

A REVIEW OF ANALYSIS OF DUST ACCUMULATION EFFECTS ON SOLAR PV PERFORMANCE WITH AN OPTIMIZED CLEANING STRATEGY: EXPERIMENTAL AND IoT-BASED APPROACH

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Abstract - Dust accumulation on solar photovoltaic (PV) panels is a critical factor that significantly degrades system performance, particularly in arid and semi-arid regions. This review paper presents a comprehensive analysis of the impact of dust deposition on PV efficiency, integrating findings from experimental studies, analytical models, and emerging intelligent monitoring approaches. The paper systematically examines the mechanisms of dust accumulation, including environmental and panel-specific factors, and evaluates their influence on optical, electrical, and thermal characteristics of PV systems. A detailed synthesis of laboratory and field-based experimental research is provided to highlight variations in performance loss under different conditions. Furthermore, existing cleaning strategies, ranging from conventional manual methods to advanced robotic and self-cleaning technologies, are critically assessed in terms of effectiveness, cost, and sustainability. Special emphasis is placed on optimized cleaning strategies that balance energy recovery and operational costs through data-driven decision-making. In addition, the role of Internet of Things (IoT)-based systems in real-time monitoring, dust detection, and automated cleaning is explored, demonstrating their potential to enhance maintenance efficiency and system reliability. The review identifies key research gaps, including the lack of standardized dust measurement techniques and limited integration of IoT with optimization frameworks, and proposes future directions for developing intelligent, cost-effective PV maintenance solutions.

Key Words: Solar photovoltaic (PV), Dust accumulation (soiling), PV performance degradation, Cleaning optimization, IoT-based monitoring, Smart maintenance systems

1. INTRODUCTION

The rapid expansion of solar photovoltaic (PV) technology has positioned it as a cornerstone of the global transition toward sustainable and low-carbon energy systems. However, despite continuous advancements in PV materials and system design, environmental factors remain a major constraint on achieving optimal performance. Among these, dust accumulation—commonly referred to as soiling—has emerged as a critical challenge, particularly in regions with

high particulate matter and limited rainfall. This section introduces the background, identifies the core problem, and defines the objectives of this review.

1.1 Background

The increasing demand for clean energy has accelerated the deployment of solar PV systems worldwide due to their scalability, declining costs, and environmental benefits. Solar PV plays a vital role in reducing greenhouse gas emissions and dependence on fossil fuels, thereby supporting global energy sustainability goals (IEA, 2023). However, the actual energy yield of PV systems often deviates from expected values due to environmental and operational factors.

Environmental conditions such as temperature, humidity, wind speed, and airborne particles significantly influence PV performance. Among these, dust accumulation is particularly detrimental because it directly obstructs solar irradiance from reaching the PV cells, thereby reducing energy conversion efficiency. The severity of this impact varies depending on dust composition, particle size, and local climatic conditions. In extreme cases, studies have reported efficiency losses ranging from 10% to as high as 70%, especially in desert and industrial regions where dust deposition rates are high (Mani and Pillai, 2010).

1.1.1 Importance of Solar PV in Global Energy Transition

Solar PV has become one of the fastest-growing renewable energy technologies due to its modular nature and declining installation costs. It contributes significantly to decentralized power generation and energy security, particularly in developing regions. The integration of PV systems into smart grids and hybrid energy systems further enhances their relevance in modern power systems (IRENA, 2022).

1.1.2 Role of Environmental Factors Affecting PV Efficiency

PV performance is highly sensitive to environmental parameters. Elevated temperatures reduce module efficiency, while humidity and wind influence cooling and dust deposition patterns. Dust accumulation, in particular, causes optical losses by reducing light transmittance and can also lead to non-uniform shading, which affects electrical characteristics such as current mismatch and hotspot formation.

