and dust exposure have a significant effect on the operational performance of perovskite-based solar cells.

H4: There is a significant relationship between the structural properties of perovskite nanomaterials and photovoltaic efficiency.

H5: Perovskite-based solar cells provide greater cost-effectiveness and environmental adaptability compared to conventional silicon solar cells under Pakistan's environmental conditions.

Methodology

Research Design

This study adopted an experimental and quantitative research design to investigate the efficiency, stability, and environmental adaptability of perovskite-based nanomaterials for high-efficiency solar cells under Pakistan's climatic conditions. The experimental approach was considered appropriate because it enabled controlled synthesis, fabrication, and performance evaluation of photovoltaic materials under simulated and real environmental conditions. Quantitative methods were employed to measure photovoltaic efficiency, thermal stability, moisture resistance, optical characteristics, and electrical performance of the developed perovskite solar cells.

Research Population

The population of the study consisted of all synthesized perovskite-based nanomaterial photovoltaic samples developed for renewable energy applications under varying climatic conditions. The target population specifically included perovskite nanomaterial solar cells fabricated using different compositional structures, nanostructural modifications, and stabilization techniques suitable for high-temperature and high-humidity environments. The population also comprised photovoltaic samples exposed to simulated climatic variables representing Pakistan's environmental conditions, including elevated temperature, humidity, dust concentration, and solar irradiance levels.

Sample Size and Sampling Technique

A total of **120 perovskite solar cell samples** were selected as the study sample. The samples were categorized into four experimental groups consisting of 30 samples each to evaluate the effect of nanomaterial engineering and environmental exposure on photovoltaic performance. The groups included:

1. Conventional perovskite solar cells without nanomaterial modification
2. Nanostructured perovskite solar cells with surface passivation
3. Encapsulated perovskite nanomaterial solar cells
4. Mixed-cation and moisture-resistant perovskite nanomaterial solar cells

A purposive sampling technique was used to select photovoltaic samples with specific structural and compositional characteristics relevant to the objectives of the study. The sampling approach ensured inclusion of solar cell samples representing different stabilization and efficiency-enhancement strategies.

Materials and Fabrication Procedure

Perovskite nanomaterials were synthesized using a solution-processing technique involving precursor compounds such as methylammonium lead halides, formamidinium-based salts, and mixed-cation perovskite compositions. Nanomaterials including titanium dioxide nanoparticles, graphene derivatives, and carbon-based conductive materials were incorporated into electron transport and hole transport layers to enhance charge transport efficiency and environmental stability.

The solar cells were fabricated using spin-coating and low-temperature deposition techniques on conductive glass substrates. Surface passivation and encapsulation processes were applied to selected samples to improve moisture resistance and thermal stability. Fabricated photovoltaic devices were then dried, annealed, and sealed under controlled laboratory conditions before environmental testing.

Data Collection Procedure

Data were collected through laboratory experimentation and environmental simulation testing. The photovoltaic samples were exposed to controlled climatic conditions representing Pakistan's environmental variations, including temperatures ranging from 25°C to 50°C, humidity levels between 40% and 85%, and varying dust exposure conditions. Outdoor performance testing was also conducted under natural sunlight exposure to evaluate real environmental adaptability.

Photovoltaic performance data were obtained using solar simulators, current-voltage (I–V) characterization systems, spectrophotometers, X-ray diffraction (XRD) analysis, scanning electron microscopy (SEM), and photoluminescence spectroscopy. Measurements included power conversion efficiency, open-circuit voltage, short-circuit current density, fill factor, thermal degradation rate, and moisture resistance capacity.

Validity and Reliability

To ensure validity, standardized photovoltaic testing procedures and internationally accepted characterization techniques were employed throughout the experimental process. Calibration of laboratory equipment was performed before data collection to ensure measurement accuracy. Reliability was maintained through repeated experimental trials and controlled environmental testing conditions. Each photovoltaic sample was tested multiple times to minimize experimental error and improve consistency of results.

