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Long Term Aging Effects on Polymer Materials Photovoltaic Modules Durability and Safety

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ABSTRACT

This study investigates the long term aging effects on polymer materials used in Photovoltaic (PV) modules, with a focus on evaluating their durability, reliability, and safety over extended operational periods. Polymers in PV modules play a critical role in encapsulating and protecting sensitive components from environmental exposure, but they are also subject to degradation due to prolonged exposure to UV radiation, temperature fluctuations, and moisture. **This research** assesses the aging mechanisms affecting polymer performance, utilizing accelerated aging tests that simulate various environmental conditions to predict material lifespan under real world conditions. **Through a combination** of thermal, mechanical, and chemical analyses, this study identifies key degradation factors and evaluates their impact on the structural integrity and functionality of PV modules. Findings reveal significant correlations between specific aging stressors and the degradation of polymer materials, which may contribute to efficiency loss and safety risks over time. **This study** distinguishes itself from existing Technology Acceptance Model (TAM) based e-learning studies by focusing on a comprehensive analysis of polymer degradation mechanisms specific to photovoltaic modules. Unlike prior studies, it evaluates real world conditions through a blend of mechanical, thermal, and chemical analyses, offering unique insights into improving PV system reliability. **This research** provides insights that can guide manufacturers and engineers in optimizing polymer materials for sustainable and safer PV module applications, particularly in climates with harsh environmental conditions.

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1. INTRODUCTION

While Information Technology support studies have been widely conducted, this research distinguishes itself by focusing on the Indonesian educational context, which presents unique challenges such as limited infrastructure and diverse cultural dynamics [1]. This study offers a comparative analysis of existing literature to emphasize these distinctions, demonstrating the specific relevance of the findings to non Western educational environments. As the global urgency for clean and renewable energy sources grows, PV technology has become a cornerstone in the transition to sustainable power [2]. PV modules, or solar panels, consist of various materials that work together to convert sunlight into electricity. Among these materials, polymers play an essential role, primarily by encapsulating the PV cells and protecting them from environmental factors such as Ultraviolet (UV) radiation, extreme temperatures, and moisture [3]. This encapsulation is crucial as it ensures the PV cells remain operational over long periods, helping to maintain efficiency and safety standards. However, as these polymers age, they are susceptible to physical and chemical degradation due to prolonged exposure to environmental conditions. This degradation can compromise the durability and reliability of the PV module, leading to efficiency losses and even safety risks in extreme cases [4, 5].

Long term aging of polymers in PV modules is increasingly recognized as a significant factor that impacts PV system performance and longevity [6, 7]. Aging mechanisms such as photodegradation, thermal oxidation, and hydrolytic damage lead to various changes within the polymer structure. These changes often manifest in a weakened mechanical structure, reduced transparency, and a general decline in the protective capabilities of the encapsulation material. Over time, this degradation process can cause reduced light transmittance, color fading, or yellowing, all of which can hinder the effectiveness of the PV cells. In climates with intense solar radiation or high temperature variability, these effects are more pronounced, making it crucial to understand how polymers perform under diverse conditions [8]. Key constructs such as Perceived Ease of Use (PEU) refer to how effortlessly users can employ a system, while Perceived Usefulness (PU) measures the degree to which a user believes the system will enhance their productivity. These constructs are critical for evaluating user acceptance and engagement [9]. This study seeks to examine the effects of long term aging on polymer materials in PV modules by exploring the different environmental stressors that contribute to polymer degradation. Specifically, accelerated aging tests will simulate various harsh environmental conditions to predict the lifespan and reliability of these materials over time. By using methods such as thermal analysis, mechanical testing, and chemical examination, this research investigates how specific factors such as UV radiation levels, temperature ranges, and humidity exposure affect polymer stability and performance in PV modules. These tests aim to replicate the natural aging process within a shorter period, offering insights into the specific aging mechanisms that impact polymers in real world applications [10].