1.1.3 Dust Accumulation as a Critical Issue Impacting Energy Yield

Dust deposition on PV panels forms a semi-transparent layer that blocks incident sunlight, leading to reduced power output. The impact is cumulative and becomes more severe over time without cleaning. Additionally, the adhesion properties of dust particles, influenced by humidity and electrostatic forces, make natural cleaning (e.g., rainfall) insufficient in many regions, thereby necessitating active maintenance strategies (Sarver et al., 2013).

1.2 Problem Statement

Despite extensive research on PV soiling, several critical challenges remain unresolved. One of the primary issues is the lack of standardized cleaning strategies that can be universally applied across different environmental and operational conditions. Existing approaches vary widely in terms of frequency, method, and cost-effectiveness, leading to inconsistent maintenance practices.

Furthermore, experimental findings on dust impact exhibit significant variability due to differences in geographical locations, dust characteristics, and PV technologies. This lack of uniformity complicates the development of generalized models and guidelines. Another key limitation is the insufficient integration of intelligent systems for decision-making. Traditional cleaning methods are often reactive rather than predictive, resulting in either excessive maintenance costs or avoidable energy losses. Therefore, there is a growing need for optimized, intelligent cleaning strategies that leverage real-time data and advanced analytics.

1.3 Objectives of the Review

This review aims to provide a comprehensive and structured analysis of dust accumulation effects on solar PV performance. First, it examines the physical and operational impacts of dust deposition on PV systems by synthesizing findings from existing literature. Second, it critically reviews

both experimental and analytical studies to identify trends, discrepancies, and key influencing factors.

In addition, the review evaluates various cleaning strategies, including conventional and advanced techniques, with a focus on their efficiency, cost implications, and sustainability. A significant emphasis is placed on optimization approaches that balance cleaning frequency with energy recovery. Finally, the paper explores the role of Internet of Things (IoT)-based monitoring and automation systems in enabling smart PV maintenance, highlighting their potential to improve system reliability and operational efficiency.

2. METHODOLOGY OF LITERATURE REVIEW

A systematic literature review methodology is essential for ensuring transparency, reproducibility, and scientific rigor in review-based research. In the context of solar PV soiling studies, a structured approach enables the identification, evaluation, and synthesis of relevant research contributions across diverse domains such as experimental analysis, modeling, and intelligent monitoring systems. This section outlines the methodology adopted to collect, filter, and analyze the literature included in this review.

2.1 Literature Search Strategy

The literature search was conducted using major scientific databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect, to ensure comprehensive coverage of high-quality peer-reviewed publications. These databases are widely recognized for indexing journals with significant impact in the fields of renewable energy and power systems. A combination of relevant keywords and Boolean operators was used to retrieve articles, including terms such as “dust accumulation”, “soiling”, “PV performance”, “cleaning strategy”, and “IoT PV monitoring”. The search strategy was designed to capture interdisciplinary research spanning environmental science, electrical engineering, and smart systems. This systematic search process minimizes selection bias and ensures that the review encompasses both foundational and recent advancements in the field (Kitchenham and Charters, 2007).

2.2 Inclusion and Exclusion Criteria

To maintain the quality and relevance of the review, specific inclusion and exclusion criteria were defined. The inclusion criteria focused on peer-reviewed journal articles published between 2015 and 2026, ensuring that the analysis reflects recent technological developments and contemporary research trends in solar PV systems. Only studies directly related to PV performance under dust or soiling conditions

were considered. In contrast, studies that addressed general environmental pollution without a clear connection to PV systems were excluded. Conference papers with insufficient experimental validation and non-English publications were also omitted to ensure consistency and reliability in the reviewed data. This filtering process helps in narrowing down the most impactful and methodologically sound studies for detailed analysis (Tranfield et al., 2003).

2.3 Classification of Reviewed Studies

The selected literature was systematically categorized into four primary groups to facilitate structured analysis and comparison. First, experimental studies include both laboratory-controlled and field-based investigations that quantify the impact of dust on PV performance. Second, analytical and modeling studies involve the development of mathematical models, simulations, and predictive frameworks to estimate soiling losses. Third, cleaning strategy research focuses on various dust mitigation techniques, including manual, mechanical, and advanced self-cleaning methods. Finally, IoT and AI-based monitoring studies examine the integration of sensors, data analytics, and automation for real-time performance tracking and intelligent maintenance. This classification enables a multidimensional understanding of the problem and highlights the interconnections between physical phenomena, system performance, and technological solutions (Sarver et al., 2013).

