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Review of Failure Modes by Component and Future Direction in Photovoltaic Module with Bibliometric Approach

Priyo Heru Adiwibowo[1*], Muhammad Zohri[2], Lalu Ahmad Didik Meiliyadi[2], Muslizainun Mustapha[3]

[1] Department of Mechanical Engineering, Universitas Negeri Surabaya, Kampus Unesa 1, Surabaya 60231, Indonesia
[2] Department of Physics Education, Universitas Islam Negeri Mataram, Mataram 83116, Indonesia
[3] Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia

Corresponding Author Email: priyoheruadiwibowo@unesa.ac.id

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ABSTRACT

The reliability of photovoltaic (PV) modules is a critical concern for the sustainable deployment of solar energy, as degradation and failure phenomena significantly affect their performance and lifespan. This study aims to review failure modes by component and identify future research directions using a bibliometric approach. A comprehensive literature search and keyword co-occurrence analysis were conducted to map dominant degradation mechanisms, environmental triggers, and emerging trends in reliability research. The results indicate that glass breakage, backsheet cracking and delamination, solar cell fractures, and junction box or diode failures are the most prevalent failure modes, often accelerated by thermal cycling, moisture ingress, and electrical stress. Material interactions, such as encapsulant degradation producing corrosive by-products, further exacerbate reliability issues. Bibliometric visualization reveals three major research clusters: material aging and durability, system optimization, and advanced diagnostic techniques, with machine learning (ML) and recycling emerging as trending topics. These findings highlight a shift toward predictive maintenance, AI-driven fault detection, and sustainable end-of-life (EOL) management. This review underscores the need for integrated multi-stress testing, improved material formulations, and intelligent monitoring frameworks to enhance PV module resilience. By consolidating current knowledge and identifying research gaps, the study provides a roadmap for developing durable, cost-effective, and environmentally responsible PV technologies.

1. INTRODUCTION

The degradation and failure of photovoltaic (PV) modules are critical issues that influence their performance and longevity. Various environmental stresses and material inconsistencies contribute to these degradation phenomena, leading to reduced efficiency and potential complete failure. Understanding these mechanisms is essential for enhancing the resilience and lifespan of PV systems. A significant factor in PV module degradation is environmental conditions, which can exacerbate various failure modes. Studies indicate that high temperatures, especially in humid climates, can increase thermal stress, leading to failures such as delamination and discoloration of the encapsulant and resulting in decreased short-circuit current (I_{SC}) and fill factor (FF) [1, 2]. For instance, prolonged exposure to elevated temperatures and humidity has been shown to correlate with significant degradation of ethylene-vinyl acetate (EVA) encapsulant and potential-induced degradation (PID), which adversely affects the electrical performance of modules in hot, humid regions [3].

Material-related degradation is also prominent, with encapsulants such as EVA being particularly susceptible to ultraviolet (UV) exposure and moisture ingress, leading to discoloration and loss of optical transmission [4]. Consequently, the degraded optical properties impair the module's power generation, potentially resulting in performance losses exceeding 50% [3]. Furthermore, the mechanical integrity of the module is compromised by thermal cycling-induced stress, which can cause fracturing of solder joints and intercell connections [5]. Moreover, studies reveal that the most critical failure modes often originate from solder joint degradation. Increased series resistance from cracked or fatigued solder joints can lead to localized hotspots, exacerbating thermal stresses and accelerating degradation [6]. The occurrence of these hotspots is often linked to suboptimal module design and operational stressors such as shading or soiling of PV surfaces, which may exacerbate resistive losses in the system [7].

The interaction between different materials used in PV constructions, such as backsheet materials and glass, is also critical. The mismatch in thermal expansion coefficients between glass, the encapsulant, and the cells may cause deformation and potential delamination under operational stresses [8, 9]. Understanding this interplay is essential for predicting and analyzing failures within modules, leading to enhanced designs that mitigate these degradation pathways [10]. Furthermore, accelerated aging tests have been instrumental in elucidating degradation mechanisms. These tests replicate real-world conditions and help establish failure rates and the reliability of PV systems [11]. For example, accelerated thermal cycling has been shown to induce mechanical failures similar to those observed in long-term field deployments, thus providing valuable insights into long-term performance expectations [12].

This study aims to unravel the complex landscape of PV module reliability by systematically mapping and analyzing failure modes across individual components through a bibliometric approach. By integrating quantitative bibliometric analysis with a qualitative literature review, the research seeks to identify dominant degradation mechanisms, their environmental and material-driven triggers, and the cascading effects on module performance and lifespan. Beyond cataloging existing knowledge, the objective is to expose critical research gaps and emerging trends that can guide innovation toward more durable, cost-effective, and sustainable PV technologies. Ultimately, this work aims to provide a strategic roadmap for future investigations that bridges the interplay among design optimization, material resilience, and operational stress mitigation to pursue next-generation solar energy solutions.

