

LIQUID RESIN INJECTION AS AN EXPERIMENTAL TECHNIQUE FOR REPAIRING GLASS DEFECTS IN PHOTOVOLTAIC MODULES

INJEÇÃO DE RESINA LÍQUIDA COMO TÉCNICA EXPERIMENTAL PARA
REPARO DE DEFEITOS VÍTREOS EM MÓDULOS FOTOVOLTAICOS

INYECCIÓN DE RESINA LÍQUIDA COMO TÉCNICA EXPERIMENTAL PARA LA
REPARACIÓN DE DEFECTOS EN VIDRIO DE MÓDULOS FOTOVOLTAICOS

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ABSTRACT

Repairing glass defects in photovoltaic modules emerges as a promising alternative, aligned with the principles of the circular economy and sustainability. This study aimed to investigate and develop an experimental method for repairing glass in photovoltaic modules, using as a reference the technique employed in the automotive industry for windshield repair. For this purpose, ordinary glass samples were prepared, in which grooves were created with abrasive sandpaper, followed by the application of a UV-LED-activated photopolymerizable resin. The samples were initially evaluated through visual inspection, UV-Visible absorption spectroscopy, surface roughness analysis, and assessment of aging effects under UVA radiation. The UV-Vis results obtained before and after the aging period revealed no significant changes in transmittance over time, indicating that the resin used for repairs retains its properties and does not alter the optical characteristics of the glass. We conclude that the evaluated repair technique demonstrates technical feasibility and potential applicability in photovoltaic modules, thereby contributing to extending the operational lifespan of these systems.

Keywords: Glass Repair. Photovoltaic Modules. Sustainability. Circular Economy.

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RESUMO

O reparo de defeitos no vidro de módulos fotovoltaicos surge como uma alternativa promissora, alinhada aos princípios da economia circular e da sustentabilidade. Este estudo teve como objetivo investigar e desenvolver um método experimental para o reparo de vidros em módulos fotovoltaicos, utilizando como referência a técnica empregada na indústria automotiva para o reparo de para-brisas. Para isso, amostras de vidro comum foram preparadas, nas quais foram criados sulcos com lixa abrasiva, seguidos da aplicação de uma resina fotopolimerizável ativada por LED UV. As amostras foram inicialmente avaliadas por meio de inspeção visual, espectroscopia de absorção UV-Visível, análise de rugosidade superficial e avaliação dos efeitos do envelhecimento sob radiação UVA. Os resultados de UV-Vis obtidos antes e depois do período de envelhecimento não revelaram alterações significativas na transmitância ao longo do tempo, indicando que a resina utilizada para os reparos mantém suas propriedades e não altera as características ópticas do vidro. Concluímos que a técnica de reparo avaliada demonstra viabilidade técnica e potencial aplicabilidade em módulos fotovoltaicos, contribuindo, assim, para o prolongamento da vida útil desses sistemas.

Palavras-chave: Reparo de Vidros. Módulos Fotovoltaicos. Sustentabilidade. Economia Circular.

RESUMEN

La reparación de defectos en el vidrio de módulos fotovoltaicos se presenta como una alternativa prometedora, alineada con los principios de la economía circular y la sostenibilidad. Este estudio tuvo como objetivo investigar y desarrollar un método experimental para la reparación de vidrio en módulos fotovoltaicos, tomando como referencia la técnica empleada en la industria automotriz para la reparación de parabrisas. Para ello, se prepararon muestras de vidrio común, en las que se crearon surcos con papel de lija abrasivo, seguidos de la aplicación de una resina fotopolimerizable activada por LED UV. Las muestras se evaluaron inicialmente mediante inspección visual, espectroscopia de absorción UV-Visible, análisis de rugosidad superficial y evaluación de los efectos del envejecimiento bajo radiación UVA. Los resultados UV-Vis obtenidos antes y después del período de envejecimiento no revelaron cambios significativos en la transmitancia a lo largo del tiempo, lo que indica que la resina utilizada para las reparaciones conserva sus propiedades y no altera las características ópticas del vidrio. Concluimos que la técnica de reparación evaluada demuestra viabilidad técnica y potencial aplicabilidad en módulos fotovoltaicos, contribuyendo así a extender la vida útil de estos sistemas.

Palabras clave: Reparación de Cristales. Módulos Fotovoltaicos. Sostenibilidad. Economía Circular.



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INTRODUCTION

In recent decades, the growing demand for electricity has driven the search for alternative sources that are both environmentally sustainable and economically viable (Tarigan, 2025; Pimpalkar *et al.*, 2023). Among these, photovoltaic solar energy stands out as renewable, abundant, and highly expandable, particularly in countries like Brazil, which experience high levels of solar irradiation throughout the year. According to recent reports, installed photovoltaic generation capacity has reached new records annually, consolidating its position as one of the main options for diversifying the global energy matrix (Ren21, 2023).

