

Article

Eco-Friendly and Structurally Efficient Photovoltaic Modules with Transparent Bio-Based Epoxy and CNF Composite Back-Sheets for BIPV Applications

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Abstract

Building-integrated photovoltaic (BIPV) systems require photovoltaic modules that simultaneously ensure structural reliability, optical transparency, and environmental sustainability. Conventional photovoltaic modules typically employ tempered glass as the front cover, which offers excellent optical performance but suffers from inherent drawbacks, including high density, brittleness, and limited design flexibility for BIPV applications. In this study, a glass-free photovoltaic module architecture is proposed, consisting of a transparent bio-based epoxy front cover and a mechanically reinforced cellulose nanofiber (CNF)/bio-based epoxy composite back-sheet. The mechanical properties of CNF/bio-based epoxy composites with CNF contents ranging from 0 to 15 wt% were systematically investigated, and the optical transmittance of the transparent bio-based epoxy was evaluated in comparison with conventional tempered glass. Structural reliability was assessed through finite element analysis under a static mechanical load of 5400 Pa, in accordance with IEC 61215 standards. In addition, the electrical performance of the proposed glass-free module was experimentally compared with that of a conventional glass-based module using identical shingled solar cells. The results reveal that CNF incorporation significantly enhances the stiffness and strength of the bio-based epoxy composite while inducing only a marginal increase in density. Under the IEC mechanical load condition, the glass-free module exhibited up to a 72% reduction in total deformation compared to the conventional glass-based module, demonstrating substantially improved structural efficiency. The transparent bio-based epoxy front layer maintained over 90% optical transmittance in the visible wavelength range at practical thicknesses of 1.0–1.5 mm, comparable to that of 3.2 mm tempered glass. Furthermore, the glass-free module preserved electrical performance, showing less than a 1% difference in maximum power output and stable current–voltage characteristics relative to the reference module. Overall, this study demonstrates that CNF/bio-based epoxy glass-free photovoltaic modules can achieve enhanced structural reliability without compromising optical transparency or electrical performance, highlighting their potential as sustainable and structurally efficient alternatives for next-generation BIPV applications.

Keywords: building-integrated photovoltaics (BIPV); cellulose nanofiber (CNF); bio-based epoxy composites; glass-free photovoltaic module; structural reliability



Academic Editor: Philippe Leclère

Received: 24 December 2025

Revised: 30 January 2026

Accepted: 10 February 2026

Published: 13 February 2026

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1. Introduction

As global efforts to address climate change and achieve carbon neutrality (net-zero) targets accelerate, reducing greenhouse gas emissions from the building sector and expanding the use of renewable energy have emerged as critical challenges. Because buildings account for a substantial share of global energy consumption and carbon emissions, building-integrated photovoltaic (BIPV) technologies, which utilize building envelopes such as rooftops, façades, and curtain walls as energy-generating elements, have attracted significant attention as a key strategy for developing sustainable urban energy systems [1–5]. Unlike conventional ground mounted photovoltaic (PV) installations, BIPV modules are directly integrated into building envelopes and are therefore continuously exposed to various mechanical and environmental loads, including wind pressure, snow loads, and thermal cycling [6–8]. As a result, BIPV modules are required to satisfy not only electrical performance requirements but also enhanced structural stability, long-term durability, and environmental sustainability. These distinct service conditions necessitate advanced material-based and structural design strategies for photovoltaic modules intended for BIPV applications [9–11].

In recent years, increasing attention has been given to photovoltaic technologies from a building-level and sustainability-oriented perspective, in which lightweight module design, material-related carbon footprint, and long-term environmental performance are considered alongside electrical efficiency. In this context, recent studies have emphasized the importance of integrating photovoltaic systems with sustainable building materials and evaluating their performance within realistic architectural and operational contexts. Furthermore, sustainability-oriented photovoltaic research has expanded the scope of building-integrated photovoltaics by addressing eco-friendly material processing, lightweight module concepts, and building-level decarbonization impacts, while comprehensively reviewing previous photovoltaic module technologies [12,13].

To overcome the structural and environmental limitations of conventional glass-based photovoltaic modules, various alternative design strategies have been explored for building-integrated photovoltaic applications. One major approach focuses on reducing or eliminating the use of glass through glass-free module architectures, which can mitigate fracture-related safety concerns and enable alternative structural designs for building environments. Glassless PV module concepts have been explored using polymeric front sheets (e.g., ETFE and fluoropolymer-based laminates) and rigid transparent polymer covers to reduce brittleness and improve mechanical reliability in building-integrated applications [14,15].

Despite these advantages, previous studies have reported that the removal of glass often results in insufficient structural stiffness and excessive deformation under mechanical loads, particularly for large area modules, thereby limiting their applicability to real BIPV façade installations [16–18]. Moreover, many existing glassless approaches rely on petroleum-derived polymers and may face challenges in sustainability and end-of-life considerations.

In this study, we propose a glass-free architecture employing a transparent bio-based epoxy as the front cover layer and a CNF/bio-based epoxy composite as a mechanically reinforced back-sheet, aiming to provide both structural robustness and improved material sustainability.

In parallel, growing attention has been directed toward the use of sustainable and bio-based materials in photovoltaic modules, driven by increasing demands for carbon neutrality and environmentally friendly building components [19–21]. Bio-based polymers and cellulose-derived materials have been investigated as alternatives to petroleum-based resins, offering reduced environmental impact and favorable intrinsic material properties. However, many of these studies have primarily focused on material-level characterization

or small-scale device demonstrations, and their translation to full-scale photovoltaic module structures suitable for BIPV applications remains limited.

Among bio-derived reinforcing materials, cellulose nanofibers (CNFs) have emerged as particularly promising candidates due to their high tensile strength, low density, and excellent reinforcing capability. Numerous studies have demonstrated that incorporating CNF into polymer matrices can significantly enhance stiffness and mechanical strength [22–26]. Nevertheless, the application of CNF-reinforced composites to glass-free photovoltaic module architectures has rarely been investigated at the module level, especially under realistic mechanical loading conditions relevant to BIPV service environments.

Despite the extensive body of research on CNF-based polymer composites and bio-based materials, several critical gaps remain unresolved for their practical implementation in building-integrated photovoltaic (BIPV) modules. Most existing studies have primarily focused on material-level mechanical enhancement or sustainability aspects, while only limited efforts have extended these materials to fully glass-free photovoltaic module architectures. In particular, the simultaneous fulfillment of optical transparency, mechanical stiffness, and structural reliability—essential requirements for BIPV applications—has rarely been systematically validated using CNF- and bio-based materials [27–30]. Furthermore, module-level reliability evaluation under standardized mechanical loading conditions, such as those specified in IEC 61215, has not been sufficiently conducted to date, largely due to the need for large-area specimen fabrication and costly testing procedures.

