

Sustainable separation of ethylene vinyl acetate from waste crystalline silicon photovoltaic modules via hexane and ultrasonic heating

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ABSTRACT

The retirement of photovoltaic (PV) modules is becoming increasingly urgent due to a significant wave of end-of-life modules emerges. If not managed properly, these modules could lead to spatial wastage, resource wastage and environmental pollution, issues that have garnered considerable attention in both research and policy discussions. Ethylene vinyl acetate (EVA) copolymer poses significant challenges in the recovery and recycling of end-of-life modules. Currently, effective and environmentally friendly separation methods utilizing organic solvents are inadequate. This study proposes a combined approach that integrates a physical method with an organic solvent technique, employing hexane and ultrasonic heating to facilitate the effective separation of EVA from waste crystalline silicon (c-Si) PV modules. By optimizing the reaction conditions—specifically, a hexane concentration of 6.1 mol/L, a temperature of 73 °C, and a solid-to-liquid ratio (S/L) of 50 g/L—the swelling of EVA can be effectively controlled, thereby enabling the efficient separation of glass from the EVA adhesive layer. The application of the ultrasonic field during the swelling process accelerates the diffusion and penetration of the solvent between the layers of EVA while also providing energy to disrupt the cross-linking bonds within the EVA matrix. This study provides a promising possibility for the sustainable and efficient recycling of waste PV panels.

1. Introduction

The heavy dependence on conventional fossil fuels and the resulting increase in environmental pollution have driven a gradual transition towards renewable energy sources [1]. The growing implementation of photovoltaic (PV) systems has significantly enhanced global capacity for renewable energy generation, thereby contributing to a decrease in carbon emissions associated with fossil fuels. The International Energy Agency (IEA) reports that 1 GW (GW) of solar energy generated from PV systems can eliminate approximately 1.4 million tons of carbon dioxide (CO₂) emissions annually compared to electricity produced from coal [2]. With the current rate of installation, it is estimated that the total global capacity of PV systems will reach 4500 GW by the year 2050 [3]. Considering that the average lifespan of solar panels is about 25 years, these systems will eventually be rendered as waste once their effective lifespan ends. Projections indicate that solar panel waste could total around 8600 tons by 2030, escalating to an astonishing 78 million tons by 2050, which is equivalent to roughly 15 million crystalline silicon

(c-Si) PV units [4]. If not properly managed, the substantial quantity of discarded PV modules could pose significant environmental and economic challenges. Alarmingly, only approximately 10 % of PV module waste is currently recycled, with the remainder either discarded or sent to landfills. Such disposal practices pose a significant risk of toxic substances, such as lead and cadmium, leaking into the environment, potentially endangering both ecosystems and human health [5]. End-of-life PV modules retain significant economic value; for instance, the recovery of metallic constituents, such as silver, copper, and aluminum—from 100 kg of such modules may generate an estimated return of \$72 USD [6]. Additionally, reintegrating reclaimed high-purity silicon wafers into solar cell manufacturing processes can reduce production costs by over 20 % for manufacturers [7]. Similarly, the high-transmittance front glass, which constitutes 65–75 % of a photovoltaic module by mass, that is suitable for closed-loop recycling, enabling direct reuse of recovered material in new module production. However, substantial technical challenges persist in the recycling and management of waste c-Si PV modules.

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To the best of our knowledge, there has yet to be a reported integrated recycling method in the literature that completely recovers both bulk and trace materials with considerable purity from c-Si PV modules [8]. Composed of various elements in order of increasing mass, c-Si PV modules include glass, aluminum frames, ethylene-vinyl acetate (EVA) copolymer transparent encapsulant layers, silicon cells, junction boxes, Tedlar protective foils, and assembly bolts. The primary challenge in recycling discarded PV modules is the separation of the laminated layers. To prevent cracking of the silicon cells due to environmental influences, the upper and lower surfaces of the cells are adhered to the glass and backsheet using EVA films under vacuum conditions [9]. The recycling process of PV modules typically consists of three phases: i) disassembly, which can be performed manually or mechanically; ii) delamination, which may involve thermal, physical/mechanical, chemical methods, or a combination thereof; and iii) separation into glass, silicon, metal, and polymer fractions [10]. Commonly adopted techniques include pyrolysis [11], chemical treatment, and mechanical processing [12]. While EVA remains highly stable at ambient temperatures, its stability decreases at elevated temperatures. Feng et al. investigated the ideal pyrolysis conditions, identifying a temperature of 500 °C maintained for 30 min as optimal [13]. These parameters facilitate the complete separation of PV modules. The pyrolysis of EVA binders occurs through deacetylation and long-chain cleavage [14]. However, thermal treatment can generate a range of undesirable by-products and emissions resulting from the decomposition of both EVA and the backsheet polymer layers [15]. Notably, the decomposition of the backsheet layer produces fluorinated hydrocarbons, which pose significant toxicity risks to human health and ecosystem [16].