2. BIBLIOMETRIC ANALYSIS

Data were retrieved from the Scopus database on November 6, 2025. During the identification phase, 999 records were identified, of which 39 duplicate records were removed. In the screening phase, 960 records were assessed based on titles and abstracts, resulting in the exclusion of 659 records and the retention of 340 records for further evaluation. During the eligibility phase, full-text assessment was conducted, and 256 records met the eligibility criteria. Following the inclusion process, 190 studies were deemed relevant. Of these, 27 studies were ultimately included in the review, as they corresponded closely to the predefined keywords recycling, delamination, and machine learning (ML) and were considered most relevant to the objectives of the study.

The selected publications were subsequently analyzed using VOSviewer to conduct a bibliometric analysis, enabling the visualization and assessment of research trends, keyword co-occurrence patterns, and relationships among authors and publications within the selected dataset. To facilitate effective network analysis and overlay visualization, the keyword co-occurrence threshold in VOSviewer was limited to approximately 26 keywords. These publications represent a focused sub-sample and were used primarily to identify current research areas and emerging hot topics within the studied field.

The Boolean search logic for the topic “Degradation and Failure Phenomena in PV Modules” focuses on identifying studies that examine physical, chemical, or electrical deterioration in solar modules. A comprehensive search string can be formulated as: ("PV module" OR "solar module" OR "solar panel" OR "PV module") AND ("degradation" OR "aging" OR "failure" OR "defect" OR "damage" OR "crack" OR "delamination" OR "corrosion" OR "discoloration" OR "potential induced degradation" OR "PID" OR "hot spot") AND ("phenomena" OR "mechanism" OR "analysis" OR "characterization" OR "monitoring" OR "diagnosis" OR "modeling"). This logic ensures the retrieval of studies covering both degradation behavior and failure mechanisms, while optional refinements (e.g., AND "silicon" OR "thin film" OR "perovskite") allow focusing on specific PV technologies or materials.

The inclusion criteria prioritize literature that directly investigates the causes, processes, and impacts of degradation and failure in PV modules. Eligible studies may involve experimental testing, accelerated aging, outdoor exposure, or simulation-based reliability analysis. Research addressing thermal, mechanical, or electrical stress, and diagnostic methods such as electroluminescence (EL), infrared thermography, or I–V characterization, is included. Only peer-reviewed journal articles, conference papers, or technical reports written in English and relevant to PV module reliability are selected to maintain scientific rigor and consistency.

The exclusion criteria remove studies unrelated to degradation or failure mechanisms in PV systems. Papers focusing purely on energy output optimization, policy or economic analysis, or non-PV renewable systems are excluded. Additionally, general reviews without new data, studies centered solely on power electronics or inverters, and works lacking any discussion of material or structural degradation are filtered out. This approach narrows the search scope to ensure retrieved literature specifically addresses degradation and failure phenomena affecting the long-term performance and durability of PV modules.

Figure 1 shows the number of documents by year in Scopus. The research trend for documents on “degradation and failure phenomena in PV modules” shows consistent interest from 2023 to 2025, with annual publications exceeding 300. This stability indicates that the topic is well-established and continues to attract researchers' attention, likely due to the growing importance of PV reliability in renewable energy systems. The slight increase in 2025 suggests ongoing advancements or emerging challenges in module degradation studies, possibly driven by innovations in materials and long-term performance analysis. However, the sharp decline in 2026, with fewer than 20 documents, is most likely due to incomplete data for the current year rather than an actual decrease in research activity. Such patterns are common in bibliometric analyses when the final year of observation is still in progress.

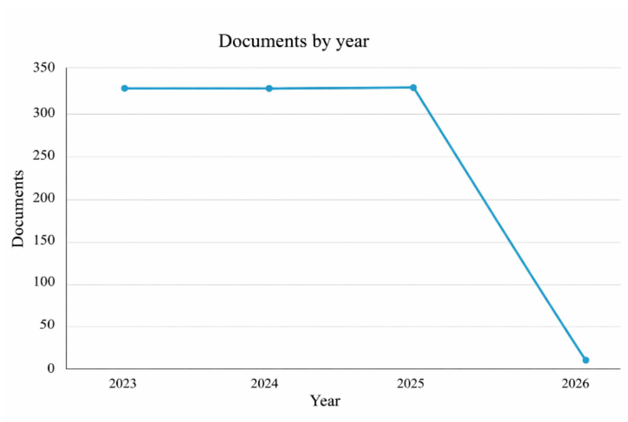

Figure 1. Documents by year

Figure 2 shows the network visualisation generated by VOSviewer, illustrating the co-occurrence structure of keywords for research on “degradation and failure phenomena in PV modules." The map reveals three major clusters. The red cluster focuses on reliability and degradation-related terms, such as degradation, degradation rate, durability, and backsheet, indicating studies focused on material aging and performance deterioration. The blue cluster emphasizes general PV concepts, including solar energy, renewable energy, efficiency, and maximum power point tracking, reflecting broader research on system optimization and energy conversion. Meanwhile, the green cluster highlights advanced diagnostic and predictive approaches, featuring keywords such as deep learning, ML, fault diagnosis, and EL, suggesting a strong trend toward AI-driven fault detection and performance monitoring.