Based on these limitations, the central research question of this study is whether a glass-free photovoltaic module architecture based on CNF-reinforced bio-based epoxy composites can simultaneously satisfy the optical transparency, mechanical stiffness, and structural reliability required for BIPV applications [31–34]. To address this question, this study proposes an eco-friendly glass-free BIPV module architecture employing a transparent bio-based epoxy as the front cover layer and a CNF/bio-based epoxy composite as a mechanically reinforced back-sheet. The objective of this work is to systematically evaluate the material-level mechanical properties of the CNF/bio-based epoxy composites, the module-level structural response under IEC 61215 mechanical load conditions, and the optical and electrical performances of the proposed module in comparison with a conventional glass-based photovoltaic module.

The scientific novelty of this study lies in the integrated module-scale validation of a fully glass-free BIPV module architecture based on CNF and bio-polymer-derived materials. Unlike previous studies that primarily addressed material reinforcement or environmental benefits in isolation, this work concurrently evaluates optical transparency, mechanical performance, and photovoltaic output under realistic BIPV service conditions. By bridging material scale composite design with module-scale structural reliability assessment, this study presents a practical and sustainable design framework that can serve as a viable alternative to conventional glass-based photovoltaic modules and provides a foundational contribution toward the development of next-generation BIPV systems.

2. Materials and Methods

2.1. Overall Experimental Procedure

The overall experimental procedure of this study is summarized as follows. First, CNF-reinforced bio-based epoxy composites with different CNF contents were fabricated to evaluate their mechanical reinforcement effects at the material level. Second, transparent bio-based epoxy without CNF was prepared and characterized in terms of optical transmittance for application as a front cover layer. Third, shingled solar cells were fabricated and integrated into both conventional glass-based photovoltaic modules and CNF/bio-based epoxy glass-free modules to ensure identical cell configurations. Fourth, module-level

structural behavior under standardized mechanical loading conditions specified in IEC 61215 was evaluated through finite element analysis. Finally, the electrical output performance of the fabricated modules was experimentally assessed and compared to clarify the influence of the glass-free CNF composite structure on photovoltaic performance.

2.2. Materials

The materials used in this study are summarized in Table 1. A petroleum-based epoxy resin, YD-128 (Kukdo Chemical, Seoul, Republic of Korea), was used. This resin is a diglycidyl ether of bisphenol A (DGEBA)-type epoxy. The bio-based epoxy resin contained 18% bio-derived oil in its resin composition and was developed to reduce the environmental burden compared to conventional petroleum-based epoxy resins.

Table 1. Summary of materials used in study.

Material	Type	Key Characteristics	Supplier
YD-128 epoxy resin	Bio-based epoxy matrix	DGEBA-type epoxy resin containing ~18% bio-derived oil	Kukdo Chemical, Seoul, Republic of Korea
Methyl hexahydrophthalic anhydride (MHHPA)	Curing agent	Anhydride-based hardener suitable for high-temperature curing	
Cellulose nanofibers (CNFs)	Reinforcing filler	Cellulose-based fibrous material used for mechanical reinforcement	Movic Advanced Material Co., Ltd., Hwaseong-si, Gyeonggi-do, Republic of Korea

Methyl hexahydrophthalic anhydride (MHHPA; 4-methyl-1,2-cyclohexanedicarboxylic anhydride) was employed as the curing agent. This anhydride-based hardener is suitable for high temperature curing processes and provides excellent thermal and mechanical stability to the cured epoxy system.

Cellulose nanofibers (CNF) were supplied in powder form by Movic Advanced Material Co., Ltd., Hwaseong-si, Gyeonggi-do, Republic of Korea. The CNF exhibited an average fiber diameter in the range of 2–5 μm and were incorporated into the composite system for mechanical reinforcement of the back-layer structure, serving as an alternative to conventional polymer back-sheets.

2.3. Mechanical Property Evaluation

Based on the materials described above, the mechanical reinforcement effect induced by CNF incorporation was quantitatively evaluated through tensile strength measurements of CNF/bio-epoxy composites and transparent bio-based epoxy composites. Tensile tests were conducted using a universal testing machine (UNITEST MD Series, Testone Co., Ltd., Siheung-si, Gyeonggi-do, Republic of Korea).

Three types of CNF/bio-based epoxy composite specimens were fabricated with CNF contents of 5%, 10%, and 15%. In addition, one transparent bio-based epoxy composite specimen without CNF was prepared as a reference, resulting in a total of four specimen groups subjected to tensile testing.

All specimens were prepared according to the Type 1A geometry specified in KS M 527, and the tensile tests were performed in accordance with the ASTM D638 standard.

For each specimen group, at least five specimens ($n = 5$) were tested to ensure statistical reliability. The reported tensile strength values represent the average of the measured data, and the corresponding standard deviations are provided to indicate experimental variability.

2.4. Solar Cell Characteristics

The photovoltaic cells used in this study were commercially available monocrystalline silicon M6-type cells manufactured by DS Energy, Hangzhou, China. These cells are based on wafers with dimensions of $166 \times 166 \text{ mm}^2$ and represent a standard cell format widely employed in current commercial photovoltaic modules, offering stable electrical performance and high applicability [35,36].

To ensure the reliability of electrical output and structural behavior comparisons, identical solar cells were incorporated into both the reference glass-based module and the CNF/bio-based epoxy glass-free module. This approach minimized variables associated with intrinsic cell characteristics and enabled a focused evaluation of the effects arising from differences in module structure and constituent materials.

2.5. Fabrication of Shingled Solar Cells

In this study, the photovoltaic cells were configured using a shingled cell architecture. Commercial monocrystalline silicon M6 solar cells were divided into five strips through a laser cutting process, and the resulting cell strips were electrically interconnected in an overlapped arrangement.

An electrically conductive adhesive was employed for interconnection between the shingled cell strips. This interconnection approach minimizes optical shading losses associated with conventional busbar-based interconnection schemes and enhances current collection efficiency [37,38].

The fabricated shingled solar cells were identically applied to both the conventional glass-based photovoltaic module and the CNF/bio-based epoxy glass-free photovoltaic module. This ensured that the effects of cell architecture and interconnection methods were excluded, enabling a fair comparison of electrical output characteristics arising solely from differences in module structure and constituent materials.

2.6. Optical Transmittance Measurement

To evaluate the optical properties of the bio-based epoxy applied as the front cover layer of the photovoltaic module, optical transmittance measurements were conducted in the visible-light region using a UV-Vis spectrophotometer. This assessment was performed to verify the high optical transparency of the front-layer material.

The results confirmed the suitability of the bio-based epoxy as a transparent cover material, and the obtained spectral transmittance was compared with that of standard glass to assess its applicability for BIPV systems.

2.7. Structural Analysis Under IEC 61215 Mechanical Load

To evaluate the mechanical stability of the glass-free photovoltaic module structure composed of a front layer and a composite back layer, a linear static structural analysis was performed using the Static Structural module in ANSYS Workbench 2020 R2 (ANSYS Inc., Canonsburg, PA, USA). The analysis model was defined with dimensions of $500 \times 550 \text{ mm}^2$ and consisted of a multilayer stack comprising a front layer, a solar cell layer, and a back layer.