2.4 Research Trends and Publication Analysis

An analysis of research trends provides valuable insights into the evolution and current direction of studies related to dust accumulation on PV systems. The year-wise distribution of publications indicates a significant increase in research output after 2018, driven by the growing deployment of solar energy systems and the recognition of soiling as a major performance constraint. Region-wise analysis reveals that a substantial portion of the research originates from arid and semi-arid regions such as the Middle East, North Africa, and parts of Asia, where dust-related losses are more pronounced. Additionally, recent studies show a clear shift toward the integration of advanced technologies, including IoT, machine learning, and automated cleaning systems, reflecting the transition from conventional maintenance approaches to smart and data-driven solutions. These trends highlight the increasing emphasis on optimization and intelligent system design in modern PV research (Elminir et al., 2006).

3. FUNDAMENTALS OF DUST ACCUMULATION ON SOLAR PV PANELS

Dust accumulation, commonly referred to as soiling, is a critical environmental phenomenon that adversely affects the performance and reliability of solar photovoltaic (PV) systems. It involves the deposition of airborne particles on the surface of PV modules, leading to reduced solar irradiance transmission and subsequent efficiency losses. Understanding the fundamental characteristics, deposition mechanisms, and influencing factors of dust accumulation is essential for developing effective mitigation and maintenance strategies.

3.1 Definition and Types of Dust (Soiling)

Soiling in PV systems refers to the accumulation of particulate matter on the surface of solar panels, which obstructs incoming solar radiation and degrades energy output. The composition and characteristics of dust vary significantly depending on the surrounding environment. Natural dust primarily consists of soil particles, sand, and mineral residues transported by wind. In industrial areas, pollutants such as carbon particles, ash, and chemical residues contribute to more adhesive and light-absorbing deposits. Additionally, biological particles such as pollen, bird droppings, and microbial residues can also accumulate on panel surfaces, further exacerbating performance degradation. The variability in dust composition influences both the optical and adhesive properties of the deposited layer, thereby affecting the severity of soiling losses (Sarver et al., 2013).

3.2 Mechanisms of Dust Deposition

Dust deposition on PV panels occurs through several physical mechanisms governed by atmospheric dynamics and particle properties. Wind transport plays a dominant role by carrying airborne particles over long distances and facilitating their interaction with panel surfaces. Once the wind velocity decreases, particles settle on the panel due to gravitational forces, a process known as gravity settling. In addition, electrostatic forces contribute to the adhesion of fine particles, especially under dry conditions where static charges accumulate on the panel surface. These mechanisms often act simultaneously, leading to complex deposition patterns that depend on environmental conditions and particle characteristics. The interaction between these forces determines the rate and persistence of dust accumulation on PV modules (Mani and Pillai, 2010).

3.3 Factors Influencing Dust Accumulation

Dust accumulation is not uniform and is influenced by a combination of environmental, structural, and geographical factors. These factors determine both the rate of deposition and the ease with which dust can be removed naturally or through cleaning processes.

3.3.1 Environmental Factors

Environmental conditions play a significant role in governing dust deposition and removal. Wind speed affects both the transport and resuspension of particles; moderate winds enhance deposition, while strong winds may remove loosely bound dust. Humidity influences particle adhesion by promoting moisture-induced bonding between dust and the panel surface. Rainfall acts as a natural cleaning mechanism, although its effectiveness depends on intensity and frequency. Temperature variations can also impact the physical properties of dust and the panel surface, indirectly affecting accumulation patterns. The combined effect of these parameters creates dynamic soiling conditions that vary over time (El-Shobokshy and Hussein, 1993).

