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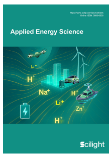

Review

Critical Encapsulant Materials for Commercial and Emerging Solar Cells: Performance, Challenges, and Perspectives

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Abstract: Solar energy, as a clean and renewable resource, plays a pivotal role in the global energy landscape due to mitigate environmental pollution and resource depletion. Photovoltaic (PV) modules, which enable efficient photoelectric conversion, are critically dependent on encapsulant materials to ensure long-term reliability and performance. However, these materials often limit the lifespan of solar cells under harsh outdoor conditions. This review systematically examines the performance, challenges, and future trends of mainstream and emerging encapsulant materials for crystalline silicon solar cells, N-type high-efficiency crystalline silicon solar cells (e.g., HJT, TOPCon, IBC), and perovskite solar cells (PSCs). It elaborates on the classification, the advantages, disadvantages and application areas, key performance indicators (e.g., barrier properties, adhesion strength) and practical industrial challenges of materials such as ethylene-vinyl acetate copolymer (EVA), polyolefin elastomers (POE), polyvinyl butyral (PVB), and thermoplastic polyurethane (TPU). The analysis underscores the importance of developing high-performance, durable, and sustainable encapsulation solutions to support the advancement of PV technology. This work aims to provide a comprehensive reference for the research and development of next-generation photovoltaic modules with enhanced efficiency and lifespan.

Keywords: photovoltaic modules; encapsulant materials; crystalline silicon solar cells; perovskite solar cells; ethylene-vinyl acetate copolymer (EVA); polyolefin elastomers (POE); polyvinyl butyral (PVB); sustainability

1. Introduction

The global energy crisis, exacerbated by the overexploitation of fossil fuels (e.g., coal, oil, and natural gas), has led to severe environmental pollution and resource depletion. Developing renewable and clean energy sources, such as solar, wind, and geothermal energy, is therefore critical for sustainable development [1]. Among these, solar energy stands out due to its abundance, wide distribution, cleanliness and low operating costs [2]. Photovoltaic (PV) technology, which converts sunlight directly into electricity via the photovoltaic effect, has become the most widely adopted method for solar energy utilization [3]. According to data released by the global energy think tank Ember, global newly installed solar capacity in 2025 led the way with an addition of 647 GW, representing an 11% increase compared to 2024, bringing the global cumulative installed photovoltaic capacity to approximately 2900 GW by the end of 2025 [4].

Solar cells are the core components of PV systems. They can be categorized by material and generation into crystalline silicon (e.g., monocrystalline silicon and polycrystalline silicon), thin film (e.g., cadmium telluride and copper indium gallium selenide), and emerging technologies (e.g., perovskite, dye-sensitized and organic solar cells) [5].

As illustrated in Figure 1, this diversity enables tailored applications but also imposes district requirements on encapsulant materials.

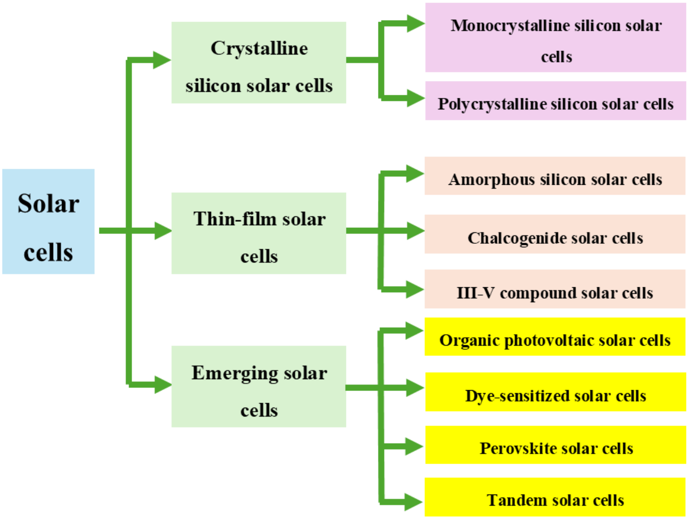

Figure 1. Classification of solar cells based on material and technology generation, including crystalline silicon, thin-film, and emerging types.

A typical crystalline silicon PV module consists of a multi-layered structure (Figure 2): solar cell, a top cover (e.g., tempered glass), an encapsulation film, a backsheet (e.g., TPT), and frame [6–8]. The encapsulation film (e.g., ethylene-vinyl acetate copolymer, EVA) serves as the adhesive layer, bonding the glass, cells, and backsheet into a robust laminate. Its primary functions include physical protection, optical coupling, electrical insulation, and environmental barrier properties [9,10]. However, PV modules operate for decades under harsh outdoor conditions (e.g., UV radiation, temperature cycles, humidity, and mechanical stress), which accelerate the degradation for encapsulant materials. This degradation manifests as delamination, yellowing, potential-induced degradation (PID), and moisture ingress, ultimately compromising module efficiency and lifespan [11–13]. Notably, while silicon wafers themselves can exceed 30 years of service, the stability of the entire module largely depends on the encapsulation system [14–16].

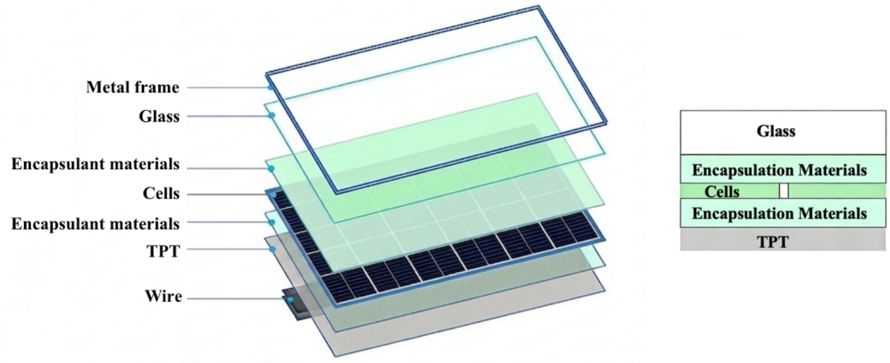

Figure 2. Schematic diagram of a typical crystalline silicon photovoltaic module structure, showing layers such as glass, encapsulation film, solar cells, and backsheet.

Despite the critical role of encapsulant materials, existing reviews often lack a systematic comparison of traditional materials (e.g., EVA, polyolefin elastomers (POE)) and emerging solutions (e.g., thermoplastic polyurethane (TPU)) for next-generation solar cells (e.g., N-type crystalline silicon and perovskite cells). Furthermore, challenges such as recyclability, cost-effectiveness, and compatibility with advanced cell technologies remain underexplored.

This review aims to bridge these gaps by providing a comprehensive analysis of encapsulant materials for commercial and emerging solar cells. We focus on:

(1) Classifying materials and evaluating their advantages, disadvantages, and key performance indicators (e.g., barrier properties, adhesion strength).
(2) Examining practical industrial challenges (e.g., stability, processing costs).
(3) Discussing frontier trends, including self-healing materials and passivation-integration technologies. By synthesizing recent advances, this work seeks to guide the development of high-performance, durable, and sustainable PV modules.