The simulation was conducted under a static mechanical load of 5400 Pa in accordance with IEC 61215, with uniform pressure applied over the entire front surface of the module. Boundary conditions were defined by fixing the module edges to simulate typical installation conditions. The boundary conditions and loading configuration used in the structural analysis are illustrated in Figure 1. The structural efficiency was assessed by comparing the total deformation of the CNF/bio-based epoxy glass-free module with that of a conventional glass-based photovoltaic module.

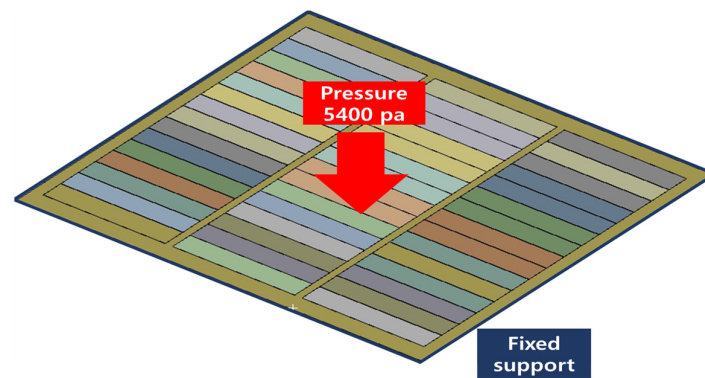


Figure 1. Boundary Conditions for Structural Analysis. The colors are used for visual distinction only.

The boundary conditions were defined to represent typical BIPV installation scenarios in which photovoltaic modules are mechanically supported by frames or clamping systems along their edges. In practical BIPV applications, modules integrated into façades or curtain wall systems are commonly constrained at the perimeter by structural frames, resulting in limited edge displacement under external loads.

2.8. Fabrication of CNF/Bio-Based Epoxy Composite Photovoltaic Modules

Figure 2 illustrates the structural configuration and layer composition of the photovoltaic modules investigated in this study. A conventional glass-based photovoltaic module (Normal PV) and the proposed CNF/bio-based epoxy glass-free photovoltaic module are compared to clarify the differences in front cover and back-sheet design.

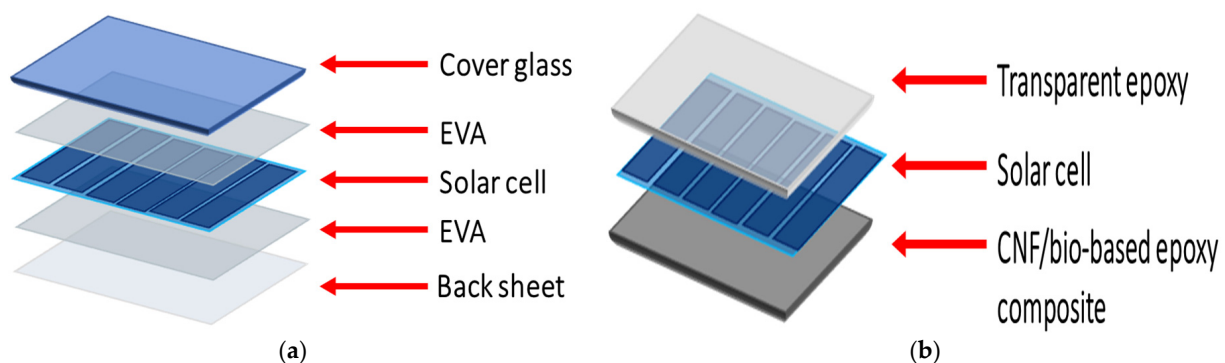


Figure 2. Layer structures of (a) conventional PV modules and (b) CNF/bio-based epoxy composite PV modules for BIPV applications. The arrows indicate the different structural layers.

Based on the structural configurations shown in Figure 3, CNF/bio-based epoxy composite photovoltaic modules with a glass-free structure were fabricated to evaluate the mechanical stability of module configurations composed of a front cover layer and a composite back layer. The composite back layer was prepared by mixing 300 g of bio-based epoxy resin with an MHHPA curing agent at a mass ratio of 7:3. CNF was incorporated into the resin mixture at contents ranging from 5 to 15 wt%, depending on the formulation, to form the composite back layer. The mixture was subjected to vacuum degassing for approximately 30 min, followed by curing at 120 °C for 1 h.

After fabrication of the composite back layer, the solar cell layer was laminated to form the module structure. The front cover layer was fabricated using the same bio-based epoxy resin and curing agent but without CNF addition to ensure optical transparency. For the front layer, 300 g of the resin–curing agent mixture was prepared and processed under identical conditions, including vacuum degassing for 30 min and curing at 120 °C for 1 h.

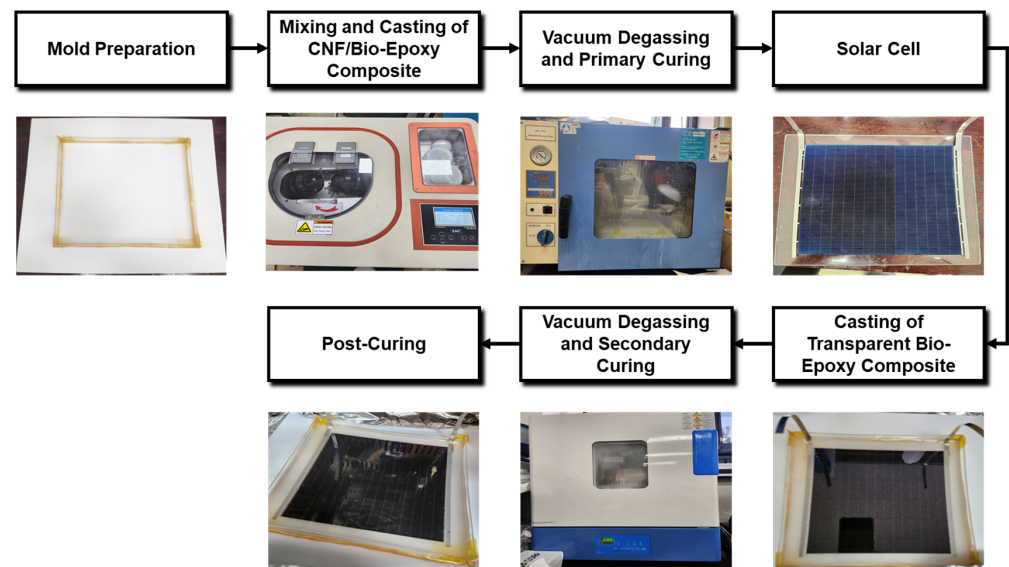


Figure 3. Schematic diagram of process.

Both the front cover layer and the composite back layer were designed as key functional layers for creating the glass-free photovoltaic module. The fabricated layers and module structures were evaluated with respect to mechanical stiffness, optical transmittance, and applicability for BIPV systems.

Figure 3 illustrates the step-by-step fabrication process of the glass-free photovoltaic module incorporating a transparent bio-based epoxy front layer and a CNF/bio-based epoxy composite back-sheet. The process begins with mold preparation, followed by mixing and casting of the CNF-reinforced bio-based epoxy composite to form the mechanically reinforced back-sheet. Vacuum degassing is then applied to remove entrapped air, and primary thermal curing is performed to obtain a solid composite layer.