3.3.2 Panel-Related Factors

The design and physical characteristics of PV panels significantly influence dust accumulation behavior. Tilt angle is one of the most critical factors; panels installed at higher tilt angles tend to accumulate less dust due to gravitational shedding and improved rainwater runoff. Surface roughness affects the adhesion of particles, with smoother surfaces generally experiencing lower dust retention. Additionally, advanced surface coatings, such as hydrophobic or anti-soiling coatings, can reduce particle adhesion and enhance self-cleaning capabilities. These panel-related factors are crucial in determining the maintenance requirements and long-term performance of PV systems.

3.3.3 Geographical and Seasonal Variations

Geographical location and seasonal changes have a pronounced impact on dust accumulation patterns. Arid and semi-arid regions, characterized by low rainfall and high dust availability, experience significantly higher soiling rates compared to humid regions where frequent precipitation aids natural cleaning. Seasonal variations, such as dry seasons or agricultural activities, can lead to increased airborne dust concentrations. Furthermore, land use patterns, including urbanization and industrialization, influence the type and concentration of particulate matter in the atmosphere. As a result, dust deposition varies

significantly with climate and land use, making location-specific analysis essential for accurate performance assessment and maintenance planning (Sayyah et al., 2014).

4. IMPACT OF DUST ACCUMULATION ON PV PERFORMANCE

Dust accumulation on solar photovoltaic (PV) modules directly affects energy generation by altering optical, electrical, and thermal behaviors of the system. The presence of particulate matter on the panel surface reduces incident solar radiation, disrupts current flow, and increases thermal stress, ultimately leading to significant performance degradation. This section provides a structured analysis of these effects based on established findings in the literature.

4.1 Optical Effects

The primary impact of dust deposition is observed in the optical domain, where it obstructs the transmission of solar irradiance to the photovoltaic cells. Dust particles form a semi-transparent layer over the panel surface, reducing the amount of light that reaches the active semiconductor layer. This reduction in transmittance depends on particle size, composition, and density, with finer particles typically causing more severe scattering and absorption of light.

In addition to general attenuation, dust accumulation can create non-uniform shading across the panel surface. Such partial shading leads to mismatch losses in PV cells connected in series, where the performance of the entire string is limited by the weakest cell. These optical losses are often the initial trigger for further electrical and thermal degradation in PV systems (Hottel and Woertz, 1942).

4.2 Electrical Performance Degradation

Dust-induced optical losses translate directly into electrical performance degradation. Since the generation of electrical current in PV cells is proportional to the incident solar irradiance, any reduction in light intensity results in lower current output and reduced overall system efficiency.

4.2.1 I-V and P-V Characteristics

The impact of dust accumulation is clearly reflected in the current-voltage (I-V) and power-voltage (P-V) characteristics of PV modules. One of the most significant effects is the reduction in short-circuit current (I_{sc}), which decreases proportionally with the reduction in incident light. In contrast, the open-circuit voltage (V_{oc}) is less sensitive to dust but may still experience minor reductions under severe soiling conditions.

Furthermore, the maximum power point (MPP) shifts downward, resulting in a decrease in maximum power output. This degradation becomes more pronounced with increasing dust density and non-uniform deposition patterns. Experimental studies have demonstrated that even moderate levels of dust can lead to noticeable reductions in output power, affecting the economic viability of PV installations (Mohamed et al., 2016).

4.3 Thermal Effects

Dust accumulation also contributes to adverse thermal effects in PV modules. The presence of a dust layer increases the absorption of solar radiation on the panel surface, leading to elevated operating temperatures. Higher temperatures reduce the efficiency of PV cells due to increased carrier recombination and reduced voltage output.

In addition, non-uniform dust deposition can cause localized heating, known as hotspot formation. Hotspots occur when certain cells receive less light due to shading, causing them to operate in reverse bias and dissipate energy as heat. This not only reduces efficiency but can also lead to long-term damage, including material degradation and potential module failure. These thermal effects further compound the overall performance loss caused by soiling (Skoplaki and Palyvos, 2009).