2. Encapsulant Materials for Photovoltaic Modules: Classification, Properties, and Applications

Encapsulant materials serve as the critical protective layer in photovoltaic (PV) modules, directly determining their long-term reliability, efficiency, and service life. This chapter provides a systematic analysis of these materials, beginning with their fundamental functions and key performance indictors (KPIs. It then classifies and examines both traditional (commercially dominant) and emerging materials, highlighting their performance trade-offs, industrial challenges, and application-specific suitability.

2.1. Fundamental Functions and Properties

The primary role of encapsulant materials is to create a hermetic barrier against environmental stressors while maintaining optical, mechanical, and electrical integrity of the PV module over decades of outdoor exposure. Their core functions and corresponding properties are summarized in Table 1.

Table 1. Core functions and corresponding material properties for encapsulant materials.

Function	Materials Properties	Impact on Module Performance
Environmental barrier	Water vapor transmission rate (WVTR, $g/m^2/day$), oxygen transmission rate (OTR, $cm^3/m^2/day$)	Prevents moisture/oxygen ingress, critical for mitigating cell corrosion and potential-induced degradation (PID)
Optical coupling	Transmittance (300–1200 nm), haze (%)	Maximizes light absorption by cells; minimizes reflection losses; Improve module efficiency
Mechanical stability	Tensile strength (MPa); Elongation at break (%)	Resists delamination and mechanical stress (e.g., from thermal cycling, hail, wind).
Electrical insulation	Dielectric strength (kV/mm); Volume resistivity ($\Omega \cdot cm$)	Prevents electrical short circuits and leakage currents.
Thermal stability	Glass transition temperature (T_g, °C); Thermal decomposition temperature (Td, °C)	Withstands operational temperature cycles (typically −40 °C to 85 °C) without degradation.
Chemical resistance	Resistance to UV, acids, alkalis, and PID-inducing ions (e.g., Na^+, Cl^-)	Avoids yellowing, brittleness, and electrochemical degradation.

Note: Material properties are defined by industrial standards such as IEC 61215 and relevant studies [1,13,17–19].

The ideal encapsulation material must balance these often-competing material properties. For instance, a material with superior barrier properties may come at a higher cost or require more complex processing.

2.2. Traditional Encapsulant Materials: Commercial Workhorses

Traditional materials (Figure 3) dominate the current PV market due to proven reliability, mature processing technologies, and cost-effectiveness.

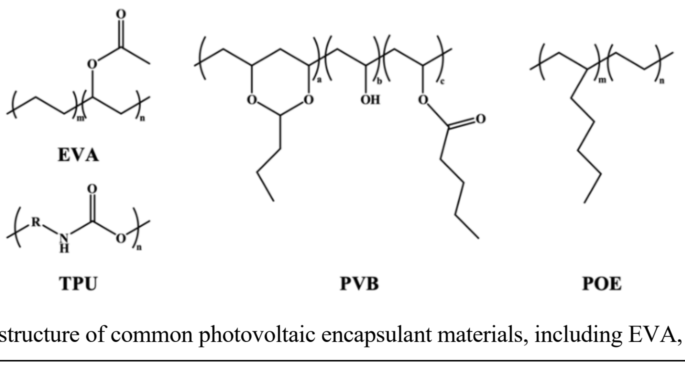

Figure 3. Molecular structure of common photovoltaic encapsulant materials, including EVA, POE, PVB, and TPU.

2.2.1. Ethylene-Vinyl Acetate Copolymer (EVA)

EVA is the industry standard, accounting for approximately 70% of the global encapsulation market [20]. It is a copolymer of ethylene and vinyl acetate (VA), with VA content typically between 28–33 wt% for PV applications. The incorporation of VA monomers disrupts the crystallinity of polyethylene, thereby modifying the material's properties. The performance of EVA is primarily governed by VA content and melt flow rate (MFR). A higher VA content enhances transparency, flexibility, adhesion and solubility but reduces electrical insulation, crystallinity [21]. Conversely, a higher MFR improves processability, while a lower MFR enhances impact resistance and environmental stress cracking resistance. The MFR for solar cell encapsulants ranges from 15 to 45 g/10 min [22]. Regarding the impact of MFR on encapsulation, a high MFR indicates good fluidity, which facilitates the filling of fine structures such as cell gaps and conductive grid lines during vacuum lamination. Additionally, under lamination pressure, it spreads more evenly, forming a uniform adhesive film layer. However, excessively high MFR can have a series of negative impacts on the long-term reliability and mechanical performance of encapsulated modules.

The commercialization of EVA began in 1981 with DuPont's Elvax 150 EVA film, which featured a VA content of 33% and a service life of 5 to 10 years, meeting the demands of early solar modules. EVA's widespread adoption is attributed to its key advantages: (1) High light transmittance (>91%), ensuring efficient photon utilization; (2) excellent adhesion to glass and backsheets; (3) a mature, low-temperature vacuum lamination process; and (4) low cost.

The encapsulation process using EVA is conducted via vacuum lamination, which involves sequential steps: (1) Layering (glass-EVA film- cell-EVA-backsheet); (2) Vacuum application; (3) Heating (≈140 °C); (4) Pressurization; (5) Curing; and (6) Cooling. However, the longevity of EVA-encapsulated modules is limited by three critical issues: adhesion strength, yellowing and potential-induced degradation (PID) [23].

Adhesion Strength: Although EVA is a polar material, its peel strength with TPT is not particularly high without the addition of additives [24]. To address this, silane coupling agents (e.g., KH550, KH551) are grafted on to EVA molecules via peroxide-initiated radical reactions. During lamination, polar groups (e.g., $-Si-O-CH_3$) form chemical bonds with hydroxyl groups on glass surfaces, enhancing adhesion [25,26]. Peel strength is the key metric for evaluating adhesion, which is highly dependent on the crosslinking degree. The studies show that the peel strength peaks at 85% crosslinking; the excessive crosslinking (>85%) induces brittleness and reduces adhesion [27–30]. Umang Desai et al. [31] demonstrated that EVA with 24% VA content maintains adhesion after damp-heat aging (85 °C, 85% RH, 1000 h), whereas higher VA content (33–40%) lead to degradation, highlighting the need to balance crosslinking degree and VA composition [32–34].

Yellowing Phenomenon: EVA undergoes photo-oxidative degradation under the influence of ultraviolet light, high temperature, and oxygen, leading to a decrease in EVA transmittance and the efficiency of solar cell modules [35–38]. This phenomenon is influenced by both physical factors (e.g., UV intensity, glass absorption, backsheet airtightness).

In the early days, Pern et al. explained that the discoloration of EVA was due to the formation of polyene groups (C=C) [39]. Recently, a new explanation has been given for the yellowing phenomenon of EVA during use. First, poor backsheet airtightness leads to moisture intrusion, which in turn leads to the formation of chromophores (the chemical interaction between EVA and water leads to the formation of chromophores). These chromophores cause EVA to absorb the colors corresponding to the 380 nm to 500 nm region (i.e., purple and blue light), causing EVA to turn yellow [40]. In addition, the loss of ultraviolet absorbers exposes the polymer segments of EVA directly to ultraviolet radiation, leading to the formation of fluorophores (α-β carbonyl fluorophores) and other chemical functional groups in EVA [41].