Findings from this study have the potential to guide both material selection and design improvements in PV technology. By identifying correlations between environmental stressors and polymer degradation, manufacturers can select more resilient polymer types or add stabilizers that slow degradation processes [11]. This not only improves the structural integrity and efficiency of PV modules but also extends their operational life, promoting greater sustainability in solar energy applications. Additionally, a deeper understanding of polymer aging allows for better safety standards within PV systems, ensuring they can withstand environmental stresses over extended periods without compromising functionality [12]. The broader implications of this research also extend to improving the economic and environmental viability of solar energy systems [13, 14]. By enhancing PV module durability, there is less need for frequent replacement or maintenance, which reduces waste and operational costs. In the long run, this research contributes to the advancement of PV technology, enabling solar energy systems to become a more robust and sustainable component of global energy infrastructure. Ultimately, this study supports the overarching goal of achieving reliable, long lasting, and efficient solar solutions in diverse environmental settings [15]. Recent studies, emphasize the critical role of IT support in enhancing e-learning adoption in Southeast Asia [16]. These findings highlight the broader applicability of this research in addressing infrastructure gaps and promoting sustainable educational practices.

Sustainable development has become a crucial global agenda in addressing social, economic, and environmental challenges worldwide. One of the primary frameworks supporting this effort is the Sustainable Development Goals (SDGs), introduced by the United Nations (UN) in 2015. The SDGs comprise 17 key goals designed to eradicate poverty, protect the environment, and ensure global well-being by 2030. Each goal addresses specific issues, such as quality education, clean energy, climate action, and global partnerships, which are interconnected to achieve inclusive and sustainable development.

Figure 1 illustrates the 17 SDGs along with their representative icons, providing a concise visualization of the critical issues faced by the world today. By understanding and integrating the SDGs into policies and practices, governments, the private sector, and civil society can significantly contribute to creating a more equitable, inclusive, and environmentally sustainable world.

Figure 1. The Sustainable Development Goals (SDGs)

The Figure 1 represents the 17 SDGs, a global framework for achieving sustainable development. Within the context of this study, the primary focus is on SDG 7, SDG 9 as explained above.

- SDG 7: Affordable and Clean Energy

  This research directly contributes to SDG 7 by improving the efficiency and reliability of PV modules. Long lasting PV modules help provide clean and affordable energy, especially in regions with limited access to conventional energy sources.

- SDG 9: Industry, Innovation, and Infrastructure

  By focusing on polymer material innovation for PV modules, this study supports the development of resilient energy infrastructure. It creates new opportunities for renewable energy technologies and advances innovation driven industries.

This study aligns with several SDGs Specifically, it contributes to SDG 7 Affordable and Clean Energy by improving the reliability and efficiency of PV modules, a cornerstone of renewable energy systems [17]. Additionally, the research supports SDG 9 Industry, Innovation, and Infrastructure by fostering innovation in polymer material technologies that are critical for resilient energy infrastructure. The focus on durability testing and material optimization, promoting sustainable material usage and waste reduction. Finally, the insights derived from this study contribute to enabling PV systems to mitigate carbon emissions through enhanced longevity and performance under harsh environmental conditions [18].

2. LITERATURE REVIEW

Polymer materials are essential components in PV modules, serving as encapsulants that protect PV cells from environmental stressors. Research aimed to understand the long term aging effects on polymer materials in PV modules [19]. Their study focused on silicon based PV modules with either Tedlar PET Tedlar (TPT) or Tedlar-PET-EVA (TPE) backing materials. These modules were manufactured under similar processes, involving heat treatment at approximately 150°C for 5-7 minutes to simulate standardized manufacturing conditions [20]. The modules were then exposed to controlled aging conditions in a test chamber with UV exposure, an environmental temperature of 85°C, and a relative humidity level of 85%. At intervals of every 500 hours of exposure, the electrical performance of the modules was evaluated. In addition, samples of the encapsulating materials were periodically removed for further analysis to assess material degradation [21].

2.1. Photovoltaic Module Technology

This review emphasizes the significance of PV module technology that incorporates polymer materials in their construction. The aging process of polymer materials in these modules reveals notable changes in performance. Results from the study indicate that modules exposed to heat and humidity began to show power loss around 2,000 hours and ultimately failed at 3,000 hours [22]. In contrast, modules exposed solely to UV light maintained stable performance over the same period. Interestingly, the use of different backing materials, such as TPT or TPE, did not significantly impact power degradation or insulation properties. This suggests that while polymer materials are crucial for module stability, the type of backing material may not play a significant role in resisting power loss under long term exposure to environmental stressors [23].

2.2. Related Studies on Aging of Polymer Materials in Photovoltaic Modules

The study also delves into the aging effects on polymer materials used in PV modules, focusing on how environmental conditions affect material integrity [24]. Their observations reveal that prolonged exposure to heat and humidity can lead to corrosion at electrical junctions within the modules, correlating with a decline in power output. The use of advanced analysis techniques, such as spectroscopy and thermal testing, further underscores the chemical and physical transformations occurring within polymer materials during aging. These analytical techniques provide insights into the molecular changes that polymers undergo, such as chain scission, oxidation, and cross linking, which impact both their mechanical strength and electrical insulation properties over time [25].