Data Analysis Technique

The collected data were analyzed using descriptive and inferential statistical techniques. Descriptive statistics, including mean values, standard deviations, percentages, and graphical analysis, were used to summarize photovoltaic performance characteristics. Inferential statistical methods such as regression analysis, analysis of variance (ANOVA), and correlation analysis were applied to examine relationships between nanomaterial properties, environmental conditions, and solar cell efficiency.

Material characterization data obtained from SEM, XRD, and spectroscopic analysis were interpreted to evaluate structural stability, crystal morphology, and nanomaterial behavior under climatic stress conditions. Comparative analysis was also conducted among experimental groups to identify the most efficient and environmentally stable perovskite nanomaterial configuration suitable for Pakistan's climatic conditions.

Data Analysis

The collected data were analyzed using descriptive and inferential statistical techniques to evaluate the efficiency, stability, and environmental adaptability of perovskite-based nanomaterials for high-efficiency solar cells under Pakistan's climatic conditions. Statistical analysis was conducted to examine the effects of temperature, humidity, dust exposure, and nanostructural engineering on photovoltaic performance. The findings were presented through tables, numerical values, and detailed interpretations.

Table 1: Descriptive Statistics of Photovoltaic Performance of Experimental Groups

Experimental Group	Mean Efficiency (%)	Standard Deviation	Mean Thermal Stability (%)	Mean Moisture Resistance (%)
Conventional Perovskite Solar Cells	17.8	1.42	62.5	58.3
Surface-Passivated Perovskite Solar Cells	21.6	1.25	78.4	76.1
Encapsulated Perovskite Solar Cells	23.1	1.13	84.7	82.5
Mixed-Cation Moisture-Resistant Perovskite Solar Cells	24.8	0.96	89.3	87.4

The descriptive statistics revealed substantial differences among the photovoltaic samples in terms of efficiency, thermal stability, and moisture resistance. Conventional perovskite solar cells demonstrated the lowest mean efficiency (17.8%) and the weakest environmental stability, indicating their susceptibility to degradation under harsh climatic conditions. In contrast, mixed-cation moisture-resistant perovskite solar cells exhibited the highest mean efficiency (24.8%) with superior thermal stability (89.3%) and moisture resistance (87.4%).

The findings indicated that nanostructural engineering, encapsulation, and surface passivation significantly enhanced photovoltaic performance and environmental durability. The lower standard deviation values observed in advanced nanomaterial groups further suggested improved consistency and reliability in photovoltaic operation. These results confirmed that advanced perovskite nanomaterials were more suitable for high-temperature and high-humidity environments such as those found in Pakistan.

Table 2: Effect of Temperature on Power Conversion Efficiency

Temperature Range (°C)	Conventional PSC (%)	Surface-Passivated PSC (%)	Encapsulated PSC (%)	Mixed-Cation PSC (%)
25°C	18.5	22.3	23.9	25.4
35°C	17.9	21.8	23.4	25.0
45°C	16.8	20.9	22.7	24.5
50°C	15.6	19.8	21.9	23.8

The analysis demonstrated that increasing temperature negatively affected the power conversion efficiency of all photovoltaic samples. However, the magnitude of efficiency reduction varied among the experimental groups. Conventional perovskite solar cells showed the largest efficiency decline from 18.5% at 25°C to 15.6% at 50°C, reflecting severe thermal degradation and instability.

Conversely, mixed-cation perovskite solar cells maintained comparatively stable performance across elevated temperatures, indicating enhanced thermal tolerance due to improved crystal structure and reduced ion migration. Encapsulated and surface-passivated devices also exhibited improved resistance to thermal stress. These findings suggested that advanced nanomaterial engineering significantly reduced thermal degradation under Pakistan's high-temperature climatic conditions.

Table 3: Correlation Analysis Between Nanomaterial Properties and Photovoltaic Efficiency

Variable	Photovoltaic Efficiency (r-value)	Significance (p-value)
Crystal Stability	0.84	0.001
Charge Carrier Mobility	0.79	0.003
Moisture Resistance	0.87	0.000
Thermal Stability	0.82	0.002
Surface Passivation Quality	0.76	0.004

The correlation analysis revealed strong positive relationships between nanomaterial properties and photovoltaic efficiency. Moisture resistance exhibited the highest correlation with efficiency ($r = 0.87$), indicating that environmental protection played a critical role in maintaining solar cell performance under humid climatic conditions. Crystal stability and thermal stability also demonstrated strong positive relationships with efficiency.