Research by Peter Klemchukle et al. [42,43] confirms that yellowing arises from reactions between peroxides and stabilizers. To mitigate this, additives such as antioxidants, UV absorbers and hindered amine light stabilizers (HALS) are incorporated. For instance, Liu Z. P. et al. [44] grated reactive -HALS onto EVA chains (EVA-g-HALs), which preserved the crosslinking network and mechanical properties after aging. Mahmoud G.A. Saleh et al. [45] and Mansoor Shafiq Durrani et al. [46] further enhanced EVA's performance using SnO_2 nanoparticles and ternary nanofillers (GNP/n-ZnO/BC), respectively, achieving a a 32.6% increase in tensile strength and >70% reduction WVTR.

Potential-induced degradation (PID): PID is one of the most critical degradation phenomena affecting the reliability of PV modules and causing power loss. In PV modules deployed in large-scale PV systems, PID can lead to significant power loss of more than 30% [47]. The large number of PV cells connected in series requires high voltage and creates a high potential difference between the PV system and the ground [38]. Depending on the position of the module in the module string, this potential difference can generate leakage current between the module frame and the solar cells, including through channels in the EVA, resulting in PID. This mechanism leads to the migration and loss of charge carriers, reducing the efficiency of the PV system [48]. López-Escalante et al. [49] reported that EVA may promote PID because sodium ions from the glass migrate through the encapsulant, which accumulates at the silicon nitride antireflection layer of the cell. One way to minimize PID is to impede the flow of ion current through the encapsulant.

Future Development: While EVA remains the industry benchmark, future efforts focus on:

(1) Developing functionalized films (e.g., light-converting) to enhance values. Chang Kyu Son et al. [50] prepared a thin film of ethylene-vinyl acetate copolymer (EVA) with homogeneously dispersed silver nanoparticles (AgNPs) from a AgNP/EVA mixture. This film was then used to encapsulate the top surface of a photovoltaic cell via lamination. To achieve uniform dispersion of the AgNPs, maleic anhydride-grafted polypropylene (PP-g-MAH) was added to the AgNP/EVA mixture as a compatibilizer. Thanks to the high dispersion of the AgNPs, the resulting film exhibited strong light-scattering properties, which in turn effectively enhanced the power conversion efficiency of the photovoltaic cell.

(2) Formulating dedicated EVA for emerging cells (e.g., N-type crystalline silicon, perovskites) with circular economy goals. These initiatives aim to address EVA's limitations in barrier properties and environmental sustainability while leveraging its cost advantage.

(3) Solve the recycling problem of solar cells encapsulated with EVA. Prior to the wide-spread adoption of new materials, overcoming the recycling challenges of existing EVA-based modules is imperative to address the impending wave of PV waste. The cross-linked structure of EVA, while ensuring module longevity (>25 years), complicates material recovery. Current recycling strategies include: (1) physical method: techniques such as liquid nitrogen embrittlement, high-voltage pulse discharge or mechanical grinding disrupt EVA adhesion. These approaches are environmentally friendly and low cost but yield limited material purity and low metal recovery. (2) pyrolysis: Thermal decomposition (350–500 °C in an oxygen-free environment) dissociates EVA layers efficiently and is suitable for industrial-scale recycling. However, it consumes significant energy (~500 kWh per ton of module), and may release harmful gases from backsheet decomposition, necessitating expensive gas treatment systems. (3) chemical methods: Solvents (e.g., toluene) or reagents (acids/bases) swell or dissolve EVA, enabling high-purity material recovery. These methods are time-consuming, generate large volumes of waste, pose secondary pollution risks, limiting their economic viability.

Integrated approaches combining multiple techniques are gaining traction to balance recovery purity, energy consumption, and cost-effectiveness. Wang X. W. et al. [51] proposed supercritical n-butanol treatment for EVA dissolution, modeling dissolution rates to optimized recovery, Touhid Bin Anwar et al. [52] demonstrated nanosecond laser-induced transient melting at the EVA-silicon interface, enabling clean separation. Zheng P. K. et al. [53] explored swelling behavior using NMP and BDG, achieving full layer separation under controlled conditions.

These efforts highlight the trend toward hybrid methodologies that enhance efficiency while minimizing environmental impact.

2.2.2. Polyolefin Elastomer (POE)

Polyolefin elastomer (POE) is a thermoplastic elastomer synthesized via the copolymerization of ethylene and α-olefins (e.g., 1-octene) using metallocene catalysts. Its molecular structure consists of crystalline regions and amorphous segments derived from the α-olefin comonomer. This unique structure endows POE with a narrow molecular weight distribution, short-chain branching, low crystallinity, and a minimal number of tertiary carbon atoms, resulting in excellent flowability, mechanical strength, corrosion resistance, UV resistance and hydrophobicity [54]. POE encapsulation film is produced using polyolefin elastomer as the primary raw material, compounded with various additives (e.g., crosslinking agents, silane coupling agents, light stabilizers, antioxidants and UV absorbers) via an extrusion process.

POE is particularly well-suited as an encapsulation material for high-efficiency solar cells. Its exceptional barrier properties, notably its extremely low water vapor transmission rate (WVTR < 1 g/m^2/day), are primarily attributed to its superior material structure and crosslinking technology, which significantly impede moisture permeation [55,56]. Furthermore, POE possesses a stable molecular structure that does not produce acidic byproducts during degradation, coupled with strong weather resistance and UV aging resistance, collectively ensuring module service life exceeding 25 years.

Recent research focuses on enhancing POE's properties. Hou J. C. et al. [57] introduced glycidyl methacrylate (GMA) monomer into POE via a photoinduced iron-catalyzed alkylation reaction, developing a novel polyolefin encapsulant for PV modules. This encapsulant is designed to exhibit high light transmittance, enhanced adhesion and higher resistivity, with the modified POE achieving an adhesive strength of 28.3 N cm^{-1}. Wang Q. C. et al. [58]

demonstrated an in-situ prepared $CsPbBr_3$ PQDs/POE encapsulating film compatible with melt extrusion for continuous mass production, showing good compatibility with silicon PV module encapsulation technology. PQDs/POE were continuously formed from a POE masterbatch mixture containing $CsPbBr_3$ precursors via a stretching operation. The authors developed a stepwise granulation method in which each $CsPbBr_3$ precursor was pre-dispersed in the POE masterbatch via melt extrusion. Homogeneous mixing of the POE masterbatch containing different perovskite precursors was achieved through co-melting extrusion at approximately 180 °C. After mechanically mixing the perovskite precursor/POE masterbatch, the mixture was fed back into the extruder to manufacture the encapsulating film. the obtained $CsPbBr_3$ PQDs/POE film possesses the excellent luminescence downshifting (LDS) properties, with a visible light transmittance exceeding 80% and a photoluminescence quantum yield as high as 98.2%. After aging at 50 °C/90% relative humidity for over 2400 h, the photoluminescence emission intensity decayed by less than 5%, demonstrating excellent operational reliability and barrier properties.