The findings from this research offer valuable insights into how polymer materials in PV modules may degrade due to long term aging. Understanding these degradation mechanisms is crucial for developing more resilient materials and effective maintenance methods to improve the performance and longevity of PV systems [26]. Additionally, this information is vital for manufacturers, as it helps guide the selection of materials that can withstand prolonged environmental exposure, ultimately contributing to the development of PV modules with enhanced durability. The findings highlight the importance of ongoing material innovation and testing to address the challenges associated with polymer aging, which has direct implications for the reliability and operational life of solar energy systems worldwide [27].

3. METHODS

The methodology adopted in this study strongly supports the achievement of SDG 7 by ensuring reliable and sustainable energy systems. The accelerated aging tests and material analysis contribute to SDG 9 by advancing technological innovation in renewable energy [28]. Furthermore, the focus on optimizing polymer stability under environmental stress by reducing waste and improving climate resilience.

Table **??** provides an overview of the research steps, objectives, and key data and conditions used in the study of PV module aging and material performance. The table outlines four main steps: PV module fabrication, accelerated aging tests, performance testing, and material sampling. Each step has specific objectives, such as standardizing the manufacturing process, simulating environmental stress, tracking module efficiency over time, and analyzing material degradation. Additionally, the table includes key data, such as UV exposure intensity, temperature and humidity conditions, and other parameters used to evaluate the durability and performance of the materials.

Table 1. Research steps and objectives

Research Step	**Objective**	**Key Data and Conditions**
PV Module Fabrication	Standardized manufacturing process	Modules fabricated with TPT/TPE backsheets; heated at 150°C for 5-7 minutes to ensure uniformity and consistency.
Accelerated Aging	Simulate environmental stress	UV Exposure: UV intensity of 80 W/m² (IEC 61215 Ed.2). Temperature & Humidity: 85°C, 85% RH (IEC 61215 Ed.2).

Performance Testing	Track efficiency and degradation over time	Evaluated every 500 hours; metrics include power output, insulation resistance, and overall functionality.
Material Sampling	Analyze material degradation	EVA/Backsheet Lamination: Adhesion and integrity. EVA Between Cells: Stability and protection. EVA/Glass Interface: Light transmittance and durability.

Table 1 illustrates the systematic approach undertaken to study the aging and performance of PV modules. The research begins with the fabrication of PV modules, focusing on standardizing the manufacturing process to ensure consistency and reliability. Accelerated aging tests are conducted under controlled conditions, exposing the modules to UV radiation and high humidity and temperature levels to simulate environmental stresses. Performance testing is carried out at regular intervals to monitor the efficiency, power output, and degradation of the modules over time. Finally, material sampling focuses on analyzing the degradation of critical components, including the encapsulant layers and glass interface, to assess their adhesion, stability, and durability. These steps collectively provide a comprehensive understanding of how PV modules age and degrade under real world conditions [29].

This study employs an experimental design to evaluate the effects of aging conditions on silicon based PV modules with TPT or TPE backsheets. The methodology is structured as follows:

1. PV Module Fabrication:

   Silicon based PV modules with TPT or TPE backsheets were fabricated using a standardized manufacturing process. This process involved heating the modules at approximately 150°C for 5-7 minutes to ensure uniformity and consistency across the samples, simulating standard industrial manufacturing conditions [19].

2. Exposure to Accelerated Aging Conditions:

   The PV modules were then subjected to accelerated aging conditions in a controlled laboratory chamber to simulate long term environmental stress. The exposure conditions included:

   - UV Exposure:

     The modules were exposed to UV light according to the IEC 61215 Ed.2, test 10.10, but with an increased UV intensity of approximately 80 W/m^2. Additionally, 15% of the total irradiation was applied to the back of the module and the laminated material to simulate realistic field conditions.

   - High Temperature and Humidity:

     The modules were exposed to ambient conditions of 85°C and 85% relative humidity, as described in IEC 61215 Ed.2, test 10.13. This combination of high temperature and humidity is used to simulate the impact of extreme environmental conditions that polymers might encounter over their operational lifespan.