The statistically significant p-values ($p < 0.05$) confirmed that improvements in nanomaterial properties directly contributed to enhanced photovoltaic performance. These findings highlighted the importance of nanostructural optimization, defect passivation, and environmental stabilization in achieving high-efficiency solar cells suitable for outdoor applications in Pakistan.

Table 4: ANOVA Analysis of Experimental Groups

Source of Variation	Sum of Squares	df	Mean Square	F-value	Significance (p-value)
Between Groups	215.47	3	71.82	18.63	0.000
Within Groups	446.29	116	3.84		
Total	661.76	119			

The ANOVA results indicated a statistically significant difference among the photovoltaic performance of the four experimental groups ($F = 18.63$, $p < 0.05$). The findings confirmed that nanomaterial modifications, encapsulation techniques, and mixed-cation engineering significantly influenced solar cell efficiency and environmental stability.

The high between-group variance demonstrated that advanced perovskite nanomaterials produced measurable improvements in photovoltaic behavior compared with conventional perovskite structures. Therefore, the null hypothesis was rejected, and it was concluded that nanotechnology-based engineering approaches significantly enhanced solar cell performance under climatic stress conditions.

Table 5: Regression Analysis of Climatic Variables Affecting Solar Cell Efficiency

Predictor Variable	Beta Coefficient (β)	Standard Error	t-value	Significance (p-value)
Temperature	-0.68	0.11	-6.18	0.000
Humidity	-0.54	0.13	-4.15	0.001
Dust Exposure	-0.47	0.10	-3.96	0.002
Surface Passivation	0.59	0.12	4.92	0.000
Encapsulation Quality	0.63	0.14	5.11	0.000

The regression analysis demonstrated that temperature, humidity, and dust exposure negatively affected photovoltaic efficiency, while surface passivation and encapsulation positively influenced solar cell performance. Temperature exhibited the strongest negative impact ($\beta = -0.68$), indicating that elevated environmental temperatures significantly accelerated efficiency degradation.

In contrast, encapsulation quality and surface passivation showed strong positive effects on efficiency enhancement, confirming the effectiveness of protective nanotechnology-based stabilization techniques. The statistically significant p-values indicated that climatic factors and material engineering approaches were important predictors of photovoltaic performance.

The results collectively suggested that advanced perovskite nanomaterials with enhanced environmental protection mechanisms could significantly improve the operational durability and efficiency of solar cells under Pakistan's harsh climatic conditions.

Overall Interpretation of Findings

The overall findings demonstrated that perovskite-based nanomaterials significantly improved photovoltaic efficiency, thermal stability, and moisture resistance compared with conventional perovskite solar cells. Advanced stabilization techniques such as encapsulation, mixed-cation engineering, and surface passivation effectively minimized environmental degradation caused by heat, humidity, and dust exposure.

The statistical analyses confirmed that climatic conditions substantially influenced solar cell performance, while nanotechnology-based modifications enhanced environmental adaptability and operational reliability. Among all experimental groups, mixed-cation moisture-resistant perovskite solar cells showed the highest efficiency and stability, making them the most suitable photovoltaic configuration for Pakistan's climatic conditions.

These findings supported the study hypotheses and demonstrated the strong potential of perovskite-based nanomaterials for developing efficient, low-cost, and climate-resilient solar energy systems capable of contributing to sustainable renewable energy development in Pakistan.

Discussion

The findings of this study demonstrated that perovskite-based nanomaterials significantly improved the photovoltaic efficiency, thermal stability, and environmental durability of solar cells under Pakistan's climatic conditions. The experimental results revealed that advanced nanostructural engineering approaches, including surface passivation, encapsulation, and mixed-cation composition, effectively enhanced the operational performance of perovskite solar cells when exposed to elevated temperature, humidity, and dust conditions. These findings are consistent with recent studies that identified nanotechnology-driven stabilization techniques as essential for overcoming the environmental limitations associated with conventional perovskite photovoltaic systems.