Despite its advantages, POE faces several significant challenges in large-scale production applications. Firstly, the lack of polar bonds in its molecular structure leads to inherently poor adhesion. Secondly, its raw material costs are relatively high compared mainstream materials like EVA. Furthermore, as a non-polar resin, POE exhibits weak intermolecular forces, which can affect the compatibility between the polymer matrix and additives. Consequently, careful selection and dosage of additives during production are crucial to prevent additive precipitation and ensure the uniformity and stability of the encapsulation film.

Research efforts are actively addressing these limitations, particularly adhesion. Liu Z. P. et al. [59] grafted reactive hindered amine stabilizers (rHALS) onto the POE backbone via reactive extrusion to prepare hindered amine-grafted POE (POE-g-HALS). Their systematic study revealed that POE-g-HALS increased the peel strength of glass/POE film interface by 29%, attributed to hydrogen bonding between the grafted HALS and hydroxyl groups on the glass surface. Xu M. N. et al. [60] incorporated compatibilizers into the POE matrix to fabricate a light-emitting film (POE/POE-g-PHEMA/EuFT), which can convert ultraviolet light into red light, potentially improving photovoltaic conversion efficiency and reducing UV aging impact, while achieving a peel strength of the film can reach 23.9 N cm^{-1}. Jin Hwan Park et al. [61] developed an acrylate-based copolymer additive to improve the interfacial adhesion between POE and glass substrate. Jin Hwan Park et al. [62] blended POE with a chemically modified hydrocarbon resin (m-HCR), using γ-methacryloyloxypropyltrimethoxysilane (MTS) as an adhesion promoter (Figure 4), and observed a linear increase in peel strength with increasing m-HCR content.

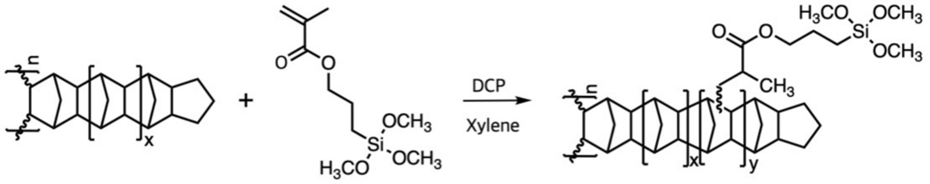

Figure 4. Synthetic diagram for m-HCR [62].

POE encapsulation film inherently possesses high electrical insulation properties, resulting in a volume resistivity that is generally superior to that of EVA [54]. However, in addition to its relatively poor adhesive performance, POE also exhibits weaker ultraviolet (UV) blocking capability compared to EVA [63]. With the rapid development of photovoltaic technology, POE has gradually become the primary encapsulation film for N-type solar cells.

2.2.3. Polyvinyl Butyral (PVB)

Polyvinyl butyral (PVB) is a thermoplastic polymer synthesized through the acid-catalyzed condensation of polyvinyl alcohol (PVA) with n-butyraldehyde (Figure 5). The molecule structure of PVB comprises three primary units: vinyl butyral, vinyl acetate, and vinyl alcohol [64]. The vinyl acetate content typically remains below 3 wt%, exerting minimal influence on material properties, whereas the proportions of vinyl butyral and vinyl alcohol critically determine performance. An increase in vinyl butyral content enhances transparency, toughness and tensile strength while higher vinyl alcohol content improves adhesion and tear strength at the expense of processability [65]. For photovoltaic applications, the vinyl alcohol content generally ranges between 17 wt% and 19 wt%.

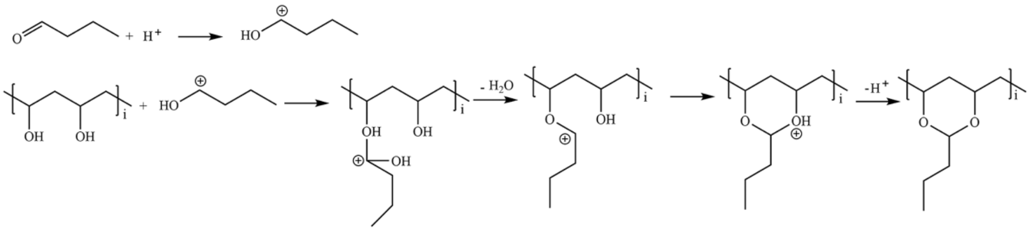

Figure 5. Reaction mechanism of PVB synthesis [66].

The industrial production of PVB predominantly employs a two-step precipitation method. Initially, an aqueous solution of PVA solution reacts with butyraldehyde under acidic conditions. As the reaction progresses, the declining hydroxyl group content reduces the solubility of the PVB resin, leading to its precipitation and resulting a heterogeneous system. This approach facilitates efficient product recovery and washing, yielding high purity PVB resin without alcohol solvent contamination [66]. Since the 1940s, PVB has been widely utilized in laminated safety glass, fiber-reinforced plastic (FRP), adhesives and fabric treatments [67].

PVB exhibits unique advantages in photovoltaic encapsulation, particularly for building-integrated photovoltaics (BIPV) (Figure 6) and double-glass modules:

Super Adhesion and Impact Resistance: The molecular structure of PVB contains highly polar hydroxyl and acetal groups, which can form strong hydrogen bonds and van der Waals forces with the silanol groups on the glass surface. The synergistic effect of these chemical and physical interactions allows PVB to adhere tightly and durably to the glass surface. Even in harsh environments such as high temperature and high humidity, its bonding interface remains stable, effectively preventing separation between the glass and the interlayer, which is the foundation for the structural integrity of safety glass [68].

Thermoplastic processability: As a thermoplastic material, PVB does not require cross-linking, simplifying processing and enabling recycling through remelting, thereby reducing production costs [67,69].

Electrical and Weather resistance: High dielectric strength and robust weatherability ensure performance stability under harsh outdoor conditions.

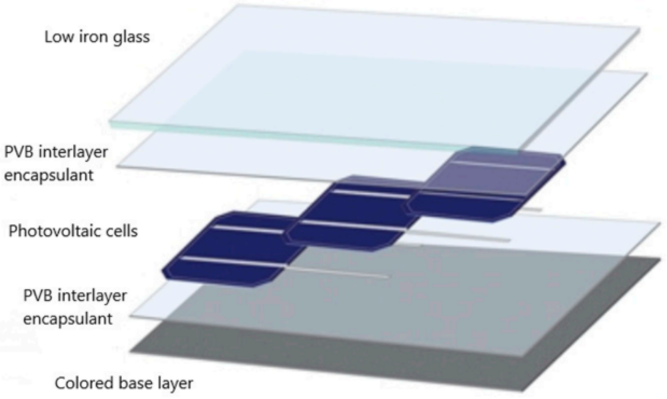

Figure 6. Solar panel composition used PVB interlayer encapsulate [67].