Subsequently, shingled silicon solar cells are positioned on the cured back-sheet, and a post-curing process is carried out to ensure structural integrity and interfacial stability. Finally, a transparent bio-based epoxy layer without CNF is cast and cured on the front side to serve as the optical front cover. This schematic summarizes the key material processing steps and layer integration sequence used to realize the proposed glass-free BIPV module architecture.

2.9. Electrical Output Measurement

The electrical output characteristics of the fabricated CNF/bio-based epoxy composite photovoltaic modules and conventional tempered glass-based reference modules were evaluated using a large-area commercial solar simulator (XHS-4040B300KPV1) under standard test conditions (STC), corresponding to an irradiance of $1000 \text{ W} \cdot \text{m}^{-2}$, an air mass of AM 1.5G, and a cell temperature of 25°C , as well as under outdoor conditions. Each photovoltaic module consisted of five series of connected shingled silicon solar cells, and three identical modules were fabricated and tested for each module configuration.

The measured parameters included open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF), maximum power output (P_{max}), power conversion efficiency (EFF), and current–voltage (I–V) characteristics. These measurements enabled a quantitative evaluation of the influence of the CNF composite-based module structure on the electrical performance of the photovoltaic modules while minimizing variations arising from intrinsic cell properties.

3. Results and Discussion

3.1. Mechanical Properties of CNF/Bio-Based Epoxy Composites

The mechanical properties of bio-based epoxy composites with CNF contents ranging from 0 to 15 wt% were systematically evaluated. As shown in Figure 4, both Young's modulus and tensile strength exhibited a continuous increase with increasing CNF content. This behavior can be attributed to the formation of effective load transfer pathways within the epoxy matrix induced by CNF reinforcement, resulting in enhanced structural stiffness of the composites.

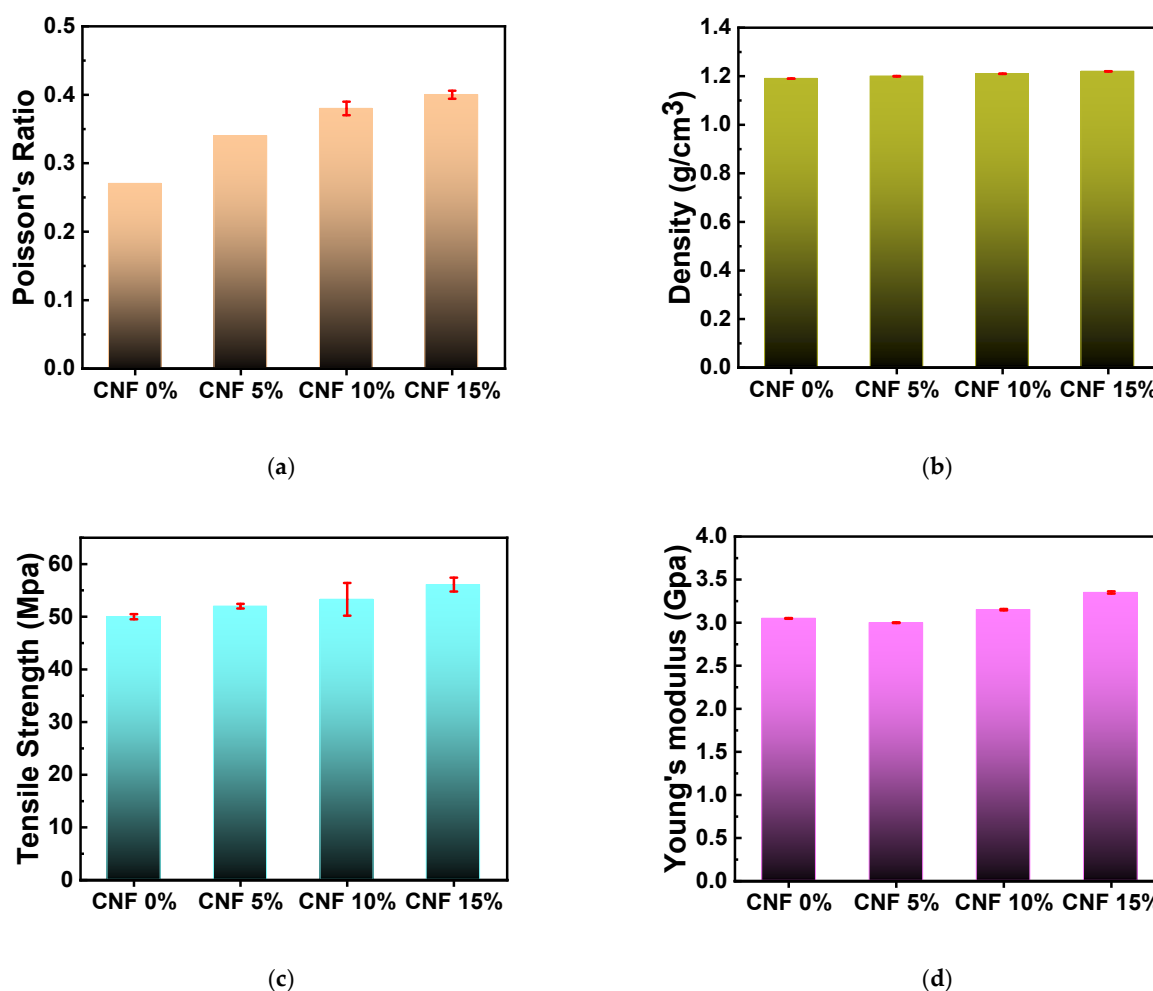


Figure 4. Effect of CNF Content on Mechanical Properties: (a) Poisson's Ratio, (b) Density, (c) Tensile Strength, and (d) Young's modulus. Different colors are used solely for visual distinction.

Young's modulus increased from 3.05 GPa for the CNF-free composite to 3.35 GPa at a CNF content of 15 wt%, corresponding to an enhancement of approximately 9.8%. Similarly, the tensile strength increased from 50 MPa (0 wt% CNF) to 56.1 MPa (15 wt% CNF), representing an improvement of approximately 12.2%, confirming the pronounced reinforcing effect of CNF incorporation. In contrast, the composite density exhibited only a marginal increase, from 1.19 g/cm³ to 1.22 g/cm³, corresponding to less than a 2.5% increase. This indicates that the improvement in mechanical performance was achieved with a negligible penalty in weight.

Notably, the density of the CNF/bio-based epoxy composites remained significantly lower than that of conventional tempered glass (approximately 2.50–2.54 g/cm³), highlighting the intrinsic material characteristics of the proposed composite system com-

pared to glass. Poisson's ratio increased from 0.27 to 0.40 with increasing CNF content, reflecting changes in the transverse deformation behavior of the matrix induced by CNF reinforcement.

These enhancements in mechanical properties are particularly beneficial when the composite is employed as a back-support layer, as they contribute to improved bending stiffness and load-bearing capacity of the photovoltaic module. When compared with representative properties of conventional PET-based back-sheets used in standard PV modules (Young's modulus ≈ 2.5 GPa, tensile strength ≈ 34 MPa, density ≈ 1.39 g/cm³, $\nu \approx 0.40$), the CNF/bio-based epoxy composite demonstrated superior mechanical performance, offering higher tensile strength (56.1 MPa) and stiffness (3.35 GPa) while maintaining a lower density (1.22 g/cm³).