In chemical methods, traditional solvents are selected based on their ability to dissolve the EVA film [17]. The swelling of the EVA encapsulant, induced by interactions with organic solvents, facilitates the separation of the glass, solar cells, and Tedlar layers during the recycling of PV modules [18]. Li et al. used N, N'-dimethylpropenylurea (DMPU) to separate the layers of PV modules, observing that the solar cells separated with DMPU retained their original size, thereby enhancing further resource recovery, in contrast to those separated with toluene. Dina et al. employed D-limonene for the treatment of photovoltaic laminates, achieving 100 % separation efficiency within 120 min, with the efficiency remaining at 100 % after three solution reuse cycles [19]. While mechanical processing is relatively environmentally friendly and easy to operate, it does not achieve complete separation of the module layers. Current PV recycling processes offer numerous opportunities for improvement. Many researchers have investigated conventional room-temperature machining. For instance, Fiandra et al. employed a milling machine for mechanical processing to prevent the formation of hydrogen fluoride (HF) and fluoride by-products from the backsheet during thermal treatment [20]. Azeumo et al. disassembled and removed the aluminum bezels from retired PV modules, reducing them to particles smaller than 0.4 cm using a knife grinder, followed by gravity separation [21]. Although mechanical separation is environmentally benign, the crushing and pulverizing steps generate substantial amounts of glass-containing dust, which increases material loss and poses significant health risks to operators [22]. Furthermore, glass particles smaller than 1 mm are unsuitable for reuse in the glass industry.

Recently, numerous studies have investigated the pyrolysis treatment of waste PV modules to determine optimal pyrolysis conditions. Wang et al. employed a two-stage pyrolysis technique to achieve complete decomposition of the EVA encapsulant in waste PV modules [23, 24]. However, significant challenges remain, including the high energy consumption associated with the thermal treatment process and the generation of harmful gases from the combustion of fluorinated backsheet materials. Additionally, several studies have explored chemical methods for treating EVA films in photovoltaic modules. These approaches focus on utilizing various chemical solvents and techniques to dissolve or weaken the adhesive properties of EVA, thereby facilitating

the separation and recovery of materials within the modules. Chemical treatment methods, particularly the dissolution of EVA with organic solvents, have proven effective in enhancing the recycling efficiency of PV modules. Solvents such as toluene, o-dichlorobenzene, and trichloroethylene cause EVA to absorb the solvent, leading to swelling and a reduction in adhesive properties, ultimately resulting in the separation of layers within the module.

In this study, we integrate a physical method with an organic solvent technique by using hexane and ultrasonic heating for the EVA separation of PV modules. Based on the chemical treatment, the application of controllable external factors such as ultrasonic heating and microwave irradiation enhances the separation process. The integration of these methods facilitates the efficient and environmentally friendly recycling of waste PV modules. This work has significant implications for the development of sustainable and effective separation techniques in the recycling of PV modules.

2. Materials and method

2.1. Materials and reagents

This experiment uses a c-Si PV module measuring 35 × 35 cm, which is subsequently cut into smaller pieces measuring 2 cm × 5 cm. The primary reagents employed in the experiment include hexane, anhydrous ethanol (95 % wt), and deionized water. The experimental apparatus comprises flasks, condensers, water bath heating devices, and an intelligent temperature display magnetic stirrer (Model B13-3), manufactured by Shanghai Sile Instruments Co., Ltd. Additionally, a SHZ-III desktop recirculating water multi-purpose vacuum pump from Zhengzhou Keda Mechanical Instrument Equipment Co., Ltd. and an FZG-15 type vacuum drying oven from Nanjing Feist Electric Heating Technology Co., Ltd. are utilized. The reaction and condensation reflux apparatus are supplied by Chengdu Dianrui Experimental Instruments Co., Ltd. An electronic balance (XPR204S/AC) with a precision of 0.0001 g is provided by Mettler Toledo Technology (China) Co., Ltd.

2.2. Material processing and experimentation

The road edge frame and junction box are manually removed. Subsequently, the components are heated using a constant-temperature electric heating plate set to 150 °C for 5 min to ensure complete detachment of the backing board. The laminate components are then cut into 2 × 5 cm pieces, and their weights are recorded. Hexane solutions of varying concentrations are prepared using anhydrous ethanol as the solvent (Fig. 1). The treated samples are placed in beakers, to which the hexane solutions are added, and the temperature is adjusted to initiate the reaction. Afterwards, the solution is filtered, and the residue is dried in an oven at 100 °C for 10 h. The hexane is recovered from the filtrate through distillation. Once the residue is completely dried, its weight is measured, and the mass change is calculated.

$$\omega = \frac{m_0 - m_r}{m_{EVA}} \times 100\% \quad (1)$$

In this study, we define the separation rate of the sample material as the difference between the mass of the sample material before the reaction (denoted as m_0) and the mass of the sample material after the reaction (denoted as m_r), divided by the total mass of the EVA in the sample (denoted as m_{EVA}). This can be mathematically expressed as Eq. (1).

3. Results and discussion

3.1. Separation rate of PV modules under different conditions

The separation efficiency of EVA from PV modules was evaluated under varying process conditions, with the results presented in Fig. 2.