Of course, PVB also has some notable disadvantages. As follows:

Discoloration: Yellowing of PVB material is a common defect, primarily attributed to the following two reasons: (1) During outdoor use, the PVB interlayer film undergoes a series of photochemical reactions and thermo-oxidative aging reactions, generating chromophores such as chromogen groups. This leads to yellowing of the interlayer film, reduced light transmittance, and consequently affects the efficiency of the solar cells [70]; (2) Over-aging of the polymeric material due to excessively high temperatures inside the autoclave during the processing of semi-finished laminated glass. The main factors contributing to the aging and yellowing of PVB interlayer films are heat, oxygen, moisture, and long-wavelength ultraviolet (UV) radiation. Typically, this issue can be mitigated by incorporating additives such as hindered phenol primary antioxidants, phosphite secondary antioxidants, and hindered amine light stabilizers.

High Water Vapor Transmission Rate (MVTR): The water vapor transmission rate of PVB is much higher than that of EVA and POE [71]. This leads to corrosion of internal circuits, accelerated power degradation (making

PID more likely to occur), and shortened module lifespan. This makes it unsuitable for high-efficiency cell modules that are sensitive to humidity.

Poor Heat Resistance: PVB has a relatively low glass transition temperature. In high-temperature environments (such as deserts or rooftop installations), it is prone to creep. This can lead to displacement between the glass and the solar cells, and over long-term use, may cause delamination or bubble formation.

Lower Light Transmittance: Compared to EVA, the light transmittance (especially the initial transmittance) of PVB is typically slightly lower, which can slightly affect the module's power generation efficiency.

Wei Q. et al. [72] developed a transparent acrylate hot-melt adhesive (AHMA) combined with PVB to encapsulate perovskite solar cells (PSCs) at 80 °C, avoiding structural damage under high temperature or ultraviolet curing. The encapsulated devices retained a power conversion efficiency (PCE) of 20.88%, demonstrating excellent stability. Atsushi Masuda et al. [73] fabricated double-glass photovoltaic modules for building-integrated photovoltaic (BIPV) applications using a vacuum laminator with PVB materials of varying acetyl group content. It was confirmed that, even without edge sealant, the modules could retain approximately 85% of their output power after a damp-heat test at 85 °C and 85% relative humidity for 49,000 h. According to the authors, this is attributed to the increased volume resistivity of the PVB. Yu W. N. et al. [74] evaluated the fire resistance of PVB- encapsulated double-glass modules in BIPV walls, assessing thermal degradation and toxic emissions under radiative heat fluxes. Iftikhar Ahmed Channa et al. [75] applied PVB/ mica composite coating to organic solar cells (OSCs), retaining over 80% initial luminance after 150 h of light exposure (Figure 7).

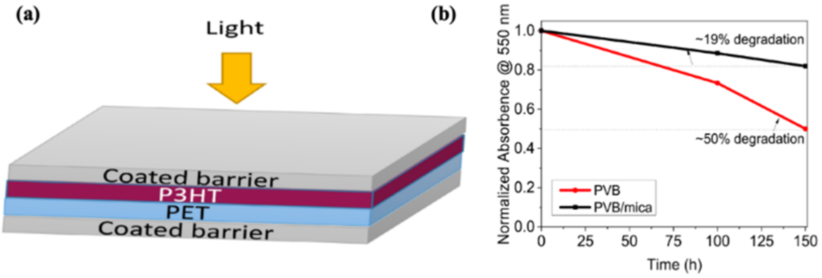

Figure 7. (**a**) Schematic diagram P3HT film deposited on PET (125 µm) substrate coated from both sides with barrier layers, where coated barrier represents PVB and PVB/mica composite; (**b**) normalized absorbance loss at 550 nm of P3HT coated with pristine PVB and PVB filled with flakes for an illumination time of 150 h with sun simulator light in ambient air [75].

Despite its advantages, PVB occupies a niche market share due to three primary limitations: (1) Narrow Processing Window: PVB lamination requires precise control of temperature, pressure, and vacuum, differing from conventional EVA processes, and demands stringent environmental cleanliness and humidity control; (2) High Cost: Photovoltaic-grade PVB films are typically more expensive than EVA; (3) Plasticizer Dependency: Low-temperature storage and poor flowability necessitate plasticizers (e.g., triethylene glycol di-2-ethyhenxanoate, DOTP, epoxidized soybean oil) at 15–40% loading, which can migrate and affect long-term stability [76,77].

2.2.4. Thermoplastic Polyurethane (TPU)

Thermoplastic polyurethane (TPU) is a linear polymer synthesized via the polycondensation of polyol and polyisocyanate, characterized by the presence of urethane linkages (–NH–COO–) within its molecular chain. By varying the raw material structures and ratios, TPU properties can be precisely tailored to produce a wide range of materials, from soft elastomers to rigid plastics. TPU used in PV encapsulation are typically synthesized from aliphatic diisocyanates (e.g., hexamethylene diisocyanate) and small-molecule diol chain extenders. This combination avoids the UV-induced yellowing associated with aromatic disocyanates (which form quinone-imine structures upon UV exposure) and ensures high transparency, as diol extenders generate fewer crystalline urea groups compared to diamine extenders [78–84].

TPU exhibits a unique combination of properties that make it suitable for advanced solar cell encapsulation, particularly for flexible and light weight modulus: excellent processibility, high elasticity, super hydrolysis and UV resistance, good chemical stability and high transparency, and remarkable abrasion resistance [85–87]. A key advantage of TPU over traditional cross-linked materials like EVA is tis recyclability; as a thermoplastic, it can be remelted after module decommissioning, enabling the recovery of valuable components such as silicon wafers and glass [88–90]. This addresses a significant limitation of conventional encapsulants and supports circular economy goals in the PV industry. Solar photovoltaic modules operate outdoors for extended periods, facing a complex stress environment where high temperature is a core factor. The surface temperature of the modules can exceed 70 °C or even higher on clear summer days. Under such continuous or cyclic high temperatures, the encapsulation material is subjected to a combination of the following stresses: (1) Internal stresses generated by the mismatch in the coefficients of thermal expansion among different materials such as glass, solar cells, and backsheets; (2) Long-term influences from wind pressure, snow load, and the modules' own weight. TPU is a thermoplastic material whose polymer chains are primarily held together by physical entanglement and relatively weak hydrogen bonds, unlike cross-linked EVA, which forms a robust three-dimensional network of covalent bonds. Under sustained stress and high temperatures, the molecular chains are more prone to relative slippage and rearrangement, leading to permanent deformation. Furthermore, TPU consists of hard and soft segments. An ideal microphase-separated structure can provide physical crosslinking points, enhancing performance. However, if the hard segment content is insufficient, unevenly distributed, or the hard segment domains are disrupted at high temperatures, their role as "physical crosslinking points" diminishes, failing to effectively restrain the movement of soft segment chains, thereby causing creep. The poor thermal creep resistance of TPU can lead to the following serious issues during the long-term operation of modules: (1) micro-cracking and breakage of solar cells; (2) delamination; (3) module deformation and power degradation.