Despite this rapid growth, challenges related to the manufacturing, maintenance, and disposal of photovoltaic modules remain significant. Large-scale production requires substantial quantities of raw materials, including critical minerals such as silver, indium, and gallium, which increases costs and places pressure on supply chains (Tas, 2023). Meanwhile, modules already in operation have an estimated lifespan of around 25 years but may experience failures or damage before that period, particularly in their glass structure, which is responsible for protecting the photovoltaic cells against weathering and mechanical impacts (Nieto-Morone *et al.*, 2024).

Glass defects such as cracks, fissures, delamination, and surface grooves directly compromise the performance of photovoltaic modules. These failures reduce conversion efficiency, accelerate degradation processes, and often render the equipment unusable, leading to premature disposal (Pimpalkar *et al.*, 2023). Although much of the current effort focuses on recycling and reuse strategies for materials, the scientific literature still reveals gaps regarding direct repair techniques for photovoltaic glass (Koester *et al.*, 2022).

The transmittance of glass is an important factor influencing both the thermo-optical properties of the photovoltaic unit and the overall performance of the system. Photovoltaic glass transmittance, defined as the ratio between transmitted and incident light, varies with different photovoltaic coverage ratios (the proportion of the area occupied by photovoltaic cells) and with the materials used in module construction. These variations affect the penetration of direct light as well as the fraction of solar radiation absorbed, transmitted, and re-radiated. In turn, this influences the temperature of the photovoltaic module and, consequently, its energy generation efficiency (Xu *et al.*, 2023).

In this context, adapting established methods from the automotive industry such as windshield repair using photopolymerizable resins emerges as a promising alternative (Chen *et*

al., 2017). These procedures are widely employed to restore the mechanical strength and optical transparency of glass, thereby preserving its structural and visual functions (Overend, 2015). Resin injection is a well-established repair technique for thermoset composites, in which low-viscosity liquid resins are introduced into the damaged area to fill crack paths and seal the affected region, preventing further propagation (Bolluk *et al.*, 2024). Applying this knowledge to the photovoltaic sector can significantly contribute to extending module lifespan, reducing replacement costs, mitigating environmental impacts, and reinforcing practices aligned with the principles of the circular economy.

Therefore, this study investigated an experimental method for repairing glass in photovoltaic modules, evaluating the effectiveness of a technique based on filling glass defects with a windshield repair resin, and analyzing the optical and surface effects on the glass samples after repair.

METHODOLOGY

Sample Preparation

The samples were prepared following a specific methodology to evaluate the feasibility of an experimental approach for repairing vitreous defects in photovoltaic modules, based on the adaptation of techniques previously employed in automotive windshield restoration (NOVUS, 1991; Datsiou, 2018).

Six samples of commercial glass (soda-lime glass) measuring 6 cm × 6 cm × 2 mm, were prepared, washed, and dried. In the glass defect simulation, each sample was subjected to different levels of mechanical abrasion. To ensure uniformity of abrasion intensity, a 1 kg mass was applied to the samples, and the grooves were created using Waterproof N° 150 wet sandpaper. The simulate wear on the glass surface were not intended to demonstrate a dominant failure mechanism, but rather to reproduce weathering conditions representative of the Northeast region of Brazil, particularly during periods characterized by stronger winds and increased deposition of solid particles. The number of times the sandpaper was passed over the surface varied between one and five times, resulting in different degrees of surface scratches. After sample preparation, the defects were filled with windscreen repair resin REDNOW, chemical composition 2-Hydroxyethyl methacrylate 97%, following an adaptated of the edge cavity repair

method described by NOVUS (Novus, 1991). The resin curing was performed using a UV-LED SUN lamp as the radiation source, operating within the spectral range of 365–405 nm. The exposure time was set to 20 minutes, with the sample positioned at a fixed distance of 8 cm from the light source. These experimental conditions were selected to ensure adequate polymerization of the material while promoting the restoration of the vitreous surface integrity.

The samples were designated and described throughout the text according to the intensity of abrasion scratched, without resin, with resin, and after aging—as detailed in Table 1.

Table 1 – Sample identification

Sample	Name	Sample	Name	Sample	Name	Sample	Name
Common glass	white glass	-	-	-	-		
Glass, 1 pass of sandpaper	P1V	Glass, 1 pass of sandpaper, no resin.	P1S SR	Glass, 1 pass of sandpaper with resin.	P1V C R	Glass with 1 pass of sandpaper and resin after aging.	P1V C R PE
Glass, 2 pass of sandpaper	P2V	Glass, 2 pass of sandpaper, no resin.	P2S SR	Glass, 2 pass of sandpaper with resin.	P2V C R	Glass with 2 pass of sandpaper and resin after aging.	P2V C R PE
Glass, 3 pass of sandpaper	P3V	Glass, 3 pass of sandpaper, no resin.	P3S SR	Glass, 3 pass of sandpaper with resin.	P3V C R	Glass with 3 pass of sandpaper and resin after aging.	P3V C R PE
Glass, 4 pass of sandpaper	P4V	Glass, 4 pass of sandpaper, no resin.	P4S SR	Glass, 4 pass of sandpaper with resin.	P4V C R	Glass with 4 pass of sandpaper and resin after aging.	P4V C R PE
Glass, 5 pass of sandpaper	P5V	Glass, 5 pass of sandpaper, no resin.	P5S SR	Glass, 5 pass of sandpaper with resin.	P5V C R	Glass with 5 pass of sandpaper and resin after aging.	P5V C R PE

Source: The author's own work.