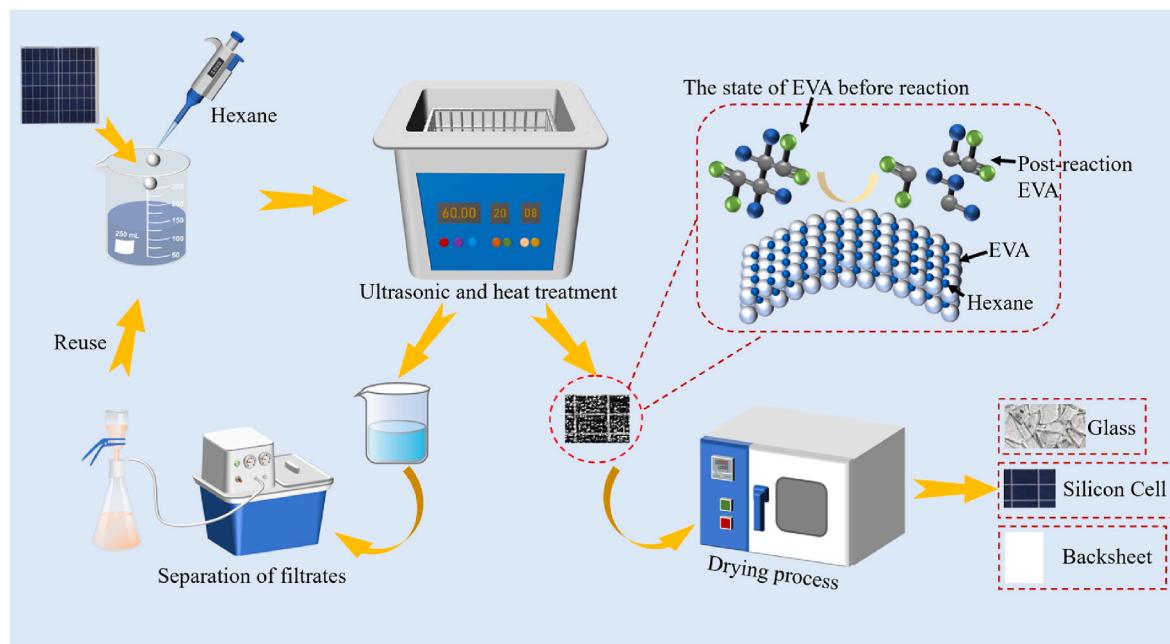


Fig. 1. Schematic diagram of EVA separation from waste c-Si photovoltaic modules by hexane integrated with ultrasonic heating.

Regarding hexane concentration, the separation efficiency showed a positive correlation with increasing solvent concentrations (Fig. 2a). Pure hexane achieved highest efficiency at 81.46 %, while concentrations of 5 mol/L and 7 mol/L yielded 76.67 % and 77.46 %, respectively. Considering environmental and energy-saving factors, 5 mol/L appears to be the optimal choice for practical applications. This trend is attributed to the reduced polarity of higher-concentration solutions, which enhances the interaction with the weakly polar EVA. At lower concentrations (1 mol/L and 3 mol/L), the dilution effect diminished solvent effectiveness, resulting in lower separation rates.

The solid-liquid ratio (S/L) exerted a notable influence on separation efficiency (Fig. 2b). A ratio of 50 g/L produced the optimal results, with efficiency declining gradually as the ratio increased to 100 g/L (a 5 % reduction after 24 h) and more sharply at 150 g/L and 200 g/L. This pattern indicates that sufficient solvent volume is critical to ensure adequate penetration into EVA layers and effective swelling.

Given that the maximum operating temperature of a c-Si PV module is 52.08 °C [25], experiments were conducted at 25 °C, 50 °C, 60 °C, 70 °C and 80 °C. As shown in Fig. 2(c), temperature played a key role in the separation process [26]. The separation rate generally increased with temperature, peaking at 70 °C. A slight decline was observed at 80 °C, likely due to hexane evaporation (its boiling point is 68.7 °C), which reduces solvent concentration. At room temperature (25 °C), the separation rate was lowest at 65.09 %, confirming the importance of thermal activation for effective EVA swelling.

Ultrasonic treatment (250W) significantly enhanced separation efficiency compared to conventional water bath heating (Fig. 2d). Moreover, following ultrasonic treatment, the separation rate continues to increase with rising temperature. Three temperature conditions—50 °C, 60 °C, and 70 °C—were employed to assess the effect of temperature variation on separation efficiency. At 50 °C, ultrasonic-treated samples consistently outperformed water bath samples, with particularly notable differences at the 4-h and 24-h marks. At 70 °C, the two methods showed comparable efficiency in the first 8 h, but ultrasonic treatment surpassed water bath heating, highlighting its ability to accelerate solvent diffusion and disrupt EVA cross-links over time. Notably, 50 °C with ultrasonic treatment achieved a separation rate nearly equivalent to 70 °C under water bath conditions.

Microwave treatment (500W) also positively impacted separation

efficiency across all tested temperatures (50 °C, 60 °C, 70 °C) relative to water bath heating (Fig. 2e). Even at 50 °C, microwave treatment yielded separation rates comparable to 70 °C water bath heating, reinforcing the utility of alternative energy inputs for process optimization. This finding is consistent with findings by Pang et al. [27] on microwave-assisted PV recycling.