Overall, these results indicate that the proposed CNF/bio-based epoxy composite exhibits excellent structural efficiency and is capable of fulfilling the mechanical requirements of a back-support layer in glass-free BIPV modules. The combination of enhanced strength, stiffness, and reduced weight highlights its strong potential as a viable alternative to conventional polymer back-sheets.

3.2. Optical Transmittance of the Transparent Bio-Based Epoxy Front Layer

The optical transmittance of the transparent bio-based epoxy composite was evaluated using UV–Vis spectroscopy for specimens with thicknesses of 1.0 mm and 1.5 mm. As shown in Figure 5, both specimens exhibited high optical transmittance exceeding 90% across the visible light region (400–800 nm), demonstrating optical performance comparable to that of conventional tempered glass with a thickness of 3.2 mm measured under identical conditions. These results confirm that the optical transparency requirements for front cover materials in BIPV applications are sufficiently satisfied.

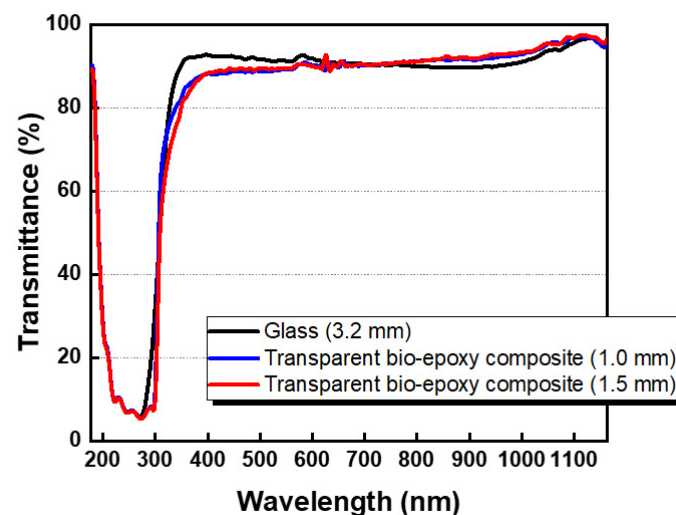


Figure 5. Transmittance comparison of glass and transparent bio-based epoxy composites.

The difference in transmittance between the 1.0 mm and 1.5 mm specimens was negligible in terms of average visible-light transmittance, indicating that light absorption and bulk scattering within the material are minimal. This behavior suggests that the bio-based epoxy matrix exhibits uniform intrinsic optical characteristics and that thickness variations within the investigated range have a limited impact on overall optical efficiency. A minor fluctuation in transmittance is observed around the 600–700 nm wavelength range for the 1.5 mm thick specimen. This behavior can be attributed to thickness dependent optical interference effects arising from multiple internal reflections within the optically transparent polymer layer. As the thickness increases, the optical path length becomes

comparable to the visible wavelength range, resulting in constructive and destructive interference at specific wavelengths. Such interference-induced oscillations are commonly observed in transparent polymeric materials with low absorption and smooth surfaces and do not indicate material degradation or optical instability. Importantly, the average visible-light transmittance remains above 90%, and no adverse impact on photovoltaic electrical performance was observed.

In addition to its high optical transmittance, the transparent bio-based epoxy exhibits a lower density and improved mechanical reliability compared to conventional tempered glass. These combined characteristics are particularly advantageous for BIPV applications, where structural safety and optical performance must be simultaneously ensured. Overall, these results demonstrate that the transparent bio-based epoxy composite is a promising candidate for use as an optically transparent front cover layer capable of replacing conventional glass in glass-free BIPV modules.

3.3. Structural Reliability Under a 5400 Pa Mechanical Load

To evaluate the structural reliability of the proposed glass-free photovoltaic (PV) module, structural finite element analysis was conducted under a static mechanical load of 5400 Pa, as specified in IEC 61215. The analysis model was constructed based on the actual module dimensions of $500 \times 550 \text{ mm}^2$, and the deformation behavior of a conventional PV module employing tempered glass (3.2 mm) was compared with that of the glass-free PV module incorporating a CNF/bio-epoxy composite back-sheet.

The detailed simulation results are summarized in Table 2. The maximum total deformation of the conventional glass-based PV module reached 3.11 mm under the applied load. In contrast, the glass-free PV modules reinforced with CNF/bio-epoxy composite back-sheets exhibited significantly lower deformations of 0.96 mm, 0.91 mm, and 0.87 mm, depending on the CNF content. This corresponds to a deformation reduction of approximately 69–72% compared to the conventional module, indicating a substantial enhancement in structural stiffness and load distribution capability.

Table 2. Total deformation and deformation reduction of glass-free PV modules with varying CNF content under a mechanical load of 5400 Pa.

CNF (wt%)	Total Deformation (mm)	Reduction vs. Glass (%)
0	3.11017	-
5	0.96434	69.0 loss
10	0.91294	70.7 loss
15	0.86545	72.2 loss

The improved deformation behavior can be attributed to the structural design strategy in which the load-bearing function was effectively redistributed by eliminating the front tempered glass layer and introducing a high stiffness CNF/bio-epoxy composite as the back-support layer. Owing to its high elastic modulus and tensile strength, the CNF composite back-sheet effectively suppressed bending deformation and served as a key structural component enhancing the overall mechanical stability of the module.

In addition to the reduction in maximum deformation, the deformation contours shown in Figure 6 reveal a clear difference in deformation distribution between the conventional glass-based module and the CNF/bio-based epoxy glass-free module. In the conventional module, deformation is highly concentrated in the central region, indicating bending dominated behavior of the tempered glass front layer under uniform pressure loading. In contrast, the glass-free module exhibits a significantly reduced and more uniformly distributed deformation profile, suggesting that the CNF/bio-epoxy composite

back-sheet effectively redistributes the applied load across the module and suppresses localized bending. This change in deformation behavior indicates a fundamental alteration in the load transfer mechanism from a glass-dominated bending response to a back-support-dominated structural response.

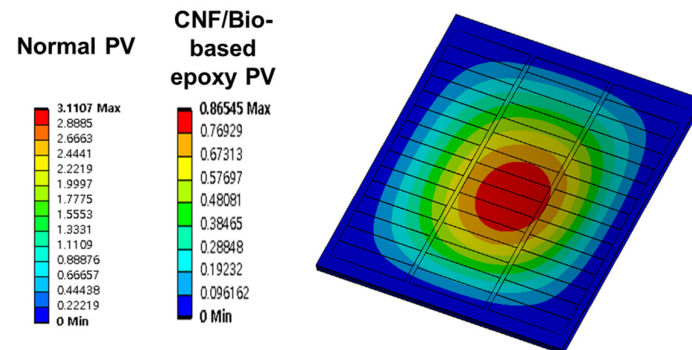


Figure 6. Simulated deformation distributions of conventional glass-based and CNF/bio-based epoxy PV modules under a mechanical load of 5400 Pa.