Recent studies demonstrate the potential of TPU in emerging PV technologies. Yue Y. Q. et al. [91] utilized moisture-resistant transparent TPU to encapsulate flexible perovskite solar cells (PSCs), achieving remarkable stability: the encapsulated devices retained 95% of their initial power conversion efficiency (PCE) after 1000 h at 25 °C and 50% relative humidity (RH), and 80% after 200 h of water immersion. Kitti Yuwawech et al. [92] applied cellulose nanocrystal (CNC)/polyurethane (PU) composites for dye-sensitized solar cells, enhancing barrier properties. Rohith Kumar Raman et al. [93] systemically designed and synthesized a series of TPUs from various polyols and isocyanates. These TPUs exhibited robust adhesion to glass substrate and allowed for low-temperature encapsulation, avoiding degradation of perovskite and organic layers. The encapsulated PSCs maintained over 93% of their initial PCE after 1000 h under harsh conditions (80 ± 5% RH). As shown in Figure 8, Francesca De Rossi et al. [94] employed PU encapsulating flexible PSC. Coating the backside of the device with this PU significantly enhanced the long-term stability of the PSC under high humidity conditions (RH > 75%), maintaining 80% of the initial efficiency after 550 h.

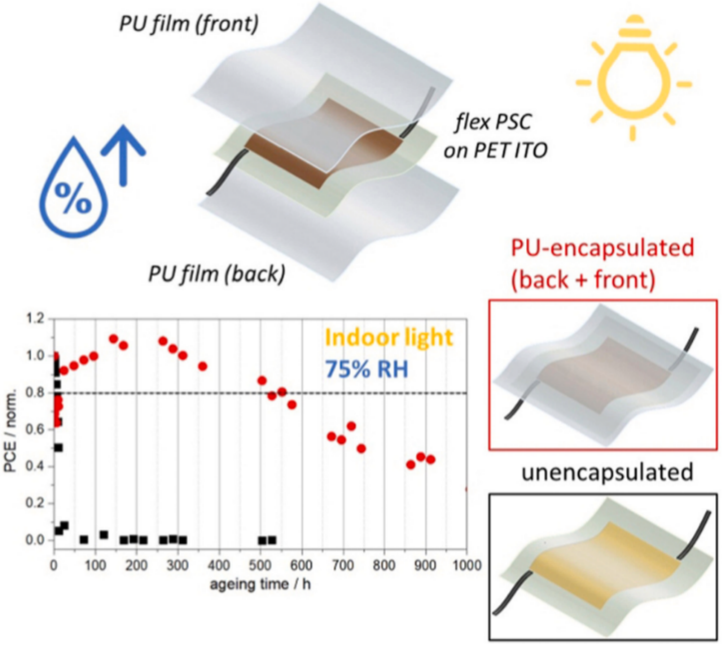

Figure 8. Long-term Stability of PU-encapsulated PSCs [94].

Despite its significant advantages, TPU faces challenges that currently limit its widespread adoption: higher material cost compared to EVA, unverified long-term reliability under extended outdoor exposure, sensitivity to processing conditions (temperature, pressure), and compatibility with existing industrial equipment [90,95,96]. Ongoing research focuses on targeted modifications to overcome these limitations, positioning TPU as a promising encapsulant for next-generation solar cells, particularly in applications demanding flexibility, recyclability, and compatibility with sensitive materials like perovskites.

3. Emerging Demands for Encapsulant Materials from Advanced Solar Cell Technologies

The rapid advancement of solar cell technologies, particularly the commercialization of N-type high-efficiency crystalline silicon cells and the promising development of perovskite solar cells (PSCs), has introduced new and stringent requirements for encapsulant materials. These next-generation technologies possess unique material properties and degradation mechanisms that necessitate encapsulation solutions beyond those used for conventional P-type crystalline silicon cells. This section analyzes the specific performance demands and corresponding material innovations driven by these advanced cell architectures.

3.1. N-Type High-Efficiency Crystalline Silicon Solar Cells (HJT, TOPCon, IBC)

N-type crystalline silicon solar cells, which utilized phosphorus-doped N-type silicon wafers, represents a significant advancement over traditional boron-doped P-type cells. The saturated molecular chain structure of N-type silicon confers inherent advantages, including superior resistance to heat, ozone, and ultraviolet radiation. These fundamental material properties translate into critical performance benefits: a high theoretical efficiency ceiling, negligible light-induced degradation (LID), and excellent temperature performance, leading to greater energy yield over the module's operational lifetime [97,98].

The predominated N-type technologies include heterojunction (HJT), tunneling oxide passivated contact (TOPCon), and interdigitated back contact (IBC). While offering superior performance, these cells, particularly HJT and TOPCon, exhibit heightened sensitivity to environmental stressors. They are more sensitive to moisture ingress and potential-induced degradation (PID) than their P-type counterparts. Furthermore, the amorphophallus (a-Si) layer in HJT cells is sensitive to UV radiation, creating a demand for encapsulation films with enhanced UV-protective or UV-conversion functionalities. Silicon heterojunction thin film solar cells are sensitive to ultraviolet (UV) light. According to the research by Shehroz Razzaq [99], UV light (365 nm) disassociates Si-H bonds, resulting in hydrogen migration away from the a-Si:H/c-Si interface and the formation of metastable defects. These defects contribute to a degradation in V_{oc} and FF, ultimately reducing overall solar cell efficiency (η). To mitigate this effect, the lower UV-damaged continuous PECVD process is developed by optimizing the hydrogen content to 33% for (a-SiOx:H) and 25% for (a-Si:H). As a result, the effective carrier lifetime inclines to ≈3.6 ms and reduces the UV-induced degradation (UVID) from 1.59% to 0.71%.

These specific challenges drive the shift towards encapsulant materials with exceptional barrier properties and chemical stability. Polyolefin elastomer (POE) has emerged as a primary encapsulation material for high-efficiency N-type modules due to its ultra-low water vapor transmission rate (WVTR < 1 g/m^2/day) and inherent anti-PID characteristics [50–52]. To balance superior performance with cost-effectiveness, composite structures like EPE films, a co-extruded three-layer material comprising EVA/POE/EVA, are gaining traction. This structure aims to leverage the excellent adhesion and processability of EVA with the superior barrier properties of POE, representing a significant development direction for the mass production of N-type modules.

3.2. Perovskite Solar Cells (PSCs)

Perovskite solar cells (PSCs) represent a revolutionary photovoltaic technology characterized by extraordinary optoelectronic properties, including high light absorption coefficients, tunable band gaps, long carrier diffusion lengths, and excellent defect tolerance. Since their first report in 2019, the certified power conversion efficiency (PCE) has rapidly advanced from 3.8% to over 27% [100,101], demonstrating remarkable potential for next-generation photovoltaics. These materials offer additional advantages such as abundant raw materials, low-cost solution processability (e.g., spin coating, blade coating, printing), and compatibility with substrates, enabling the development of light weight and versatile PV modules.