Due to the softening of EVA during heating, it is possible to remove the backsheet or a portion of the glass [28]. Heat pretreatment at 200 °C showed no beneficial effect on separation efficiency (Fig. 2f). Comparative analysis of pretreated and untreated samples revealed no significant difference in 24-h separation rates, with untreated samples occasionally performing marginally better. This finding suggests that heat pretreatment at 200 °C does not enhance the final separation rate of the samples, which eliminates the need for energy-intensive pretreatment steps, that simplifying the process and reducing costs.

3.2. Orthogonal experiments for EVA removal

To determine the optimal process parameters for EVA separation, orthogonal experiments were conducted with three factors: hexane concentration (A), temperature (B), and solid-liquid ratio (C), each tested at three levels (Table S1). The experiment design and results are detailed in Table S2. The three-factor fluctuation chart (Fig. S1) shows that factors A (concentration) and B (temperature) exhibit similar trends, initially increasing before leveling off, while factor C demonstrates a gradual decrease in its effect. The impact of the three factors on the separation rate was ranked as B > A > C, confirming temperature as the most critical parameter. Response surface analysis further elucidated interactions between factors (Fig. 3). When factor C was held constant, the interaction between A and B revealed that the highest separation rate occurred at medium temperature (70 °C) and high concentration (7 mol/L). Similarly, optimal results for A and C interactions were observed at high concentration (7 mol/L) and low solid-to-liquid ratio (50 g/L), while B and C interactions peaked at medium temperature (70 °C) and low solid-to-liquid ratio (50 g/L).

Using Design Expert 11 software, the theoretical optimal conditions were determined as: hexane concentration 6.1 mol/L, temperature 73 °C, and solid-to-liquid ratio 50 g/L, yielding a predicted separation rate of 85.64 % (Fig. 4a-d). Validation experiments under these

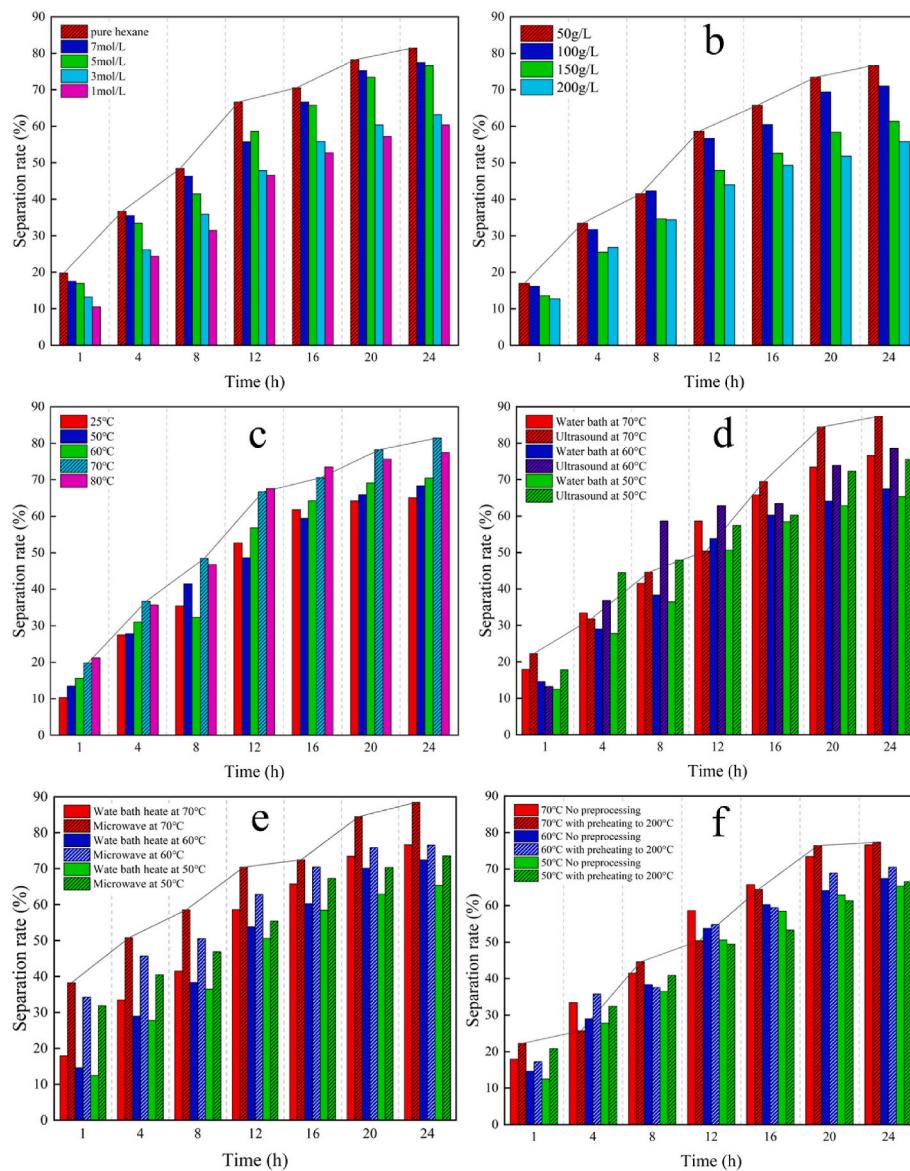


Fig. 2. Separation rate of samples under different conditions: (a) solution concentration, (b) solid-liquid ratio, (c) reaction temperature, (d) ultrasonic (250W) and heating, (e) microwave (500W) and heating, (f) preheating.

conditions achieved a separation rate of 83.5 %, closely matching the theoretical value and confirming the reliability of the optimized parameters. Visual inspection of samples before and after treatment (Fig. 4e and f) confirmed effective layer separation.