This visualization demonstrates the interdisciplinary nature of the topic, bridging materials science, energy engineering, and artificial intelligence. The dense connections between clusters indicate that degradation studies are increasingly integrated with predictive modeling and renewable energy optimization. For instance, links between PV modules and deep learning suggest a growing interest in using AI for early failure detection, while connections to EL point to advanced imaging techniques for defect analysis. Overall, the network reflects a shift from traditional reliability assessments toward data-driven and automated solutions, highlighting emerging research directions in PV module performance and sustainability.

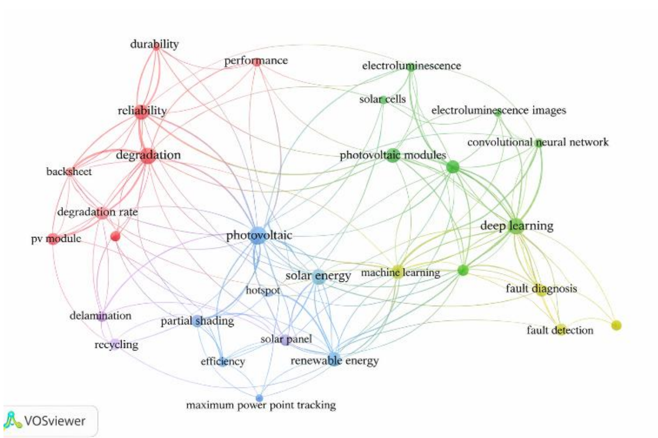

Figure 2. Network visualization

The keyword "recycling" is a trending keyword, as shown in Figure 3, and is colored yellow. The recycling of PV modules, particularly regarding degradation and failure phenomena, is receiving increasing attention as the global push for sustainability intensifies. Advances in recycling technology, economic feasibility, and ecological benefits form the cornerstone of this discourse. According to Walzberg et al. [13], sociotechnical factors significantly influence the effectiveness of recycling initiatives. They identify that understanding the economic implications of end-of-life (EOL) PV modules, including costs for manufacturers, recyclers, and installers, is vital to sustainability in the circular economy (CE) of PV systems. This perspective aligns with D'Adamo et al. [14]'s exploration of the economic viability of recycling crystalline silicon PV modules, which highlights emissions reduction through material recovery and profitability in various market contexts. Their research underscores that, with effective recovery efforts, financial benefits can be realized alongside environmental gains.

Technological enhancements in recycling processes have become more pronounced, as outlined by Lee et al. [15], who describe the necessary steps for recycling, including dismantling and decomposing module components. These improvements have gradually lower operational costs; however, the existing high initial cost often impedes widespread adoption. Innovations such as the low-energy chemical delamination processes described by Vaněk et al. [16] exemplify ongoing efforts to develop simpler, more efficient recycling methodologies. Research indicates various failure mechanisms related to module degradation. The dominant sources of degradation in crystalline silicon PV modules include structural weakening of the encapsulant due to thermal stress, solder joint failure caused by mechanical stress, and material fatigue over time [5, 17]. Studies by Pozza and Sample [17] highlight the specific degradation dynamics observed during extended field exposure, providing critical insights for reliability assessments of PV technologies [18]. Additionally, Jordan et al. [18] refined these ideas by emphasizing the need for consistent definitions and classifications of degradation and failure modes to improve predictive analytics in the industry.

The promotion of high-value material extraction from EOL modules has become a recurring theme, with suggestions to focus more on recycling silicon powder rather than whole wafers to optimize economic returns and sustainability [19]. Emerging initiatives also address the challenges presented by new materials in next-generation PV products, which may undergo different degradation pathways that remain largely unexplored [20, 21]. To bolster the recycling industry, efficient operational models must be implemented to assess degradation mechanisms comprehensively. Mulazzani et al. [19] advocated for a greater focus on this aspect, asserting that understanding failure modes should be evaluated alongside current and emerging recycling techniques [22]. In this context, the relentless improvement of predictive modeling frameworks can significantly enhance module reliability predictions, as emphasized by Springer et al. [20].

The keyword delamination is trending, as shown in Figure 3, and is colored yellow. The phenomena of delamination, degradation, and failure in PV modules have garnered increasing attention in recent years, reflecting the growing deployment of PV technologies and the critical need to ensure their reliability and longevity. Delamination can occur at various interfaces within the module structure, adversely affecting both electrical performance and mechanical integrity of the system. It primarily manifests at the interfaces between the encapsulant material and the solar cells or the glass cover, due to a loss of adhesion induced by environmental factors or material degradation. Research indicates that failure mechanisms may originate from multiple sources, such as moisture ingress and thermal fluctuations, which exacerbate the degradation of encapsulation materials, such as EVA [23, 24]. For instance, moisture can infiltrate through the backsheet due to mechanical stress or material fatigue, facilitating delamination and promoting other failure modes such as discoloration and reduced insulation [25].