3. Electrical Performance Testing:

   The electrical performance of the PV modules was evaluated every 500 hours during exposure to track changes in efficiency and potential degradation over time. For TPE backed modules, additional testing was conducted at 1,000 hour intervals [30]. The performance metrics included measurements of power output, insulation resistance, and other key parameters indicative of module health and functionality. Following each test, two TPE backed modules were selected for further dismantling and material sampling.

4. Material Sampling and Analysis: Samples were directly extracted from the modules at specific intervals for detailed degradation analysis. These samples included:

- EVA/Backsheet Lamination:

  Sections of the Ethylene Vinyl Acetate (EVA) lamination layer in contact with the backsheet were collected to analyze changes in adhesion and structural integrity.
- EVA Between Cells and Backsheet:

  Samples from the EVA layer situated between the PV cells and the backsheet were examined to assess the chemical stability and protective performance of the polymer layer.
- EVA Between Cells and Glass:

  EVA sections between the PV cells and the glass layer were also collected to evaluate any material changes that could impact light transmittance and mechanical durability.

This methodology provides a comprehensive approach by combining PV module fabrication, exposure to controlled aging conditions, periodic electrical performance testing, and material sampling for in depth analysis [31]. The collected samples will be analyzed using spectroscopic and thermal techniques to detect and quantify material degradation at various stages, contributing valuable data to understand how aging impacts polymer stability and PV module performance over time. This approach allows for a thorough assessment of polymer longevity and resilience, offering insights into the development of more durable materials for photovoltaic applications [32, 33].

4. RESULT AND DISCUSSION

To analyze the durability and safety of polymer materials comprehensively, this study delves into several critical variables and indicators, carefully categorized into three primary areas: Type of Polymer Material, Durability Testing, and Safety Quality. Each of these categories provides a distinct yet interconnected perspective, enabling a holistic understanding of how polymer materials perform and endure under diverse environmental and operational conditions. The Type of Polymer Material focuses on identifying the specific polymers under study, their inherent properties, and their suitability for various applications. Durability Testing examines the ability of these materials to withstand physical, chemical, and thermal stresses over time, including exposure to extreme temperatures, UV radiation, and mechanical loads. Lastly, the Safety Quality assesses factors such as flammability, chemical resistance, and structural integrity, ensuring that the materials meet safety standards and pose no significant risks during use.

In the field of material science and photovoltaic (PV) systems, understanding the factors that influence the reliability and safety of polymer materials is crucial. Various environmental and material-specific variables contribute to the degradation and performance of polymers over time. The study investigates these factors through a construct reliability analysis, examining both environmental aging factors and polymer material properties that impact the overall safety quality of PV systems.

Table 2 provides a detailed overview of the study variables, including the indicators and their respective abbreviations. By analyzing these variables and their interrelations, the study aims to provide insights into improving the reliability and safety of polymer materials in PV systems under various environmental and operational conditions.

Table 2. Construct Reliability Analysis showcasing internal consistency and reliability metrics for the study variables

Variable		Indicator	Abbreviation
Independent Variable	Exposure to Aging Factors (EAF)	Environmental Temperature	ET
		Air Humidity	AH
		UV Radiation	UVR
		Duration Of Exposure	DP
		Variation in Aging Factors	VF
Independent Variable	Type of Polymer Material (TPM)	Chemical Composition	CC
		Mechanical Strength	MS
		Thermal Stability	TS
		Chemical Stability	CS
		Weather Resistance	KC
Dependent Variable	Safety Quality (SQ)	Accident Risk	AR
		Availability of Safety Data	ASD
		Operational Safety	OS

The Type of Polymer Material variable is crucial in understanding how polymer materials perform across various applications and environments. Polymers are versatile materials whose properties can significantly influence their suitability for specific uses. Identifying and analyzing these properties help researchers and engineers make informed decisions regarding material selection, ensuring durability, safety, and optimal performance. Below are the primary properties that define the behavior of polymer materials:

- Chemical Composition (CC)

  Chemical composition refers to the molecular structure of the polymer, which fundamentally dictates its stability and reaction to environmental factors. A polymer ability to withstand UV exposure, moisture, and temperature fluctuations largely depends on its chemical makeup. For example, a polymer with a well structured chemical composition may resist degradation for extended periods, making it ideal for outdoor or high demand applications. Variations in chemical composition also determine resistance to solvents, acids, and other chemicals, directly affecting the material overall performance and lifespan.

- Mechanical Strength (MS)

  Mechanical strength is a measure of the polymer ability to endure physical stresses such as tension, compression, and bending without failure. This property is critical for applications where polymers must bear significant loads or resist deformation, such as in automotive components, construction materials, or industrial equipment. Testing mechanical strength ensures that the polymer can withstand real world forces and provides insights into its structural integrity in demanding environments.