Scanning electron microscope (SEM) analysis of samples after hexane-ultrasonic treatment (Fig. 5) provided insights into the morphological changes of EVA and silicon wafers. Following the ultrasound-hexane treatment, the surface of the solar cell remained intact, with no apparent defects observed. Residual EVA transformed from a continuous flat structure to discrete spherical particles (Fig. 5a–c), indicating loss of adhesive properties. Silicon wafer surfaces showed minimal EVA residue. Silicon wafer surfaces showed minimal EVA residue (Fig. 5d–f) and remained structurally intact, ensuring their suitability for subsequent recycling.

3.3. Mechanism of EVA swelling and removal

For polymeric materials such as crosslinked EVA, the dissolution process is typically slow and often involves an initial swelling phase prior to complete dissolution. During this phase, the crosslinked regions

swell without completely dissolving. To elucidate the mechanism by which ethane solvent dissolves EVA, it is crucial to first comprehend the adhesion mechanism of EVA. The adhesion mechanism of EVA to incompatible components in PV modules is depicted in Fig. 6. PV module mainly contains three adhesive interfaces: glass-EVA, EVA-silicon solar cell (SCA), and EVA-TPT backsheet (Fig. 6). The bond strength of EVA tends to increase with higher vinyl acetate (VA) content. This phenomenon occurs because the percentage of polar functional groups, specifically acetate groups, responsible for bond formation increases with higher VA content, thereby enhancing bond strength. This observation is consistent with the decrease in VA content of EVA following swelling by hexane. EVA is classified as a weakly polar polymer material, typically containing 18 %–40 % VA, which is synthesized through the copolymerization of non-polar ethylene and highly polar vinyl acetate [29]. In contrast, glass is a strongly polar material characterized by a smooth surface and polar -OH groups, while the TPT backsheet, a fluorinated material, exhibits weaker polarity and a similarly smooth surface. The surface of silicon solar cells, on the other hand, is both highly polar and relatively rough. Due to the differences in polarity and surface roughness between EVA and materials such as glass, TPT

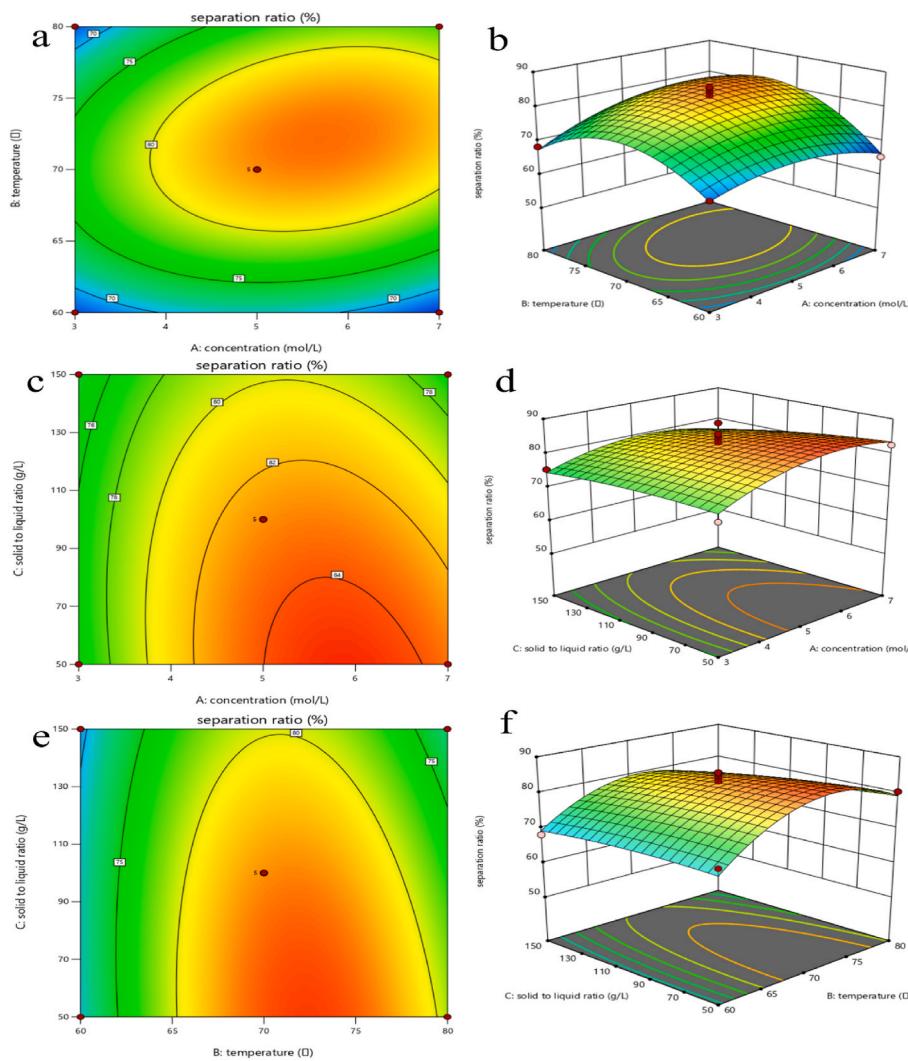


Fig. 3. Response surface 3D plots for the effect of separation rate: (a, b) concentration and temperature; (c, d) concentration and solid to liquid ratio; (e, f) temperature and solid to liquid ratio.