However, the large-scale commercialization of PSCs is critically hampered by their poor intrinsic stability. Organic-inorganic hybrid perovskite materials (e.g., $CH_3NH_3PbI_3$) are highly sensitive to environmental factors including moisture, heat, and light, leading to rapid decomposition and performance degradation [102,103]. The degradation mechanisms involve multiple pathways: (a) Moisture-induced decomposition: Water vapor infiltration leads to the formation of intermediate hydrates (e.g., $MAPbBr_3{\cdot}H_2O$), which disrupt the crystal structure through hydrogen bonding and eventually cause irreversible decomposition into PbI; (b) Oxygen-induced degradation: under illumination, iodide vacancies facilitate oxygen diffusion, generating reactive superoxide species that decomposition; (c) Thermal instability: Phase transitions and chemical decomposition occur during device fabrication, encapsulation, and long-term operation, especially at elevated temperatures; (d) Light-induced degradation: Photo-induced ion migration leads to phase segregation and defect formation, further compromising device performance. This sensitivity presents significant challenges for encapsulant materials, which must address several unique requirements: (1) Low Temperature Processing: The encapsulation process for the perovskite layer is typically carried out at relatively low temperatures to prevent thermal degradation of both the perovskite layer and the organic charge transport materials. For $MAPbI_3$, significant thermal decomposition begins at 80–100 °C. Even for the more stable $FAPbI_3$, very rapid decomposition occurs at around 150 °C. (2) Ultra High Barrier Properties: The material must provide exceptional barrier against water vapor and oxygen (extremely low WVTR and OTR) to completely isolate the perovskite layer from the atmosphere exposure. (3) UV and Chemical Inertness: The encapsulant should block UV radiation and remain chemically inert to prevent reactions with cell components [104].

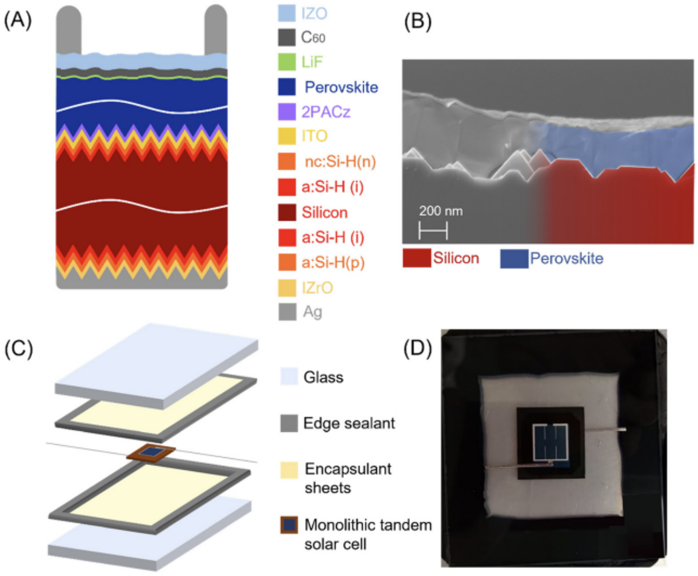

Figure 9. Schematic diagram of a typical PSC (**A**) Schematic representation of the textured monolithic perovskite/silicon tandem solar cell. (**B**) Cross-sectional scanning electron microscopy image of the tandem solar cell. (**C**) Minimodule components representation. (**D**) Top view of the tandem minimodule [103].

In addition to the core requirements of low temperature processability, ultra-high barrier properties, and UV/chemical inertness, ideal encapsulant materials for PSCs should also exhibit low cost, good processability, and environmental friendliness to support large-scale commercialization. A schematic diagram of a typical PSC structure is shown in Figure 9. Commonly used encapsulation materials include glass substrate, EVA, POE and butyl rubber [105]. Among them, thin film encapsulation represents one of the most prevalent technical approaches for PSC [106]. Typically, the thin film is positioned between the glass substrate and the top cover, forming a physical barrier via polymer encapsulation material to prevent the decomposition of cell components and protect the device from environmental damage. However, EVA-based encapsulation requires high processing temperatures (>130 °C), which can induce thermal degradation of perovskite layers and lead to acetic acid release, causing device yellowing and performance decay. Moreover, most polymer encapsulants struggle to simultaneously achieve high flexibility (critical for adhesion to device layers) and superior barrier properties against moisture and oxygen permeation. Based on the analysis above, there is an urgent need to identify a polymer that enables low-temperature encapsulation and possesses good chemical inertness for the encapsulation of perovskite solar cells (PSCs).

Recent advances in encapsulation strategies have demonstrated significant progress in enhancing PSC stability: Yibo Xu et al. [107] achieved effective encapsulation of PSC using thermoplastic polyolefin (TPO), which exhibited considerable durability under ambient atmosphere and even water immersion conditions. The TPO-encapsulated devices retained 80% of their initial efficiency after 770 h exposure. Chieh-Ming Tsai et al. [108] developed a solvent-free hybrid coating composed of polyfluorinated ester imide and silica nanoparticles. This coating combines low moisture permeability and high transparency, enabling encapsulated PSCs to operate continuously for 400 h at 65 °C and 65%RH. Lei Shi et al. [109] employed high-performance polyisobutylene (PIB) as an encapsulation layer on flat glass/FTO/TiO_2/$FAPbI_3$ substrates. The PSCs with PIB edge sealing maintained stable operation for 500 h, highlighting the effectiveness of this approach.

Furthermore, innovative module designs, such as structures that physically separate the perovskite layer from the charge-transport layers, enable the replacement of individual degraded components, thereby simplifying maintenance and improve overall system stability. These encapsulation strategies collectively contribute to significantly enhancing the operational stability and lifespan of perovskite solar cells in complex environments.

4. Advances in Frontier Research Encapsulant Materials

The encapsulant materials for photovoltaic modules are evolving from passively providing physical barriers to actively enabling multi-functional integration. Frontier research is increasingly focused on developing intelligent, sustainable, and high-performance materials that can autonomously respond to environmental changes, self-repair damage, and integrate passivation and encapsulation functions. This chapter reviews two key cutting-edge directions: intelligent self-healing encapsulant materials and high-performance passivation-encapsulation integration technology, highlighting their mechanisms, representative studies, and future challenges.

4.1. Intelligent Self-Healing Encapsulant Materials

Conventional encapsulant materials serve as static protective layers, however, microcracks, delamination, and material aging caused by environmental stressors inevitably occur during long-term outdoor exposure. Self-healing encapsulant materials represent a transformative advancement, as they can autonomously detect and repair damage, thereby significantly extending module lifespan and improving reliability, particularly for degradation-sensitive cells like perovskites.