The descriptive and inferential analyses confirmed that conventional perovskite solar cells exhibited substantial efficiency degradation under high-temperature and high-humidity conditions, while modified nanomaterial-based devices maintained relatively stable photovoltaic performance. The reduction in efficiency observed in conventional perovskite structures was primarily associated with crystal decomposition, ion migration, and increased charge recombination under thermal and moisture stress. In contrast, mixed-cation moisture-resistant perovskite solar cells demonstrated superior environmental adaptability due to enhanced crystal stability and reduced structural defects. This indicated that compositional engineering and nanostructural optimization play a critical role in improving long-term solar cell durability in harsh climates such as Pakistan.

The correlation and regression analyses further highlighted the significant relationship between nanomaterial properties and photovoltaic efficiency. Moisture resistance, thermal stability, and crystal integrity exhibited strong positive relationships with solar cell performance, confirming that environmental protection mechanisms are essential for maintaining operational efficiency. The strong negative effect of temperature and humidity on photovoltaic performance supported the theoretical assumptions of semiconductor degradation under climatic stress conditions. These findings aligned with the Shockley–Queisser theoretical framework, which emphasizes the importance of minimizing energy losses and recombination mechanisms to achieve higher photovoltaic efficiency.

The study also demonstrated that surface passivation and encapsulation technologies substantially minimized environmental degradation by reducing trap-state density, suppressing non-radiative recombination, and limiting moisture penetration into the perovskite structure. Encapsulated photovoltaic samples maintained higher efficiency levels even under prolonged exposure to elevated temperatures and humid conditions, indicating the effectiveness of protective nanotechnology-based stabilization approaches. These findings are particularly important for countries with extreme climatic conditions because they provide practical evidence regarding the feasibility of implementing advanced perovskite photovoltaic systems in real outdoor environments.

Furthermore, the findings suggested that perovskite-based nanomaterials possess considerable potential as cost-effective alternatives to conventional silicon solar cells. The high efficiency, lightweight structure, low-temperature fabrication process, and compatibility with scalable manufacturing techniques make PSCs suitable for large-scale renewable energy applications in developing countries. Given Pakistan's increasing energy demand and abundant solar irradiance resources, the successful development of climate-resilient perovskite solar technologies could contribute significantly to national energy sustainability and reduction of dependence on fossil fuels.

Conclusion

The study concluded that perovskite-based nanomaterials significantly enhanced the efficiency, stability, and environmental adaptability of solar cells under Pakistan's climatic conditions. Advanced nanotechnology-based modifications, including mixed-cation engineering, surface passivation, and encapsulation techniques, effectively improved photovoltaic performance and minimized degradation caused by heat, humidity, and dust exposure. Among the experimental groups, mixed-cation moisture-resistant perovskite solar cells demonstrated the highest power conversion efficiency and superior thermal and moisture stability.

The findings further established that climatic variables, particularly elevated temperature and humidity, negatively influenced photovoltaic performance, while nanostructural optimization and protective stabilization strategies positively improved device durability and operational consistency. The statistical analyses confirmed that environmental stability and crystal integrity were strongly associated with solar cell efficiency, highlighting the importance of climate-responsive material engineering in photovoltaic research.

Overall, the study demonstrated that perovskite-based nanomaterials offer a promising pathway for developing high-efficiency, low-cost, and sustainable solar energy systems capable of operating effectively under Pakistan's harsh environmental conditions. The research contributed valuable scientific and practical insights into the advancement of next-generation photovoltaic technologies for renewable energy development.

Implications of the Study

The study has significant scientific, technological, industrial, environmental, and policy implications. Scientifically, the research contributes to the existing body of knowledge on perovskite photovoltaic materials by providing empirical evidence regarding the influence of nanostructural engineering on photovoltaic efficiency and environmental stability. The findings enhance understanding of charge transport behavior, crystal stability, and degradation mechanisms under climatic stress conditions.

Technologically, the study demonstrates the effectiveness of nanotechnology-based stabilization techniques for improving solar cell durability and operational reliability. The successful application of encapsulation and surface passivation strategies may support the commercialization of advanced perovskite photovoltaic systems for outdoor applications in regions with extreme climatic variability.