backsheet, and silicon solar cells, the bonding strength and durability among these components are relatively low. To enhance the adhesive properties of EVA, coupling agents are often introduced to strengthen the chemical bonding between EVA and these surfaces. These coupling agents contain two functional groups that can bond with both the substrate and the adhesive (EVA). Silane coupling agents are among the most commonly used, forming bonds through -Si-C- and -Si-O- linkages, effectively bonding EVA to the substrate. The organosilane functional group ($X-(CH_2)_3-Si-(OCH_3)_3$), acting as a bonding promoter, facilitates the formation of interfacial bonds in PV modules, thereby establishing a strong connection between the encapsulant layer (EVA) and the underlying layers, such as the solar cell, glass, and backsheet. The mechanism of silane-induced crosslinking is illustrated in Fig. 6, where the functional group X forms a bond with the polymer layer, while the $Si-(OCH_3)_3$ component of the organosilane interacts with the inorganic substrate layer to form siloxane ($Si-O-Si$) functional groups, which are responsible for providing interfacial adhesion. Silane-induced crosslinking occurs within the EVA film and at the interfaces between the EVA and the backsheet or glass.

The swelling effect of hexane on the EVA in PV modules is a critical process that facilitates the disassembly and recycling of these components. When hexane comes into contact with EVA, it induces two primary effects [30]: dissolution and expansion. (a) Dissolution: This initial phase occurs when the solvent first encounters the non-crosslinked

segments of the EVA. The solvent molecules interact with the polymer chains, breaking the intermolecular forces and leading to the dissolution of EVA, particularly at the glass interface, where a higher degree of dissolution is observed [31]. (b) Expansion: Upon further contact with the crosslinked regions, the solvent causes the EVA to swell. This swelling results from the penetration of solvent molecules into the EVA network, increasing the distance between polymer chains and resulting in an expansion of the material [32]. It has been noted that exposure of the junction between EVA and silicon wafer cells to a humid environment compromises adhesion at this interface, and prolonged exposure significantly weakens this adhesion [33]. The swelling effect of EVA increases the gap between the solar cell and the tempered glass. Once complete dissolution and swelling are achieved, the separation of all components is finalized. During the dissolution process, EVA integrates into the liquid phase. As the reaction temperature increases, the hexane solvent becomes viscous decreases and reactive, enhancing the flowability of EVA. This process facilitates the separation of individual components within PV laminates. Additionally, while the hexane interacts with EVA, it does not affect other components of the PV module. Notably, the presence of an ultrasonic field may intensify these changes. Research indicates that within an ultrasonic field, the sonolysis of water molecules in the reagent generates $H\cdot$ and $O\cdot$ radicals [34]. These radicals may contribute to the degradation of EVA polymer molecules, leading to further breakage of crosslinks. As the degree of crosslinking in

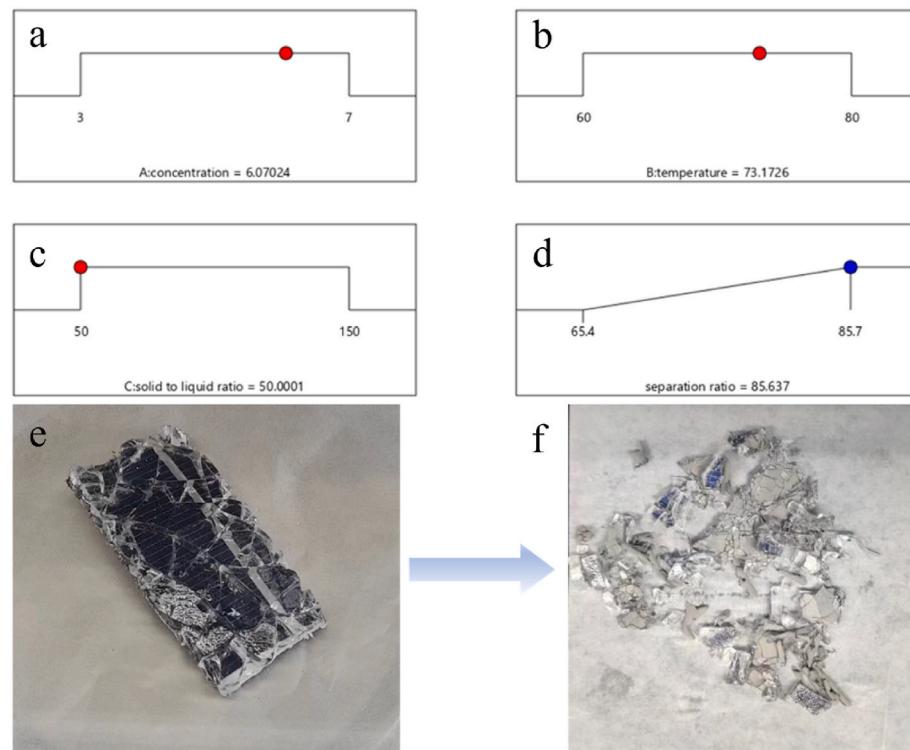


Fig. 4. Theoretical optimal separation conditions and rates, and actual separation effects: (a) optimal reaction concentration; (b) optimal reaction temperature; (c) optimal solid-liquid ratio for the reaction; (d) separation rate under the optimal reaction conditions; (e) sample before the reaction; (f) sample after the reaction.