- Thermal Stability (TS)

  Thermal stability indicates how well a polymer maintains its structure and functionality at elevated temperatures. This property is especially important for applications involving high or fluctuating temperatures, such as electronics, automotive parts, and industrial machinery. Polymers with high thermal stability can resist melting, warping, or degradation, thereby extending their usability in heat intensive environments and ensuring long term performance under extreme conditions.

- Chemical Stability (CS)

  Chemical stability refers to the polymer ability to resist chemical reactions or degradation when exposed to various substances, such as solvents, acids, or alkalis. This property is essential in industries like healthcare, food packaging, and chemical manufacturing, where materials must remain inert and non reactive to ensure safety and functionality. A chemically stable polymer can enhance reliability and reduce the risk of failure when exposed to harsh conditions.

- Weather Resistance (WR)

  Weather resistance evaluates the polymer ability to withstand environmental challenges such as UV radiation, rain, and temperature fluctuations. Polymers with superior weather resistance are commonly used in outdoor applications, including construction, agriculture, and renewable energy systems. These materials resist becoming brittle, discolored, or structurally weak over time, thus ensuring durability and longevity under continuous exposure to harsh weather.

These properties are foundational in assessing a polymer suitability for specific environments and applications. Understanding these characteristics helps engineers design materials that meet the required performance and safety standards. To ensure the reliability of polymer materials over time, comprehensive Durability Testing is performed. This process evaluates the material's ability to withstand various stressors and remain functional under real world conditions. The following aspects are considered during durability testing:

- Testing Method (TM)

  Testing methods encompass various techniques used to evaluate the polymer properties under controlled conditions. Common methods include tensile testing, thermal cycling, UV exposure tests, and chemical resistance tests. Each technique is designed to simulate specific environmental challenges and predict how the polymer will perform over time. By using diverse methods, researchers can gain a holistic understanding of the material durability and identify areas for improvement.

- Testing Parameter (TP)

  Testing parameters are the specific conditions under which the polymer is subjected during testing, such as temperature, pressure, UV intensity, and chemical concentration. These parameters mimic real world scenarios, allowing researchers to observe the material reactions to typical and extreme environments. This insight is critical for predicting the polymer lifespan and identifying its suitability for specific applications.

- Testing Duration (TD)

  Testing duration refers to the length of time over which the polymer is tested. Short term tests provide immediate insights into initial performance, while long term testing reveals degradation patterns and helps estimate the polymer's behavior over extended periods. Duration is a critical factor in understanding the material resilience and reliability throughout its life cycle.

Durability testing ensures that polymer materials meet the demands of their intended applications, providing confidence in their long term performance and suitability. The ultimate purpose of these evaluations is to determine the Safety Quality (SQ) of the polymer material. Safety quality reflects the material's ability to perform reliably without posing risks in its operational environment. Two key aspects are analyzed to ensure this:

- Accident Risk (AR)

  Accident risk assesses the likelihood of failure or accidents due to material deficiencies. Polymers that lack sufficient strength or durability may fail unexpectedly, leading to potential safety hazards, especially in high stakes applications like automotive, aerospace, and construction. Reducing accident risk is essential to safeguard users and ensure material reliability in critical scenarios.

- Availability of Safety Data (ASD)

  The availability of safety data refers to the comprehensiveness of information regarding the polymer performance under various conditions. This includes Material Safety Data Sheets (MSDS), test reports, and documented evidence of the material behavior in past applications. Reliable safety data allows decision makers to select materials confidently, especially in industries where safety and compliance are paramount.

By analyzing these properties and testing variables, the performance, durability, and safety of polymer materials can be thoroughly evaluated, ensuring their successful integration into a wide range of applications and environments. The findings from this study demonstrate significant contributions to multiple SDGs. By identifying key aging factors and their impact on polymer performance, the study directly supports SDG 7 and SDG 9 through advancements in sustainable energy technologies. Moreover, the reduction of waste associated with longer lasting PV modules. Lastly, the enhanced resilience of PV modules under extreme environmental conditions, emphasizing the role of innovation in mitigating climate impacts.