Delamination can also be exacerbated by PID, particularly in crystalline silicon-based PV modules. PID leads to the migration of sodium ions from the glass, which can result in reaction-induced delamination at the transparent conductive oxide (TCO) layer interface within the module [26]. This finding underscores the critical importance of material selection and layer adhesion in preventing failures, especially under the high-voltage biases typical of operational environments [27]. The implications of delamination are profound: it not only reduces energy yield but also acts as a catalyst for more extensive degradation. For a PV module, early signs of structural failure might not manifest immediately in efficiency losses; however, subsequent environmental exposure can lead to severe damage, such as cell cracking and glass breakage. Research findings suggest that monitoring and assessing these early markers can substantially improve maintenance strategies and module longevity [28, 29].

Furthermore, the methods used to diagnose and characterize delamination are continually evolving. Advanced techniques, such as fluorescence imaging and non-destructive testing, have become valuable for assessing the extent of degradation and determining failure modes without compromising module integrity [30]. Enhanced characterisation of delamination phenomena is critical to improving design resilience and ensuring that PV systems can withstand the operational stresses expected throughout their lifetimes. As the field evolves, it is evident that understanding the multifaceted nature of delamination and degradation is pivotal. Strategies focusing on materials innovation, enhanced encapsulation techniques, and predictive maintenance will be essential to maximize the operational lifespan and efficiency of PV systems [31]. Ongoing challenges from environmental effects, electrical stresses, and material fatigue will likely continue to shape research trajectories in PV reliability and sustainability.

The keyword ML is a trending keyword, as shown in Figure 3, and is colored yellow. The application of ML to analyze degradation and failure phenomena in PV modules is rapidly evolving. Recent studies indicate a strong trend towards leveraging advanced AI techniques for efficient monitoring, fault detection, and maintenance optimization of PV systems. By employing diverse ML architectures, researchers have reported significant enhancements in predictive maintenance and fault diagnosis, which are essential for maximizing the operational efficiency and longevity of solar energy systems. One promising research avenue is the integration of ML with traditional methods to improve fault detection. For instance, Rchid et al. [32] emphasized a dual maintenance strategy whereby techniques such as XGBoost and Random Forest are used for real-time fault detection, while Artificial Neural Networks (ANN) and Convolutional Neural Networks (CNN) are utilized to track gradual degradation over time, thus fostering preventive maintenance. This integrated framework not only aids in timely detection but also significantly reduces operational costs and enhances energy efficiency.

A pivotal study by Li [33] highlights the application of a stacked auto-encoder network to predict stiffness degradation in PV modules, particularly in instances where pre-existing cracks are present. The model demonstrated a high predictive accuracy, with an R^2 value of 0.961 and a low root mean square error (RMSE) of 4.02%, underscoring the potential of ML in condition monitoring of PV modules. This indicates that ML models can effectively capture the complex behaviors of PV systems under real-world conditions, thus facilitating early intervention and maintenance. Furthermore, Namoune et al. [34] introduced a robust ML and deep learning framework that incorporates systematic variation of Single Diode Model (SDM) parameters to evaluate PV module health conditions. By generating synthetic datasets reflective of realistic degradation scenarios, this approach could automate fault classification and improve detection accuracy. Efforts like these exemplify ongoing innovations in ML model optimisation increasingly aligned with the physical realities of PV modules.

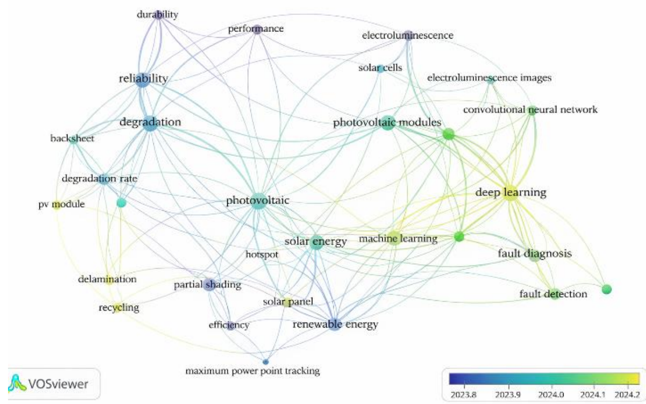

Figure 3. Overlay visualization

Advancements in defect detection methodologies, such as the YOLOv7-GX algorithm discussed by Wang et al. [35], further illustrate the growing trend of employing deep learning for real-time identification of faults, including hot spots and structural damage. These proactive measures are crucial; as noted by Badr et al. [36], the increasing proliferation of PV systems necessitates rapid fault detection to maintain grid stability and overall efficiency. Moreover, advances in monitoring technologies, as highlighted by Seigneur [37], offer opportunities to reduce the Levelized Cost of Energy (LCOE) through proactive monitoring systems that incorporate ML-driven analysis of IV curve measurements at both string and module levels. Such advancements facilitate a detailed understanding of degradation patterns that affect performance and support strategic financial planning in PV installations.