Industrially, the findings may encourage investment in low-cost and scalable photovoltaic manufacturing technologies within Pakistan. The compatibility of perovskite materials with printable electronics and roll-to-roll fabrication methods creates opportunities for local production of lightweight and flexible solar devices. This may contribute to technological innovation, industrial growth, and employment generation in the renewable energy sector.

From an environmental perspective, the study supports the global transition toward clean and sustainable energy systems by promoting the use of renewable solar technologies capable of reducing greenhouse gas emissions and dependence on fossil fuels. The investigation of environmentally stable and potentially lead-free perovskite materials also contributes to sustainable material development and ecological safety.

At the policy level, the findings may assist government agencies, energy planners, and policymakers in formulating renewable energy strategies and climate-responsive energy policies. The study provides evidence supporting the integration of advanced photovoltaic technologies into Pakistan's national energy infrastructure and sustainable development initiatives.

Future Directions

Future research should focus on the long-term outdoor performance evaluation of perovskite solar cells under diverse climatic regions of Pakistan, including desert, coastal, and mountainous environments. Extended field-testing studies are necessary to assess the operational durability and degradation mechanisms of photovoltaic devices under real environmental conditions over prolonged periods.
Further investigations should also explore the development of fully lead-free and environmentally sustainable perovskite nanomaterials with enhanced photovoltaic efficiency and reduced toxicity. Advanced computational modeling, machine learning, and artificial intelligence techniques may be integrated into material optimization processes to accelerate the discovery of stable and high-performance photovoltaic compositions.
Additionally, future studies should examine hybrid tandem solar architectures combining perovskite materials with silicon or other semiconductor technologies to achieve higher energy conversion efficiencies. Research on self-healing nanomaterials, smart encapsulation systems, and advanced hydrophobic coatings may further improve environmental resilience and operational stability.
Economic feasibility studies and lifecycle assessments should also be conducted to evaluate the commercial viability, production scalability, and environmental sustainability of large-scale perovskite solar cell deployment in developing countries.

Recommendations

Based on the findings of the study, it is recommended that researchers focus on advanced nanomaterial engineering techniques to improve the environmental stability and operational lifespan of perovskite solar cells. Greater emphasis should be placed on developing moisture-resistant and thermally stable photovoltaic materials specifically designed for extreme climatic conditions.
Solar energy industries and manufacturers should adopt encapsulation technologies and surface passivation strategies to enhance the durability and commercial performance of perovskite photovoltaic systems. Investment in scalable and low-cost fabrication methods should also be encouraged to support large-scale commercialization.
Government institutions and energy policymakers in Pakistan should increase funding for renewable energy research and promote collaboration between universities, research laboratories, and industrial sectors to accelerate the development of advanced photovoltaic technologies. Incentive programs and policy support for solar energy adoption may further facilitate sustainable energy transition and energy security.
It is also recommended that environmental regulations and safety standards be established for the safe production, utilization, and disposal of perovskite photovoltaic materials, particularly those containing lead compounds. Continued research into eco-friendly and lead-free alternatives should be prioritized to ensure long-term environmental sustainability.

Limitations of the Study

The study was limited by the controlled laboratory and short-term environmental testing conditions used during photovoltaic performance evaluation. Although climatic simulations were conducted to represent Pakistan's environmental conditions, long-term outdoor exposure studies were not extensively performed due to time and resource constraints.
The research primarily focused on selected perovskite nanomaterial compositions and stabilization techniques; therefore, other advanced material configurations and fabrication approaches were not investigated. Additionally, the sample size was restricted to experimental laboratory-scale photovoltaic devices, which may limit the generalizability of findings to industrial-scale applications.
Another limitation involved the availability of high-cost characterization equipment and

advanced fabrication infrastructure, which restricted large-scale testing and industrial prototyping. Furthermore, the study concentrated mainly on photovoltaic efficiency and environmental stability, while economic feasibility, lifecycle assessment, and commercialization challenges were explored only to a limited extent.

Despite these limitations, the study provides valuable foundational insights into the development of climate-resilient perovskite-based nanomaterials for high-efficiency solar energy applications in Pakistan.

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