4.4 Quantitative Performance Loss

Quantitative analysis of dust effects reveals a strong correlation between dust density and power loss in PV systems. As the concentration of deposited particles increases, the reduction in energy output becomes more significant. Empirical studies have established relationships between dust accumulation (measured in g/m^2) and efficiency loss, enabling predictive modeling of performance degradation.

Experimental investigations indicate that fine dust particles, due to their higher surface coverage and stronger adhesion, can cause power losses of up to approximately 31% under controlled conditions. The severity of these losses varies depending on environmental conditions, cleaning frequency, and panel characteristics. Such findings underscore the importance of regular maintenance and optimized cleaning strategies to sustain PV system performance (Sayyah et al., 2014).

5. REVIEW OF EXPERIMENTAL STUDIES ON DUST EFFECTS

Experimental investigations form the backbone of research on dust accumulation in solar photovoltaic (PV) systems, providing empirical evidence of performance degradation under controlled and real-world conditions. These studies enable the quantification of soiling losses, validation of analytical models, and evaluation of mitigation strategies. This section synthesizes key findings from both laboratory-based and field-based experiments, followed by a comparative and critical analysis.

5.1 Laboratory-Based Experimental Studies

Laboratory-based experiments are designed to isolate and control variables influencing dust accumulation, allowing precise evaluation of its impact on PV performance. In controlled dust deposition experiments, researchers apply known quantities and types of dust onto PV module surfaces to simulate soiling conditions. These setups enable systematic variation of parameters such as particle size, density, and distribution, facilitating detailed analysis of optical and electrical losses.

Artificial dust simulation is another widely used approach, where standardized materials (e.g., silica, carbon particles) are used to replicate environmental dust. Such simulations help in understanding the interaction between dust properties and PV surfaces under repeatable conditions. Laboratory studies have demonstrated that fine particles cause greater efficiency loss due to higher surface coverage and stronger adhesion, even at lower mass densities. These controlled experiments are essential for establishing baseline relationships between dust characteristics and performance degradation (El-Shobokshy and Hussein, 1993).

5.2 Field-Based Experimental Studies

Field-based studies provide real-world insights into the effects of dust accumulation under varying environmental conditions. These experiments typically involve long-term monitoring of PV systems installed in outdoor environments, where performance metrics such as power output, irradiance, and temperature are continuously recorded. Real-time outdoor performance monitoring allows researchers to capture the dynamic nature of soiling, including deposition and natural cleaning events such as rainfall.

Seasonal variation studies further enhance understanding by analyzing how dust accumulation changes across different times of the year. For instance, higher soiling rates are often

observed during dry seasons, while rainy periods contribute to partial or complete cleaning of panel surfaces. Field experiments conducted in arid and semi-arid regions consistently report higher efficiency losses compared to humid regions. These studies highlight the importance of location-specific maintenance strategies and provide valuable data for validating predictive models (Mani and Pillai, 2010).

5.3 Comparative Analysis of Experimental Results

A comparative analysis of experimental studies reveals significant variability in reported results, primarily due to differences in geographical location, dust composition, and PV technology. For example, panels exposed to desert dust typically experience higher performance losses compared to those in urban environments, where particulate matter may have different optical properties. Similarly, the type of PV technology—such as monocrystalline, polycrystalline, or thin-film—affects the sensitivity to dust accumulation.

Variations in experimental methodologies, including measurement techniques and cleaning intervals, also contribute to inconsistencies across studies. Some experiments report linear relationships between dust density and efficiency loss, while others observe nonlinear behavior due to factors such as particle clustering and partial shading. This diversity of findings underscores the need for standardized testing protocols and unified performance metrics to enable more consistent comparisons (Sarver et al., 2013).

5.4 Key Findings from Literature

A synthesis of experimental literature reveals several consistent trends regarding dust effects on PV performance. One of the most important findings is the strong correlation between dust density and efficiency loss, with higher deposition levels leading to greater reductions in power output. This relationship is influenced by particle size, composition, and environmental conditions, but remains a fundamental characteristic of PV soiling behavior.