3. FAILURE MODES IN PHOTOVOLTAIC MODULES

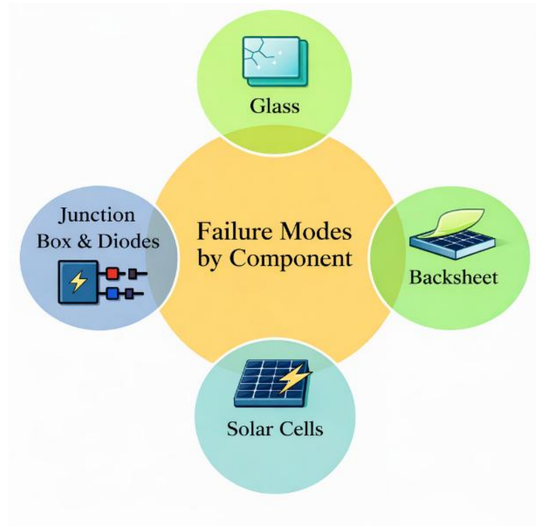

Figure 4. The failure modes by component in the photovoltaic (PV) module

Failure modes in PV modules vary by component. The glass can suffer breakage due to mechanical stress or erosion of protective coatings, compromising structural integrity and light transmission. The backsheet, which insulates and protects the module, often experiences cracking, chalking, or delamination under UV exposure and thermal cycling, leading to moisture ingress and electrical hazards. Solar cells face electrical degradation, such as PID, Light-Induced Degradation (LID), and Light and Elevated Temperature Induced Degradation (LETID), along with physical issues such as microcracks and hotspots that reduce efficiency and can trigger thermal damage. Finally, the junction box and diodes, critical for electrical connectivity and safety, are prone to failures like arcing and thermal runaway, which can cause catastrophic module failure or fire risks, as shown in Figure 4.

3.1 Glass in photovoltaic modules

Glass is a critical component in PV modules, primarily serving as the front cover and increasingly as the rear cover in bifacial designs. Low-iron soda-lime float glass is widely adopted due to its high optical transparency, mechanical strength, and cost-effectiveness. Beyond its role as an effective electrical insulator and barrier against moisture and gas ingress, glass ensures the long-term durability of PV modules under diverse environmental conditions [38]. The standard thickness for PV glass is typically 3.2 mm, although variations exist for applications such as building-integrated photovoltaics (BIPV) [39].

Despite the application of strengthening processes such as tempering or annealing, glass breakage remains the most common failure mode in PV modules [40]. Breakage can occur during transportation, installation, or operation due to thermal and mechanical stresses, including hot spots, static loads, and dynamic forces [41]. Frameless modules are particularly susceptible to edge impacts and improper clamping during installation. For crystalline silicon (c-Si) modules, glass fracture does not necessarily lead to immediate performance loss, as the cells and encapsulant may remain intact. Conversely, in thin-film modules, glass breakage can directly compromise functionality and accelerate degradation by eliminating the barrier properties against moisture and oxygen [18]. These findings underscore the critical importance of mechanical design and handling protocols to mitigate the risks of breakage [42].

Anti-reflective (AR) and anti-soiling coatings applied to PV glass are designed to minimize optical losses due to reflection and surface contamination. Reflection losses typically account for approximately 4%, while soiling can lead to power losses exceeding 50% under severe conditions [43, 44]. However, these coatings gradually erode due to environmental exposure, reducing their effectiveness over time. Although coating degradation does not pose a direct safety hazard, it results in a measurable decline in power output, emphasizing the need for improved coating durability and maintenance strategies [43].

Encapsulant discoloration is primarily attributed to additive degradation rather than polymer chain photo-oxidation [45, 46]. This phenomenon reduces light transmission to the cells, causing power loss. Although modern encapsulant formulations exhibit improved stability, discoloration remains a concern for long-term field performance [24, 47, 48]. Delamination, another critical failure mode, occurs due to diminished interlayer adhesion resulting from physical and chemical aging [49, 50]. This defect facilitates moisture ingress, accelerating cell degradation and corrosion.

Material interactions further exacerbate reliability issues. For instance, the degradation of EVA can generate acetic acid, which promotes corrosion, PID, and oxidation of metallic contacts [51]. Key encapsulant properties, such as polarity, electrical resistivity, and water vapor permeability, significantly influence these degradation pathways. Consequently, research efforts are increasingly directed toward developing alternative encapsulant materials with enhanced resistance to environmental stressors [45].