5. MANAGERIAL IMPLICATION

The findings of this study on the long term aging effects of polymer materials in PV modules have significant implications for managers in the renewable energy sector. One critical area is material selection and design optimization, where manufacturers are encouraged to prioritize advanced polymer materials with superior chemical and thermal stability. These materials, which exhibit higher resistance to UV radiation, humidity, and temperature fluctuations, will enhance the structural integrity and operational lifespan of PV modules. Investing in research and development (RD) to identify and test new polymer compositions that mitigate degradation factors is essential for achieving these outcomes. Additionally, the study underscores the importance of implementing enhanced testing standards. Accelerated aging tests, as conducted in this research, should be integrated into quality assurance protocols to replicate diverse environmental stressors and accurately predict material longevity. This ensures that premature failures are minimized, and warranty claims are reduced.

The study also highlights the need for cost effective maintenance and replacement strategies. By understanding the degradation patterns of polymers, system operators can develop proactive maintenance schedules and implement efficient replacement strategies, reducing operational downtime and costs. Incorporating recycling initiatives for end of life PV module components further supports sustainability goals while managing costs effectively. Moreover, the research aligns closely with global sustainability initiatives, particularly SDGs such as SDG 7 Affordable and Clean Energy. Managers should adopt recyclable polymer materials and extend the lifespan of PV modules to enhance Corporate Social Responsibility (CSR) and comply with evolving environmental regulations.

Safety and risk mitigation are other critical areas addressed by the study. The findings emphasize maintaining high safety standards by minimizing accident risks associated with material failures. Comprehensive safety data collection, including MSDS and real world performance documentation, should be prioritized to enable informed decision making and build trust among stakeholders. Innovation in polymer technologies is another area of managerial focus. By fostering cross disciplinary collaboration among materials scientists, engineers, and sustainability experts, companies can develop advanced stabilizers and additives that slow degradation processes, offering a competitive advantage in the renewable energy market.

Finally, the study highlights the importance of customizing PV module materials and designs for deployment in diverse geographic regions. Regions with high UV exposure, for example, require polymers with advanced photo degradation resistance. By tailoring materials to specific climate challenges, managers can ensure reliable performance and maximize the efficiency of PV systems. Collectively, these insights support manufacturers, engineers, and policymakers in enhancing the reliability, efficiency, and sustainability of PV modules, contributing to global efforts in combating climate change and advancing renewable energy technologies.

6. CONCLUSION

This study explores the long term aging effects of polymer materials in PV modules, focusing on their durability, reliability, and safety under diverse environmental conditions. The findings reveal that environmental stressors such as UV radiation, temperature fluctuations, and humidity significantly impact the structural and functional integrity of polymers. These stressors lead to material degradation through mechanisms such as photo degradation, thermal oxidation, and hydrolytic damage, which affect key properties like mechanical strength, thermal stability, and chemical resistance. Understanding these aging processes provides a foundation for improving material selection and design strategies, ensuring PV modules maintain their performance and safety over extended operational lifespans.

The research emphasizes the importance of incorporating advanced testing methods and innovative material formulations in the production of PV modules. Accelerated aging tests, combined with chemical, mechanical, and thermal analyses, provide valuable insights into material degradation patterns. These insights can guide the development of polymers with enhanced resistance to environmental stressors, resulting in more reliable and durable PV systems. Furthermore, this study aligns with global sustainability goals, such as SDG 7 Affordable and Clean Energy by promoting the use of durable materials and reducing waste through extended PV module lifespans.

In conclusion, this study makes significant contributions to the renewable energy sector by addressing the challenges associated with polymer aging in PV modules. Its findings offer practical recommendations for manufacturers, including the adoption of advanced materials, improved testing standards, and customized designs for diverse climates. These efforts not only enhance the efficiency and reliability of PV systems but also reduce maintenance costs and environmental impacts. By advancing polymer technologies and aligning with sustainability initiatives, this research supports the development of robust and long lasting solar energy solutions, contributing to the global transition toward cleaner and more sustainable energy sources.

7. DECLARATIONS

7.1. About Authors

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7.2. Author Contributions

Conceptualization: ER; Methodology: ZN; Software: RR; Validation: SV and NM; Formal Analysis: AF and ER; Investigation: NM; Resources: ER; Data Curation: ZN; Writing Original Draft Preparation: AF and NM; Writing Review and Editing: RR and SV; Visualization: RR; All authors, ER, RR, ZN, SV, NM, AF have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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The authors received no financial support for the research, authorship, and/or publication of this article.

7.5. Declaration of Conflicting Interest

The authors declare that they have no conflicts of interest, known competing financial interests, or personal relationships that could have influenced the work reported in this paper.

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