It should be noted that the reference glass-based module (Normal PV) employed a commercially adopted polymer-based back-sheet representative of state-of-the-art back-sheet materials commonly used in conventional photovoltaic modules. Such polymer back-sheets, typically based on PET or fluoropolymer-based multilayer structures, primarily function as electrical insulation and environmental protection layers, with limited contribution to load-bearing performance. In contrast, the CNF/bio-epoxy composite back-sheet in the proposed glass-free module is intentionally designed to act as an active structural component. The pronounced reduction in deformation therefore highlights a functional transition of the back-sheet from a passive protective layer to an active load-bearing element, distinguishing the proposed design from conventional back-sheet-based PV modules.

Although the proposed glass-free module exhibited an increase in mass of approximately 1.1 kg compared to the conventional glass-based module, it demonstrated markedly lower deformation under identical loading conditions. This result confirms a significant improvement in structural efficiency, defined as load-bearing performance per unit mass. These findings suggest that a back-support reinforcement strategy, rather than simple weight reduction, is an effective approach for achieving the high structural reliability and long-term durability required for BIPV modules.

Although the proposed glass-free module exhibited a moderate increase in mass compared to the conventional glass-based module, the observed improvement in structural efficiency originates from the redistribution of load-bearing functions rather than from simple weight reduction. In the conventional module, the tempered glass front layer dominates the bending response under mechanical loading, whereas in the proposed module, the high-stiffness CNF/bio-epoxy composite back-sheet actively contributes to load support. As a result, the proposed module achieves significantly lower deformation per unit mass, indicating an enhanced structural efficiency despite the slight increase in total mass.

While the present study primarily focuses on static mechanical performance and initial electrical validation of the proposed glass-free PV module, long-term durability aspects such as ultraviolet exposure, thermal cycling, moisture ingress, and hygrothermal aging will be systematically investigated in future work. In addition, although the CNF/bio-epoxy composite back-sheet was successfully demonstrated at the laboratory scale, future studies will address large-area module fabrication, CNF dispersion uniformity, and process

scalability to facilitate practical BIPV applications. These follow-up investigations will enable a comprehensive assessment of long-term reliability and industrial applicability of the proposed glass-free PV module architecture. Nevertheless, the glass-free PV module incorporating a CNF/bio-epoxy composite back-sheet fully satisfies the IEC 61215 mechanical load criteria and demonstrates strong potential to provide the structural stability required for direct integration into building envelopes in BIPV applications.

3.4. Electrical Output Performance

To evaluate the electrical output performance of the CNF/bio-based epoxy glass-free photovoltaic (PV) module, comparative measurements were conducted against a reference glass-based module employing identical monocrystalline silicon (M6) solar cells. Except for the front cover and back-support materials, the cell configuration and interconnection conditions were kept identical for both modules to isolate the effects of module structural differences on electrical performance. The fabricated glass-free PV module prior to electrical characterization is shown in Figure 7.

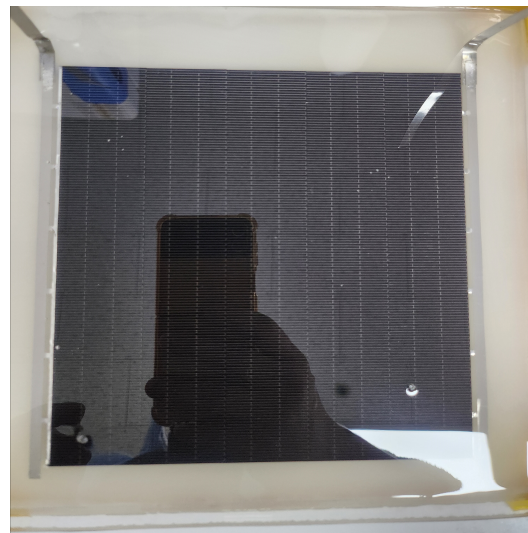


Figure 7. A photograph of the glass-free photovoltaic module incorporating a CNF/bio-epoxy composite.

As shown in the I–V curves presented in Figure 8, the CNF/bio-based epoxy module exhibited a curve shape very similar to that of the reference glass-based module, with no significant differences observed in the open-circuit voltage (V_{oc}) or short-circuit current (I_{sc}). Minor fluctuations observed in the I–V curves are attributed to the shingled cell architecture and electrically conductive adhesive interconnections, which can introduce localized contact resistance and series resistance effects, rather than to the instability of the encapsulation materials. Quantitative output analysis (Table 3) indicated that the V_{oc} and I_{sc} of the CNF/bio-epoxy module were 3.4518 V and 2.0302 A, respectively, which were comparable to or slightly higher than those of the reference module (3.4481 V and 2.0119 A). These results reflect the high optical transmittance of the transparent bio-based epoxy front layer in the visible wavelength region.

Table 3. Measured data value of module sample.

Parameter	Normal PV	CNF/Bio-Based-Epoxy PV
V_{oc} (V)	3.4481	3.4518
I_{sc} (A)	2.0119	2.0302
FF (%)	80.9424	79.5091

Table 3. Cont.

Parameter	Normal PV	CNF/Bio-Based-Epoxy PV
P _m (W)	5.6152	5.5719
EFF (%)	21.5391	21.3729

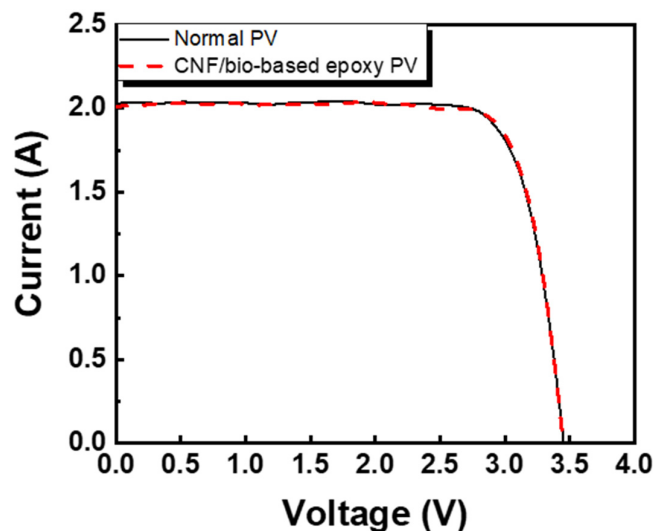


Figure 8. I–V characteristics of the conventional glass-based PV module and the CNF/bio-based epoxy glass-free PV module.

In contrast, the fill factor (FF) of the CNF/bio-based epoxy module was slightly reduced to 79.51% compared to 80.94% for the reference module, resulting in a corresponding decrease in maximum power output ($P_{\max}$) from 5.6152 W to 5.5719 W, corresponding to an approximate reduction of 0.8%. This minor decrease in output is attributed not to optical losses, but rather to changes in internal resistance associated with the module encapsulation structure and the incorporation of the composite back-support layer. Consistently, no pronounced distortion was observed in the knee region of the I–V curves, indicating that the overall electrical behavior of the module remained stable.