3.2 Backsheet in photovoltaic modules

The backsheet serves as a critical component of PV modules, providing electrical insulation and environmental protection. Typically, backsheets are multilayered structures comprising an outer weather-resistant layer, a middle electrical-insulating layer (commonly polyethene terephthalate, PET), and an inner adhesive layer, often EVA [24]. Fluoropolymer-based materials such as polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF), and fluorinated ethylene-propylene (FEP) are commonly used for the outer layer due to their strong carbon–fluorine bonds, which confer superior resistance to environmental degradation [52]. However, cost considerations have driven the adoption of non-fluoropolymer alternatives such as PET, polyamide, and polyolefin, which, although more economical, exhibit reduced weatherability and long-term durability [53].

Backsheet degradation is highly dependent on its material composition and structural configuration. The most common failure modes include discoloration, chalking, cracking, and delamination [54]. Discoloration typically results from photo-oxidation processes that generate chromophoric species responsible for yellowing [55]. Although discoloration does not immediately impair module performance, it serves as an early indicator of chemical and physical deterioration that may progress to embrittlement and cracking [56]. To mitigate UV-induced degradation, pigments such as titanium dioxide (TiO_2) and barium sulfate ($BaSO_4$) are often incorporated into the outer layer. Nevertheless, surface degradation can lead to chalking and gloss loss, compromising aesthetic quality and signalling advanced material ageing [57].

Cracking and delamination represent severe failure modes that significantly impact module reliability. Cracks in the backsheet reduce electrical insulation, increase leakage current, and allow moisture ingress, accelerating corrosion and degradation of internal components. Cracking is generally associated with polymer chain scission and increased crystallinity due to prolonged weathering [55]. Delamination occurs either at the encapsulant–backsheet interface or between backsheet layers, often triggered by poor adhesion or environmental stressors such as damp heat and UV exposure [58]. When delamination develops near module edges or junction boxes, it poses electrical safety hazards, whereas delamination in the central region can increase thermal resistance, leading to elevated cell operating temperatures [59].

Comparative studies reveal that fluoropolymer-based backsheets exhibit superior resistance to UV radiation, moisture, and thermal cycling compared to non-fluoropolymer alternatives [60]. Although non-fluoropolymer backsheets are more cost-effective, they are more susceptible to early-stage degradation, such as chalking and cracking, under accelerated aging conditions [55]. Field investigations further indicate that degradation patterns vary significantly across different climatic zones, underscoring the importance of selecting materials tailored to specific environmental exposures [61].

Recent research emphasizes the need for advanced polymer formulations and multilayer designs that balance cost, durability, and sustainability [52].

3.3 Solar cell

Cell cracking is one of the most critical reliability issues in PV modules due to the inherent brittleness of semiconductor materials [62]. Cracks can originate during manufacturing processes due to residual stresses induced by thermal cycles, soldering, and lamination [63]. Additionally, mechanical loads encountered during transportation, installation, or field operation, such as static pressure, cyclic loading, and wind or snow loads, are major contributors to crack initiation and propagation [64]. The impact of cracks on module performance varies significantly, ranging from minor power losses to severe failures, including hot spot formation and electrically inactive regions. Over time, cracks tend to propagate under thermomechanical stresses, further compromising module integrity [64]. Although thin-film technologies exhibit greater resistance to cracking, damage to the glass substrate or encapsulant can still trigger fracture events [63].

Field studies and accelerated aging tests confirm that crack occurrence strongly correlated with module design, cell thickness, and handling practices [62]. Advanced diagnostic techniques, such as EL and UV fluorescence imaging, have been widely employed to quantify crack density and assess its correlation with power loss [62]. These findings underscore the need for improved mechanical robustness in cell architecture and for optimised manufacturing processes to minimise residual stress.

Hot spots arise when localized resistive regions within a module experience high current flow, typically due to shading, soiling, or defective interconnections [65]. This localized heating accelerates material degradation and can lead to irreversible damage, including encapsulant browning and solder-joint failure. The severity of hot-spot formation depends on the degree of mismatch among cells and the effectiveness of bypass diodes in mitigating reverse-bias conditions [65].

LID is a well-documented phenomenon that primarily occurs during the initial exposure of PV modules to sunlight. LID typically results in power losses of up to 5% and is attributed to the formation of metastable defects within the silicon lattice, often linked to boron–oxygen complexes and thermal processing effects [66]. Although LID is predictable and generally accounted for in module performance ratings, its magnitude and recovery behavior vary depending on cell technology and operating conditions [66]. Strategies to mitigate LID include optimized doping profiles and advanced passivation techniques during cell fabrication.