Another critical insight is the influence of cleaning frequency on system performance. Regular cleaning significantly improves energy yield, but excessive cleaning can increase operational costs and resource consumption, particularly in water-scarce regions. Therefore, determining an optimal cleaning schedule is essential for balancing performance recovery and maintenance expenses. These findings emphasize the importance of integrating experimental data

with optimization techniques to develop efficient and sustainable cleaning strategies (Sayyah et al., 2014).

6. IOT-BASED MONITORING AND SMART CLEANING SYSTEMS

The integration of Internet of Things (IoT) technologies into solar photovoltaic (PV) systems has transformed traditional maintenance practices into intelligent, data-driven processes. IoT enables continuous monitoring, early fault detection, and automated decision-making, which are essential for mitigating dust-related performance degradation. This section reviews the role of IoT, sensing technologies, system architecture, and the integration of artificial intelligence (AI) for smart PV maintenance.

6.1 Role of IoT in PV Systems

IoT plays a pivotal role in modern PV systems by enabling real-time monitoring of operational parameters such as irradiance, temperature, power output, and environmental conditions. Through interconnected sensors and communication networks, system operators can access live performance data and identify anomalies caused by dust accumulation. Real-time monitoring facilitates timely intervention, reducing energy losses and improving system reliability. Moreover, IoT platforms support remote diagnostics and predictive maintenance, which are particularly beneficial for large-scale solar farms distributed across remote locations (Gubbi et al., 2013).

6.2 Sensors for Dust Detection

Accurate detection of dust accumulation is essential for implementing effective cleaning strategies. Optical sensors are commonly used to measure transmittance loss or irradiance reduction caused by dust layers on PV panels. These sensors provide quantitative data on soiling levels and are often integrated with reference clean panels for comparative analysis.

In addition, image processing systems have gained prominence for dust detection. These systems use cameras combined with computer vision algorithms to analyze surface conditions and identify dust patterns. Advanced techniques leverage machine learning models to classify dust severity and predict its impact on performance. Compared to traditional sensors, image-based methods offer higher spatial resolution and adaptability to varying environmental conditions (Kim et al., 2020).

6.3 IoT Architecture for Smart PV Maintenance

A typical IoT architecture for smart PV maintenance consists of four key layers: data acquisition, communication, data processing, and control. At the data acquisition level, sensors collect real-time information on environmental and system parameters. This data is transmitted through communication networks to cloud-based platforms, where it is stored and processed.

The analytics layer applies algorithms to interpret the data, detect anomalies, and estimate soiling levels. Based on these insights, control signals are generated to trigger maintenance actions such as cleaning. This end-to-end architecture—data acquisition → cloud → analytics → control—enables automated and efficient management of PV systems. Such frameworks significantly enhance operational efficiency by minimizing manual intervention and optimizing resource utilization (Al-Fuqaha et al., 2015).

6.4 Integration with AI and Automation

The integration of AI with IoT further enhances the capability of PV maintenance systems by enabling predictive and autonomous operations. Predictive cleaning systems use historical and real-time data to forecast dust accumulation trends and determine optimal cleaning schedules. These systems reduce unnecessary cleaning while preventing excessive performance losses.

Autonomous robotic cleaning is another significant advancement, where robots equipped with sensors and control systems perform cleaning operations without human intervention. These robots can operate based on AI-driven decisions, adapting to environmental conditions and panel configurations. The combination of IoT, AI, and automation represents a paradigm shift toward smart and sustainable PV system management (Qasem et al., 2019).

7. COMPARATIVE DISCUSSION AND CRITICAL ANALYSIS

A comprehensive review of the literature reveals both advancements and limitations in current approaches to addressing dust accumulation in PV systems. This section synthesizes key findings, identifies research gaps, discusses challenges, and outlines future research directions.