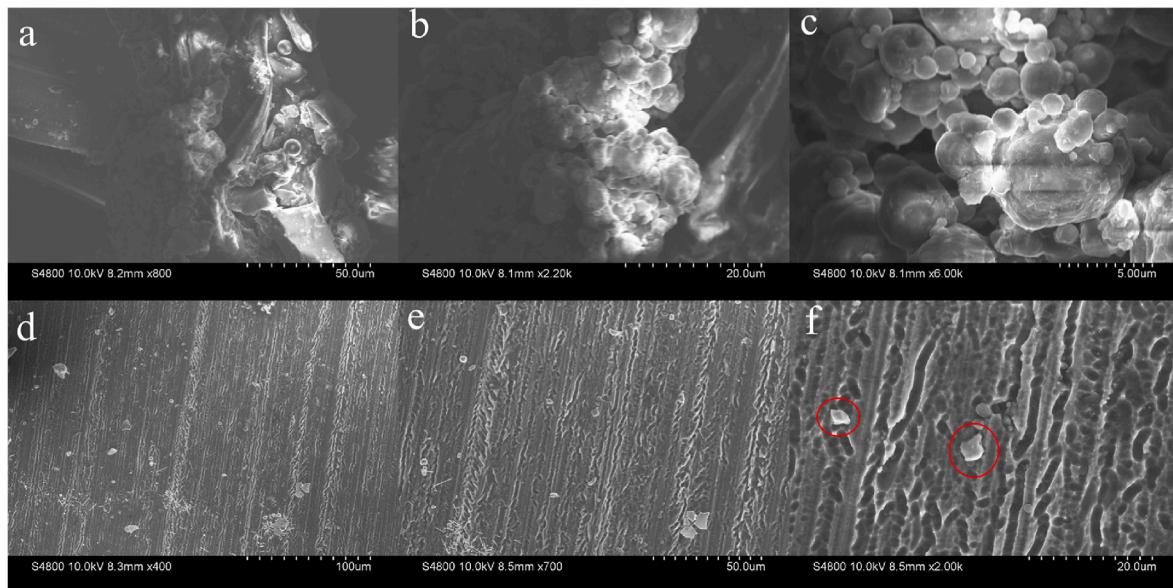


Fig. 5. SEM images of the surface of EVA and silicon wafer cells after hexane and ultrasonic co-treatment: (a–c) EVA residue; (d–f) the silicon wafer.

EVA diminishes, molecular chain mobility increases [35]. This heightened mobility renders the material more prone to flow and deformation, potentially resulting in a reduction in overall viscosity as the molecular chains slide more readily under stress. Consequently, the dissolution and expansion process in hexane solvent ensures a high recovery rate of the laminated components of the PV module. Furthermore, an increase in solvent temperature may accelerate molecular motion, thereby promoting the interaction between EVA and the solvent, which enhances the dissolution and degradation effects, aligning with the aforementioned experimental results.

The mechanism by which hexane acts on EVA involves complex intermolecular interactions at the microscopic level [36]. Initially, hexane molecules can insert themselves between the EVA molecular chains through interactions with the EVA segments, leading to the physical separation of the chains and alterations in their spatial structure [37]. As hexane is a nonpolar solvent [38], its molecular structure is akin to the nonpolar components of EVA, such as the ethylene units, facilitating its approach to the EVA molecular chains. Furthermore, the vinyl acetate units in EVA contain polar groups that are connected to other segments via hydrogen bonds and polar interactions. The

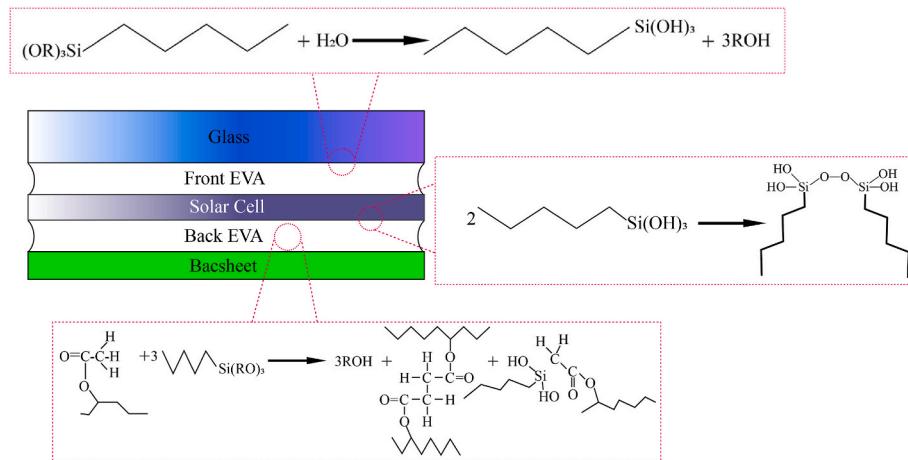


Fig. 6. Schematic depicting bonding mechanism at the adhesive interfaces.