Overall, despite the structural modification associated with the glass-free design, the CNF/bio-based epoxy PV module maintained electrical output performance comparable to that of the conventional glass-based module. These findings demonstrate that the transparent bio-based epoxy front layer and the CNF composite back-sheet can be effectively applied to BIPV modules without significant degradation in optical or electrical performance, while simultaneously enhancing structural reliability. This highlights the proposed module configuration as a viable design strategy for achieving both mechanical robustness and electrical performance retention in next-generation BIPV systems.

4. Conclusions

This study addressed the central research question of whether a glass-free photovoltaic module architecture based on cellulose nanofiber (CNF)-reinforced bio-based epoxy composites can simultaneously satisfy the structural reliability, optical transparency, and electrical performance required for building-integrated photovoltaic (BIPV) applications. To this end, a transparent bio-based epoxy was employed as the front cover layer, and a CNF/bio-based epoxy composite was introduced as a mechanically reinforced back-sheet.

Mechanical property evaluations demonstrated that CNF incorporation effectively enhanced the stiffness and tensile strength of the bio-based epoxy composites, while the associated increase in density remained minimal. Structural finite element analysis

conducted under a static mechanical load of 5400 Pa in accordance with IEC 61215 revealed that the proposed glass-free photovoltaic module exhibited up to a 72% reduction in total deformation compared to a conventional glass-based module, indicating a substantial improvement in structural efficiency.

Optical transmittance measurements showed that the transparent bio-based epoxy front layer maintained transmittance values exceeding 90% in the visible wavelength range for thicknesses of 1.0–1.5 mm, demonstrating optical performance comparable to that of conventional tempered glass. Electrical output evaluations further confirmed that the glass-free photovoltaic module exhibited stable I–V characteristics, with a difference in maximum power output of less than 1% compared to the reference glass-based module.

Overall, the results clearly demonstrate that the proposed glass-free photovoltaic module incorporating CNF/bio-based epoxy composites can effectively overcome the structural limitations associated with glass removal while preserving optical transparency and electrical performance. From a BIPV perspective, this work highlights the effectiveness of a back-support reinforcement strategy that transforms the back-sheet from a passive protective layer into an active load-bearing structural component. Although further studies on large-area fabrication and long-term durability are required, the present findings establish a practical and sustainable design framework for next-generation BIPV modules where both structural reliability and material sustainability are critical.

Author Contributions: Conceptualization, C.L., Y.N. and J.L.; methodology, C.L. and H.C.; formal analysis, C.L. and H.C.; investigation, C.L. and Y.N.; data curation, C.L.; writing—original draft preparation, C.L.; writing—review and editing, H.C. and J.L.; visualization, C.L. and Y.N.; supervision, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry and Energy (MOTIE), Republic of Korea, under Grant No. RS2022-KP002701. This work was also supported by the Technology Innovation Program (Grant No. RS-2024-00427007, “Development of CNF Composite Insulation Boards with Dielectric Strength of 40 kV/mm for High-Efficiency Transformers”) funded by the Korea Planning & Evaluation Institute of Industrial Technology (KEIT).

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pillai, D.S.; Shabunko, V.; Krishna, A. A comprehensive review on building integrated photovoltaic systems: Emphasis to technological advancements, outdoor testing, and predictive maintenance. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111946. [\[CrossRef\]](#)
2. Nejat, P.; Jomehzadeh, F.; Taheri, M.M.; Gohari, M.; Majid, M.Z.A. A global review of energy consumption, CO₂ emissions and policy in the residential sector (with an overview of the top ten CO₂ emitting countries). *Renew. Sustain. Energy Rev.* **2015**, *43*, 843–862. [\[CrossRef\]](#)
3. Belloni, E.; Bianchini, G.; Casini, M.; Faba, A.; Intravaia, M.; Laudani, A.; Lozito, G.M. An overview on building-integrated photovoltaics: Technological solutions, modeling, and control. *Energy Build.* **2024**, *324*, 114867. [\[CrossRef\]](#)
4. Chen, T.; An, Y.; Heng, C.K. A review of building-integrated photovoltaics in Singapore: Status, barriers, and prospects. *Sustainability* **2022**, *14*, 10160. [\[CrossRef\]](#)
5. Kuhn, T.E.; Erban, C.; Heinrich, M.; Eisenlohr, J.; Ensslen, F.; Neuhaus, D.H. Review of technological design options for building integrated photovoltaics (BIPV). *Energy Build.* **2021**, *231*, 110381. [\[CrossRef\]](#)
6. Shukla, A.K.; Sudhakar, K.; Baredar, P. A comprehensive review on design of building integrated photovoltaic system. *Energy Build.* **2016**, *128*, 99–110. [\[CrossRef\]](#)
7. Agathokleous, R.A.; Kalogirou, S.A. Status, barriers and perspectives of building integrated photovoltaic systems. *Energy* **2020**, *191*, 116471. [\[CrossRef\]](#)