PID represents a significant reliability challenge in field-deployed PV systems, particularly under high system voltages [66]. PID occurs when a large potential difference exists between the module frame and the solar cells, facilitating leakage currents and ionic migration, primarily sodium ions, from the glass into active layers such as TCO or antireflective coatings [66]. This process leads to increased recombination, shunt formation, and, in severe cases, p–n junction corrosion, resulting in substantial power loss [67].

Preventive measures against PID include the use of high-resistivity encapsulants, sodium-free glass, and barrier layers to inhibit ion migration [66]. Additionally, inverter designs that minimize potential differences, such as transformerless configurations that employ virtual DC bus concepts, have proven effective in reducing PID risk [68]. Recent studies emphasize that PID susceptibility is highly dependent on module design, material selection, and system grounding practices, highlighting the need for integrated solutions across the PV value chain [66].

3.4 Junction box and diodes

Bypass diodes play a critical role in PV modules by providing an alternative current path under reverse-bias conditions, thereby preventing localized overheating and mitigating power losses when cells are shaded or electrically damaged [18]. These diodes are typically integrated within the junction box and are essential for maintaining module reliability under partial shading or mismatch scenarios [69]. However, bypass diodes are also recognized as a frequent source of module failure in field conditions [18].

Failure mechanisms include electrical arcing, electrostatic discharge, and thermal runaway, all of which can compromise diode integrity and pose severe safety hazards [18]. Progressive degradation due to high operating temperatures and thermal cycling further exacerbates these risks by weakening semiconductor junctions and internal contacts [42]. Studies indicate that diode failures often manifest as increased series resistance or complete open-circuit conditions, resulting in significant performance losses and potential fire hazards [18]. These findings underscore the importance of robust diode design, effective heat dissipation strategies, and stringent quality control during manufacturing.

The junction box, typically mounted on the rear side of PV modules, serves as a protective enclosure for electrical interconnections, external cables, and bypass diodes [70]. Constructed from weather-resistant materials such as polycarbonate and bonded to the backsheet, the junction box is designed to withstand environmental stressors while ensuring electrical safety [71]. Despite its protective function, junction box failures remain among the most commonly reported issues in field-aged PV systems.

Observed failure modes include detachment from the module, inadequate sealing, corrosion of metallic components, and electrical arcing caused by damaged cables or poor connections [70]. Such defects can lead to substantial power losses and pose severe safety risks due to high current flow within the system. Statistical analyses of large-scale field data reveal that junction box reliability is strongly influenced by material selection, adhesive performance, and assembly quality [71]. Furthermore, climatic conditions such as high humidity and thermal cycling accelerate degradation, highlighting the need for improved sealing technologies and corrosion-resistant materials [70].

4. CHALLENGES

PV modules are subjected to a combination of external and internal stressors that collectively influence their long-term performance and reliability. Rather than being driven by a single factor, degradation typically results from the interplay of environmental conditions, module architecture, and material properties [72]. Traditional indoor aging tests, which often apply isolated stress factors, fail to replicate the complex conditions encountered in real-world environments.

Consequently, several failure modes, such as PID, Light and Elevated Temperature-Induced Degradation (LeTID), and backsheet cracking, have only been identified after years of field exposure [73]. This gap has prompted the development of advanced testing methodologies, including combined accelerated stress testing and agnostic stress protocols, which aim to induce failures more realistically and capture interactions among module components [74].

The PV market is increasingly driven by cost pressures and the demand for higher efficiency, leading to the rapid introduction of new technologies and materials without extensive long-term reliability data. While these innovations enhance performance metrics, they also introduce unforeseen risks associated with material compatibility. For example, the degradation of EVA encapsulant can generate acetic acid, which, when combined with impermeable backsheet layers, accelerates the corrosion of metallic contacts and other sensitive components [75]. Such interactions underscore the necessity for comprehensive qualification protocols that extend beyond current IEC standards, ensuring that each module design and material combination is rigorously evaluated under multi-stress conditions [76].

5. FUTURE DIRECTIONS: BALANCING PERFORMANCE, COST, AND SUSTAINABILITY

The ongoing evolution of PV technology underscores the need to balance performance, cost, and sustainability, particularly regarding degradation and failure phenomena in solar modules. As demand for renewable energy intensifies, understanding these factors is critical not only for improving efficiency and reliability but also for mitigating environmental impacts throughout the life cycle of PV systems. Long-term performance degradation is a recognised issue in PV modules, particularly in crystalline silicon technologies, which, although generally reliable, can experience gradual decreases in efficiency over time. Studies show that operational costs and energy production are significantly affected by these degradation patterns, making it essential to monitor and analyze performance over time [77]. Environmental ageing, accelerated by conditions such as high humidity, extreme temperatures, and prolonged solar exposure, exacerbates performance issues and can lead to failures, including cell cracking and delamination [78]. Addressing these accelerated-ageing processes through both laboratory testing and field data is vital for developing accurate degradation models and improving the reliability of PV systems [79].