introduction of hexane as a solvent allows it to competitively bind to these polar groups, thereby disrupting hydrogen bonds and interactions. As shown in Fig. 7 following the combined treatment with hexane and ultrasound, both the main and side chain structures of EVA were modified. The long alkane chains of EVA experienced partial degradation, and the cross-linking bridges between the main chains were disrupted [39]. This disruption of the EVA network structure resulted in a reduced degree of cross-linking. Additionally, the side chains of the vinyl acetate monomer were cleaved, leading to a decrease in the content of polar methyl and ester groups [40]. Moreover, intermolecular van der Waals forces—including dispersion forces, induction forces, and orientation forces—play a crucial role in this process. In the case of hexane and EVA, the primary interaction is attributed to dispersion forces, which arise from instantaneous dipole interactions caused by the random movement of electrons within the molecules. As hexane molecules approach the EVA molecular chains, these forces facilitate attraction, disrupting the original interactions among the EVA chains. As hexane molecules continuously penetrate and interact with the EVA chains, the EVA chains gradually separate and dissolve in hexane. This process represents a dynamic equilibrium, where hexane molecules consistently interact with the EVA chains, while the dissolved EVA chains may also re-aggregate. However, due to the solvent action of hexane, this equilibrium tends to favor dissolution. Once a sufficient number of EVA chains are dissolved in hexane, a uniform EVA-hexane solution is formed, in which the EVA chains are dispersed as individual molecules or smaller aggregates within the hexane [41]. This transition highlights the susceptibility of EVA to the influence of organic solvents. Understanding these mechanisms is essential for optimizing

the performance of EVA in various applications.

4. Conclusion

This study investigates the adhesion mechanisms at the interfaces of photovoltaic laminates and proposes a green, low-energy controlled treatment method integrating mechanical heating pretreatment with hexane as the primary solvent. Compared to conventional mechanical treatments, it better preserves the integrity of glass and wafers, while it significantly reduces energy consumption and environmental impact relative to thermal treatments. Ultrasonic treatment at 70 °C further enhances the efficiency of component separation. After treatment, laminates are fully delaminated, yielding relatively intact glass and wafer cells with no significant cell damage. Experimental findings demonstrate that hexane, as a green solvent in combination with ultrasonic heating, significantly improves EVA removal efficiency while showcasing its selective and environmentally friendly properties. The low environmental impact of hexane establishes its suitability as an ideal solvent for the treatment of waste photovoltaic modules. Future study should investigate the synergistic effects of various solvents and treatment methods, optimize recycling processes, and advance large-scale application. In summary, the integrated approach of hexane, ultrasound, and heating offers an innovative and effective solution for efficient recycling of waste photovoltaic modules, with substantial academic and practical application value.

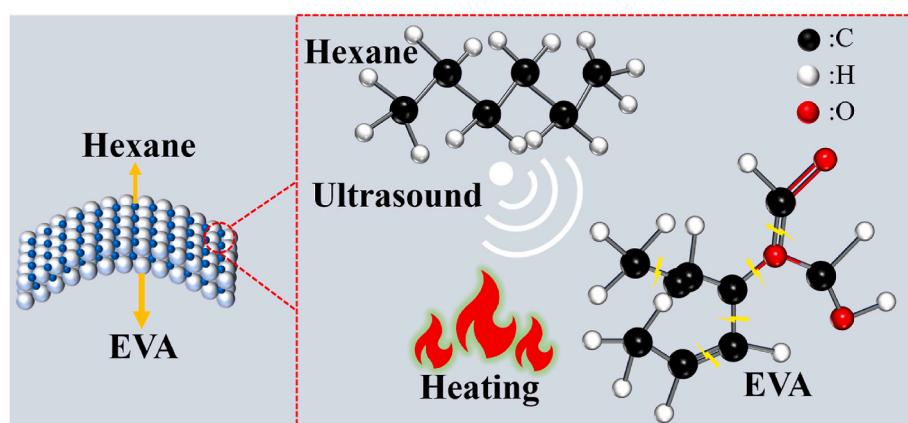


Fig. 7. Schematic diagram of the mechanism of hexane enhanced swelling and dissolution of EVA.

CRediT authorship contribution statement

Qing Huang: Writing – review & editing, Funding acquisition, Conceptualization. **Junnan Wang:** Writing – original draft, Formal analysis, Data curation. **Mouyong Huang:** Formal analysis, Data curation. **Haolin Zhang:** Software, Conceptualization. **Fengshan Yu:** Writing – review & editing, Conceptualization. **Jianming Zhu:** Writing – review & editing, Project administration. **Lijun Xu:** Writing – review & editing. **Li Zhang:** Writing – review & editing. **Wenyi Yuan:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.solmat.2025.113897>.

Data availability

Data will be made available on request.

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