8. Jelle, B.P. Building integrated photovoltaics: A concise description of the current state of the art and possible research pathways. *Energies* **2015**, *9*, 21. [\[CrossRef\]](#)
9. Miettunen, K.; Hadadian, M.; García, J.V.; Lawrynowicz, A.; Akulenko, E.; Rojas, O.J.; Vapaavuori, J. Bio-based materials for solar cells. *WIREs Energy Environ.* **2024**, *13*, e508. [\[CrossRef\]](#)
10. Wang, X.; Yao, C.; Wang, F.; Li, Z. Cellulose-based nanomaterials for energy applications. *Small* **2017**, *13*, 1702240. [\[CrossRef\]](#)
11. Zeng, J.; Li, R.; Liu, S.; Zhang, L. Fiber-like TiO₂ nanomaterials with different crystallinity phases fabricated via a green pathway. *ACS Appl. Mater. Interfaces* **2011**, *3*, 2074–2079. [\[CrossRef\]](#)
12. Wu, Q.; Yu, Y.; Xia, X.; Gao, Y.; Wang, T.; Sun, R.; Guo, J.; Wang, S.; Xie, G.; Lu, X.; et al. High-Performance Organic Photovoltaic Modules Using Eco-Friendly Solvents for Various Indoor Application Scenarios. *Joule* **2022**, *6*, 2138–2151. [\[CrossRef\]](#)
13. Norouzi, M.; Haddad, A.N.; Jiménez, L.; Mohajerani, M.; Boer, D. Long-Term Decarbonization Prediction of Buildings Accounting for Temporal Variations in Grid and Material Emission Factors: A Case Study of Timber-Framed Passive Houses in the United Kingdom. *Renew. Energy* **2025**, *242*, 122476. [\[CrossRef\]](#)
14. Singh, A.; Umakanth, V.; Tyagi, N.; Kumar, S. A comparative study of different polymer materials for the development of flexible crystalline silicon modules. *Sol. Energy Mater. Sol. Cells* **2023**, *264*, 112259. [\[CrossRef\]](#)
15. Martins, A.C.; Chapuis, V.; Virtuani, A.; Li, H.-Y.; Perret-Aebi, L.E.; Ballif, C. Thermo-mechanical stability of lightweight glass-free photovoltaic modules based on a composite substrate. *Sol. Energy Mater. Sol. Cells* **2018**, *187*, 82–90. [\[CrossRef\]](#)
16. Batista, F.; Guimarães, A.S.; Palmero-Marrero, A.I. Building integrated photovoltaics: A multi-level design review for optimized implementation. *Renew. Sustain. Energy Rev.* **2025**, *220*, 115837. [\[CrossRef\]](#)
17. Ballif, C.; Perret-Aebi, L.E.; Lufkin, S.; Rey, E. Integrated thinking for photovoltaics in buildings. *Nat. Energy* **2018**, *3*, 438–442. [\[CrossRef\]](#)
18. Al Mahdi, H.; Leahy, P.G.; Alghoul, M.; Morrison, A.P. A review of photovoltaic module failure and degradation mechanisms: Causes and detection techniques. *Solar* **2024**, *4*, 43–82. [\[CrossRef\]](#)
19. Imbuluzqueta, G.; Cano, F.J.; Iglesias, U.; Aizpurua, J.; Hernández, J.M.; Yurrita, N.; Cambarau, W.; Zubillaga, O. Photovoltaic module with encapsulant system based on recyclable composite material. *Sol. Energy* **2025**, *300*, 113799. [\[CrossRef\]](#)
20. Al-Saleem, N.K.; Al-Naghmaish, A.; Madani, M.; Alfawwar, W.; Elbasiony, A.M.; Alharthi, S.; Haque, M.A.; Ghobashy, M.M. Multifunctional roles and advances of polymers in solar cell technologies: A review. *RSC Adv.* **2025**, *15*, 35998–36049. [\[CrossRef\]](#)
21. Kim, D.; Lim, H.; Kim, S.H.; Lee, K.N.; You, J.; Ryu, D.Y.; Kim, J. Recent developments of polymer-based encapsulants and backsheets for stable and high-performance silicon photovoltaic modules: Materials nanoarchitectonics and mechanisms. *J. Mater. Chem. A* **2024**, *12*, 7452–7469. [\[CrossRef\]](#)
22. Masoodi, R.; El-Hajjar, R.F.; Pillai, K.M.; Sabo, R. Mechanical characterization of cellulose nanofiber and bio-based epoxy composite. *Mater. Des.* **2012**, *36*, 570–576. [\[CrossRef\]](#)
23. Mehdiinia, M.; Farajollah Pour, M.; Yousefi, H.; Dorieh, A.; Lamanna, A.J.; Fini, E. Developing bio-nano composites using cellulose-nanofiber-reinforced epoxy. *J. Compos. Sci.* **2024**, *8*, 250. [\[CrossRef\]](#)
24. Azhary, T.; Wildan, M.W. Mechanical, morphological, and thermal characteristics of epoxy/glass fiber/cellulose nanofiber hybrid composites. *Polym. Test.* **2022**, *110*, 107560. [\[CrossRef\]](#)
25. Subbotina, E.; Montanari, C.; Olsén, P.; Berglund, L.A. Fully bio-based cellulose nanofiber/epoxy composites with both sustainable production and selective matrix deconstruction towards infinite fiber recycling systems. *J. Mater. Chem. A* **2022**, *10*, 570–576. [\[CrossRef\]](#)
26. Roszowska-Jarosz, M.; Masiewicz, J.; Kostrzewa, M.; Kucharczyk, W.; Żurowski, W.; Kucińska-Lipka, J.; Przybyłek, P. Mechanical properties of bio-composites based on epoxy resin and nanocellulose fibres. *Materials* **2021**, *14*, 3576. [\[CrossRef\]](#)
27. Park, M.J.; Youn, S.; Jeon, K.; Lee, S.H.; Jeong, C. Optimization of shingled-type lightweight glass-free solar modules for building integrated photovoltaics. *Appl. Sci.* **2022**, *12*, 5011. [\[CrossRef\]](#)
28. Lisco, F.; Martins, A.C.; Virtuani, A.; Ballif, C. Glass-free lightweight solar modules for integrated photovoltaics: The use of Velcro as an alternative mounting system. In Proceedings of the 37th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal, 7–11 September 2020; pp. 7–11. [\[CrossRef\]](#)
29. Martins, A.C.; Chapuis, V.; Virtuani, A.; Perret-Aebi, L.E.; Ballif, C. Hail resistance of composite-based glass-free lightweight modules for building integrated photovoltaics applications. In Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, The Netherlands, 25–29 September 2017; pp. 25–29. [\[CrossRef\]](#)
30. Desai, U.; Courtant, M.; Eder, G.C.; Oreski, G.; Faes, A.; Ballif, C. Novel mechanically robust and environmentally stable lightweight colored photovoltaic modules based on composite polymer backsheets. *Sol. RRL* **2025**, *9*, 202500177. [\[CrossRef\]](#)
31. Nair, S.S.; Dartailh, C.; Levin, D.B.; Yan, N. Highly toughened and transparent biobased epoxy composites reinforced with cellulose nanofibrils. *Polymers* **2019**, *11*, 612. [\[CrossRef\]](#)
32. Retegi, A.; Algar, I.; Martin, L.; Altuna, F.; Stefani, P.; Zuluaga, R.; Gañán, P.; Mondragon, I. Sustainable optically transparent composites based on epoxidized soybean oil (ESO) matrix and high contents of bacterial cellulose (BC). *Cellulose* **2012**, *19*, 103–109. [\[CrossRef\]](#)

33. Yang, X.; Cheng, F.; Fan, Y.; Song, Y.; He, N.; Lai, G.; Gong, Z.; Shen, J. Highly transparent acrylate epoxidized soybean oil based UV-curable silicone-modified coatings with good thermal stability and flame retardancy. *Prog. Org. Coat.* **2022**, *165*, 106769. [[CrossRef](#)]
34. Wu, X.; Zheng, S.; Bellido-Aguilar, D.A.; Silberschmidt, V.V.; Chen, Z. Transparent icephobic coatings using bio-based epoxy resin. *Mater. Des.* **2018**, *140*, 516–523. [[CrossRef](#)]
35. Benda, V.; Černá, L. PV cells and modules—State of the art, limits and trends. *Heliyon* **2020**, *6*, e05666. [[CrossRef](#)]
36. Saga, T. Advances in crystalline silicon solar cell technology for industrial mass production. *NPG Asia Mater.* **2010**, *2*, 96–102. [[CrossRef](#)]
37. Bae, J.; Jee, H.; Park, Y.; Lee, J. Simulation-based shading loss analysis of a shingled string for high-density photovoltaic modules. *Appl. Sci.* **2021**, *11*, 11257. [[CrossRef](#)]
38. Jaubert, J.-N.; Nair, S.V.; Cai, J.; Lv, R.; Marteau, B.; Xu, T.; Zhang, G.; Ruda, H.E. Conductive adhesive based shingled solar cells: Electrical degradation under cyclic loading. *Sol. Energy Mater. Sol. Cells* **2022**, *245*, 111823. [[CrossRef](#)]

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