The core healing mechanisms rely on the incorporation of dynamic reversible chemical bonds or specific interactions within the polymer matrix, enabling crack repair under external stimuli such as heat, light or moisture. A notable example is the work of Professor Lu Guanghao’s team at Xi’an Jiaotong University [110], who developed an ionic polymer encapsulation material (EP) containing dynamic alkoxypolyvinylimidazolium bis(trifluoromethanesulfonyl)imide groups. The thermal responsiveness of the ionic aggregates enables rapid self-repair: cracks were completely healed within 6 min at 50 °C and in just 50 s at 85 °C. This efficient healing capability effectively restores the barrier function of the encapsulation layer, preventing further moisture or oxygen ingress. Monojit Bag et al. [111] demonstrated a novel class of ultraviolet (UV)-curable, solvent-free, self-healing sealant based on coumarin-functionalized three-arm star polyisobutylene (PIB) to enhance the environmental stability of flexible solar cells. The encapsulated devices maintained up to 85% of their initial efficiency even after 20 days. The slight decrease in efficiency primarily stemmed from a reduction in the short-circuit current density (J_{sc}), while the open-circuit voltage (V_{oc}) and fill factor (FF) remained largely unaffected. In real usage scenarios, PSCs can be mechanically damaged by harsh weather conditions such as hailstorms, which may even lead to Pb leakage. Yan Jiang et al. [112] have found that the key factor in limiting Pb leakage is the ability of certain polymers to self-repair when heated above their glass transition temperature. The authors demonstrated that by sandwiching an epoxy-based polymer with a glass transition temperature of approximately 42 °C between the perovskite solar module and a top glass cover, the Pb leakage rate could be effectively reduced from 30 mg h^{-1} m^{-2} to 0.08 mg h^{-1} m^{-2} under simulated sunny weather conditions, compared to modules encapsulated only on the bottom side. Wen Liu et al. [113] integrated supramolecular polymers with dynamic imine-crosslinked SiO_2 nanoparticles to develop a self-healing hydrophobic coating (SHC). The SHC combines strong hydrophobicity, low water vapor permeability, and excellent self-healing capability, maintaining its protective function even after surface treatment and perovskite deposition. In addition to suppressing moisture penetration, the SHC can also interact with PbI_2, regulating the orientation of the PbI_2 layer, thereby guiding perovskite crystallization towards dense stacking, reducing residual PbI_2, and promoting preferential crystal orientation.

Despite promising results, challenges remain for large-scale application, including high material cost, the need to validate long-term outdoor durability, and the complexity of manufacturing processes. Future research will focus on developing new material systems capable of healing under milder conditions (e.g., triggered by light or mechanical stress) and integrating multifunction, such as combining superior UV blocking or light-conversion capabilities.

4.2. High-Performance Passivation and Encapsulation Integration Technology

Traditionally, surface passivation (reducing electronic defects at cell interfaces) and macroscopic encapsulation (providing environmental protection) have been implemented as separate processes. Integrated passivation-encapsulation technology represents a paradigm shift, merging these functions into a single material layer to minimized optical/electrical losses and enhance stability.

A representative case is the dual passivation strategy using an ultrathin adamantane-based plasma polymer (ADA) film, deposited via remote plasma-assisted vacuum deposition (RPAVD) [114] The ADA film simultaneously passivate interface defects in mental halide perovskite solar cells (MHPSCs) and act as a dense barrier against moisture and UV radiation. The encapsulated devices retained 80% of their initial efficiency after 4000 min of damp-heat testing, demonstrating significantly improved durability. Chun-Kai Huang et al. [115] passivated silicon nitride through plasma-enhanced chemical vapor deposition, and the efficiency of the perovskite solar cells only decreased by about 9.1%. This is because the plasma-enhanced chemical vapor deposition imparts much less external energy to the perovskite solar cells. Jionghua Wu et al. [116] utilized a vacuum grease primarily composed of polydimethylsiloxane (PDMS), which not only protected perovskite devices from moisture and oxygen but also significantly increased their power conversion efficiency from 23.91% to 25.34%. Further studies revealed that this enhancement can be attributed to the formation of coordination bonds between the oxygen atoms in PDMS and lead within the perovskite structure. This mechanism improves efficiency and suppresses the formation of Pb0 defects, which are otherwise major contributors to efficiency loss and instability.

This integration technology marks a transition from "individual component optimization" to "system function integration." Future development will focus on designing module structures that allow easy replacement of degraded components, for example, physically separating the perovskite layer from chare-transport layers to simplify maintenance and improve overall system repairability.

In summary, frontier research in encapsulant materials is driving a functional evolution from passive protection to active intelligence and integrated design. These innovations provide critical support for enhancing the durability, sustainability, and adaptability for next-generation photovoltaic modules.

5. Conclusions and Perspectives

5.1. Summary

Solar energy, characterized by its nearly infinite reserves, wide distribution, and near-zero carbon emissions during utilization, represents a pivotal solution to the global energy crisis and climate change. Photovoltaic (PV) modules, which enable direct and efficient conversion of sunlight into electricity, facilitate the large-scale, low-cost utilization of this renewable resource. However, the long-term reliability of PV modules remains a critical challenge due to their exposure to harsh outdoor environments, including high temperatures, high humidity, and intense ultraviolet radiation. The service life and power generation stability of PV modules often determined not by the solar cells themselves, but by the performance and durability of the encapsulant materials. Degradation of these materials, such as seal failure, moisture-induced corrosion, potential-induced degradation (PID) and delamination caused by thermal cycling, constitutes the primary cause of performance decline in PV systems.

The current landscape of encapsulant materials is diverse, tailored to different module technologies and cost requirements. Ethylene-vinylene acetate copolymer (EVA), with its high transparency, strong adhesion, and mature low-cost processing, dominates the market. However, EVA exhibits limitations in PID resistance and barrier properties. To address the demands of high-efficiency cells, particularly moisture, and acid-sensitive N-type TOPCon and HJT cells, Polyolefin elastomer (POE) has emerged as a preferred high-end material due to its superior moisture barrier and PID resistance. Specialized materials also serve niche applications: polyvinyl butyral (PVB) shows promise in building-integrated photovoltaics (BIPV), while polyisobutylene (PIB) is effective in edge sealing. Recent innovations focus on developing high-performance, multifunctional encapsulant materials compatible with next-generation technologies such as perovskite solar cells (PSCs), which are extremely sensitive to water and oxygen.

5.2. Perspectives

Future advancements in PV encapsulation will be guided by two core principles: sustainability and circular economy. The technological roadmap will evolve along two primary directions: (1) the development of novel, easily recyclable and cost-effective encapsulant materials; and (2) the establishing of efficient, economical the recycling system for end-of-life modules, particularly those encapsulated with EVA. In the long term, the design of inherent recyclable encapsulant materials, such as thermoplastics (e.g., TPU) or dynamic polymers, will be crucial. Such materials would allow safe and economic disassembly at end-of-life, enabling high-purity recovery of silicon, glass, and metals, and facilitating a close-loop lifecycle for PV modules. This transition from "green electricity" to "green materials" will position solar energy as a model sustainable industry, aligning technological progress with ecological stewardship.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Glossary of Abbreviation

Abbreviation	**Description**
AHMA	Acrylic hot melt adhesive
BIPV	Building-integrated photovoltaics
CNC	Cellulose nanocrystals
DOTP	Dioctyl terephthalate
EVA	Ethylene-vinyl acetate copolymer
ESO	Epoxidized soybean oil
GMA	Glycidyl methacrylate
GNP	Graphene nanosheets
IIR	Isobutylene isoprene rubber
MTS	γ-Methacryloxypropyltrimethoxysilane
OSC	Organic solar cells
PCE	Photoelectric conversion efficiency
PET	Polyethylene terephthalate
POE	Polyolefin elastomers
PSC	Perovskite solar cells
PID	Potential induced degradation
PIB	Polyisobutylene
PSC	Perovskite solar cells
PVA	Polyvinyl alcohol
PVAc	Polyvinyl acetate
PVF	Polyvinyl fluoride
PVB	Polyvinyl butyral
PVF	Polyvinyl fluoride
TPO	Thermoplastic polyolefins
TPU	Thermoplastic polyurethane
VA	Vinyl acetate
WVTR	Water vapor transmission rate

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