7.1 Synthesis of Literature Findings

The literature consistently agrees that dust accumulation significantly reduces PV performance, with losses varying depending on environmental conditions and maintenance

practices. Experimental and analytical studies converge on the importance of regular cleaning and the effectiveness of advanced monitoring systems. However, contradictions arise in the reported magnitude of efficiency loss and the effectiveness of different cleaning techniques, largely due to variations in dust characteristics, climatic conditions, and experimental methodologies. While some studies advocate frequent cleaning, others emphasize optimization to balance cost and performance, highlighting the need for context-specific solutions (Sarver et al., 2013).

7.2 Research Gaps Identified

Despite extensive research, several gaps remain in the field. One major limitation is the lack of standardized methods for measuring dust accumulation and quantifying soiling losses. Different studies use varied metrics, making it difficult to compare results and develop universal guidelines. Additionally, there is limited integration of IoT systems with optimization frameworks, particularly in terms of combining real-time monitoring with cost-benefit analysis for cleaning decisions. This gap restricts the practical implementation of intelligent maintenance strategies in large-scale PV systems.

7.3 Challenges

The adoption of advanced IoT and AI-based solutions faces several challenges. High initial costs associated with sensors, communication infrastructure, and automation systems can be a barrier, especially for small-scale installations. Furthermore, regional variability in environmental conditions complicates the design of generalized solutions, as strategies effective in one location may not be suitable for another. Issues related to data reliability, system interoperability, and maintenance of IoT devices also pose additional challenges in real-world deployments (Said et al., 2018).

7.4 Future Research Directions

Future research should focus on the development of hybrid systems that integrate IoT and AI for intelligent and adaptive PV maintenance. Such systems can leverage real-time data and predictive analytics to optimize cleaning schedules and improve energy yield. Additionally, advancements in smart coatings and materials, such as self-cleaning and anti-soiling surfaces, hold significant potential for reducing maintenance requirements.

Further work is also needed to establish standardized protocols for dust measurement and performance evaluation, enabling more consistent and comparable

research outcomes. The convergence of material science, data analytics, and automation technologies is expected to drive the next generation of efficient and sustainable PV systems.

8. CONCLUSION

This review comprehensively analyzed the impact of dust accumulation on solar photovoltaic (PV) performance by synthesizing findings from experimental, analytical, and technology-driven studies. Dust deposition was identified as a critical factor causing significant optical, electrical, and thermal degradation, ultimately reducing energy yield. The review highlighted that the extent of performance loss is highly dependent on environmental conditions, dust characteristics, and system design parameters. Experimental studies consistently demonstrated a strong relationship between dust density and efficiency reduction, while also emphasizing the importance of location-specific analysis. Various cleaning strategies, ranging from manual methods to advanced robotic and self-cleaning technologies, were critically evaluated, revealing trade-offs between cost, effectiveness, and sustainability. Furthermore, the integration of Internet of Things (IoT) and artificial intelligence (AI) technologies has emerged as a promising solution for real-time monitoring, predictive maintenance, and optimized cleaning scheduling. Despite these advancements, the absence of standardized methodologies and inconsistent findings across studies remain key concerns. Overall, this review underscores the necessity of adopting intelligent, data-driven approaches for maintaining PV performance. Future developments should focus on integrating optimization techniques with IoT-based systems to achieve efficient, cost-effective, and sustainable solar energy generation, particularly in dust-prone regions.

9. LIMITATIONS OF THE REVIEW

This review is subject to certain limitations that should be acknowledged. First, the analysis is restricted to peer-reviewed studies published within a defined time frame, which may exclude relevant earlier contributions or emerging unpublished research. Second, variability in experimental methodologies, dust measurement techniques, and reporting standards across studies makes direct comparison challenging. Third, the review primarily focuses on commonly studied PV technologies, with limited coverage of emerging or niche systems. Additionally, regional bias exists, as a significant portion of the literature originates from dust-prone areas, potentially limiting the generalizability of findings to other climates. Finally, while

IoT and AI-based approaches are discussed, their large-scale practical implementation and long-term performance validation remain insufficiently explored in the available literature.

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