Technological advancements are pivotal in overcoming the limitations imposed by degradation phenomena. Current research highlights the efficacy of complex modeling techniques in accurately predicting degradation rates and forecasting the remaining useful life (RUL) of PV modules under varying operational conditions [80]. This modelling is paramount, as it provides critical data that can inform operational and maintenance strategies, thereby extending the lifecycle of PV systems and aligning with sustainability goals [81]. Emerging methodologies, such as Bayesian modelling of degradation patterns, enhance predictive maintenance strategies by offering a more nuanced understanding of nonlinear degradation behaviours often overlooked by traditional linear models [82]. Such innovations highlight a shift toward more intelligent prognostic frameworks that dynamically adapt to changes in environmental conditions, enhancing system robustness while minimizing costs associated with unexpected failures [83].

From a sustainability perspective, minimizing the environmental footprint of PV production and operation is becoming increasingly important. As highlighted in several studies, linear assumptions about degradation may not hold across all operational contexts, potentially leading to underestimates of ecological impacts [84]. Hence, employing a comprehensive life-cycle assessment (LCA) to understand the overall greenhouse gas emissions associated with various PV technologies can provide valuable insights into their environmental sustainability [85]. The future trajectory of PV technology must fuse considerations of performance, cost, and sustainability through sophisticated modeling, robust testing, and environmental assessment strategies. As the industry continues to innovate, addressing degradation and failure phenomena will be crucial for achieving not only economic viability but also environmental stewardship within the renewable energy landscape.

From an industrial perspective, the increasing focus on degradation-aware PV system management reflects a clear shift toward improving operational reliability and optimizing costs in large-scale deployments. Utilities and PV plant operators are increasingly adopting condition-monitoring systems, predictive maintenance frameworks, and data-driven diagnostics to proactively address degradation phenomena, such as delamination, microcracks, and power loss. These approaches enable operators to prioritize maintenance activities, reduce unplanned downtime, and make informed decisions regarding module replacement or repowering strategies. Integrating degradation modeling into asset management platforms also supports more accurate financial forecasting, as performance losses directly impact the levelized cost of electricity (LCOE). In this context, ML–based prognostic tools offer tangible industrial value by translating complex operational data into actionable insights, thereby improving system availability and supporting long-term investment confidence in PV infrastructure.

Future technical improvements should focus on integrating advanced data analytics with material and design innovations to mitigate degradation at both the module and system levels. Enhanced encapsulation materials, improved interfacial adhesion, and robust module architectures can reduce susceptibility to environmental stressors such as humidity, thermal cycling, and UV exposure. At the same time, coupling these material advancements with intelligent modeling techniques, such as hybrid physics-informed and data-driven ML models, can significantly enhance the accuracy of degradation predictions. These models enable adaptive performance forecasting and real-time health assessments, facilitating smarter inverter control, optimized operating conditions, and extended service life. By aligning materials engineering with intelligent diagnostics, the PV industry can achieve meaningful technical improvements that enhance durability, reduce lifecycle costs, and strengthen the overall sustainability profile of next-generation solar energy systems.

6. CONCLUSIONS

This study systematically reviewed the failure modes of PV modules by component and explored future research directions using a bibliometric approach. The analysis revealed that degradation in PV modules is multifactorial, driven by environmental stressors, material properties, and design configurations. Key findings indicate that glass breakage, backsheet cracking and delamination, cell cracking, and junction box or diode failures are among the most critical reliability challenges. These failure modes often interact, accelerating overall degradation and reducing module efficiency and lifespan.

The bibliometric analysis highlighted emerging trends, including the integration of ML for predictive maintenance, advanced diagnostic techniques such as EL imaging, and a growing interest in recycling strategies for EOL modules. These developments underscore a shift toward data-driven reliability assessments and sustainable lifecycle management. Importantly, the study emphasizes that current qualification standards may not fully capture complex multi-stress interactions, necessitating more comprehensive testing protocols. The implications of these findings are significant for both industry and research. Improving material resilience, optimizing module architecture, and adopting intelligent monitoring systems can substantially enhance PV reliability and reduce operational costs. Furthermore, addressing recycling and circular-economy considerations will be essential to minimising environmental impacts as PV deployment scales globally.

This research contributes to existing knowledge by systematically consolidating fragmented insights on PV module failure modes from a component-level perspective, while uniquely integrating bibliometric evidence to reveal evolving research priorities at the intersection of reliability, data analytics, and sustainability. By linking traditional degradation mechanisms with emerging tools such as ML, advanced diagnostics, and recycling strategies, the study advances understanding of how technical, operational, and environmental factors converge throughout the PV lifecycle. Importantly, it identifies clear priorities for future research, including the development of standardized multi-stress testing frameworks, explainable, physics-informed AI models for degradation prediction, and scalable recycling solutions compatible with new module materials. These directions provide a structured roadmap for aligning academic research with industrial needs and long-term sustainability objectives.

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