For visual inspection, the criteria established by the International Energy Agency Photovoltaic Power Systems protocol (Köntges *et al.*, 2014) were adopted, with emphasis on repair uniformity and minimizing defect visibility (Venkatesh, 2021). The protocol (Köntges *et al.*, 2014) addresses the classification of failure modes in photovoltaic modules, highlighting the importance of consistent terminology. It clearly distinguishes between failure mode, failure mechanism, and root cause. Köntges *et al.* (Köntges *et al.*, 2014) emphasize that the same visible

defect may originate from different causes. Visual inspection is presented as a fundamental initial step for identifying defects, and a systematic classification based on module components is proposed. This approach facilitates comparison across studies and diagnostic procedures. It also contributes to improving the reliability of photovoltaic systems. Finally, the importance of this standardization for maintenance and quality control strategies is reinforced.

To quantify the light transmittance of the samples before and after the repair process, ultraviolet–visible (UV–Vis) spectroscopy was performed using a UV-Vis 2600 PLUS spectrophotometer, covering the spectral range from 200 to 1400 nm, a range widely adopted for the characterization of glass.

Subsequently, the UV–Vis spectra obtained during the pre-abrasion, post-groove creation, and resin-filling stages were compared to quantify the efficiency of the technique in restoring the material's optical properties.

Optical Profilometry Tests

To assess the surface roughness of the samples before and after repair, optical profilometry was performed using a Taylor Hobson MP CCI Optical Profilometer. For the determination of roughness parameters, regions of the samples that exhibited the best surface integrity after visual inspection were selected. All analyses were conducted in triplicate, and the results are reported as the mean values of the three-dimensional surface roughness (Sa).

Aging Tests

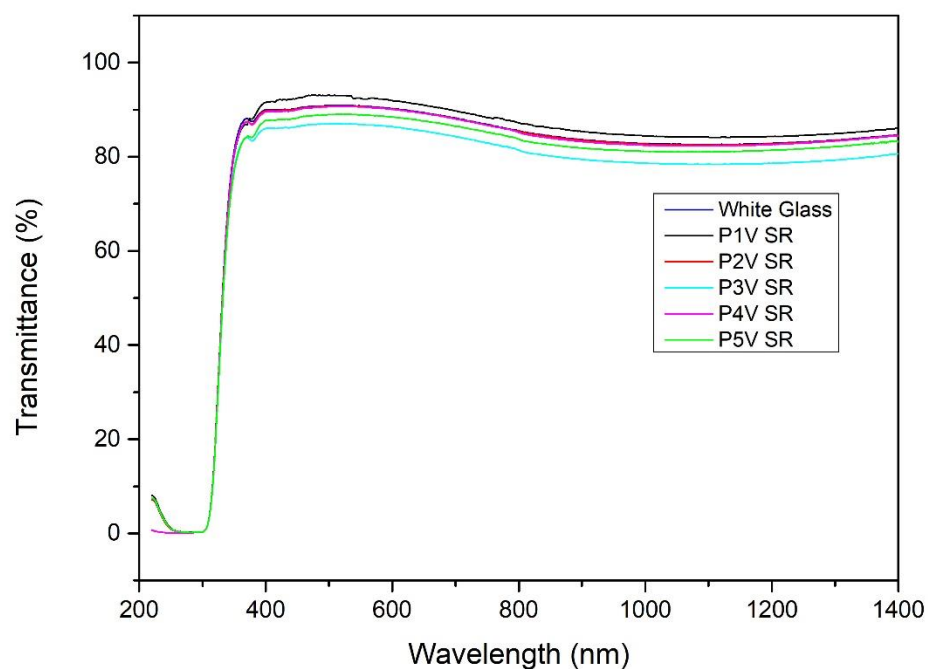
Aging tests were conducted over a 30-day period, totaling 240 hours, with 8 hours of exposure per day to simulate typical daily sunlight conditions for photovoltaic applications. The samples were exposed to a UVA lamp with a wavelength of 365 nm inside an insulated chamber, followed by analysis using UV-Vis spectroscopy.

RESULTS AND DISCUSSIONS

UV-Visible Spectroscopy

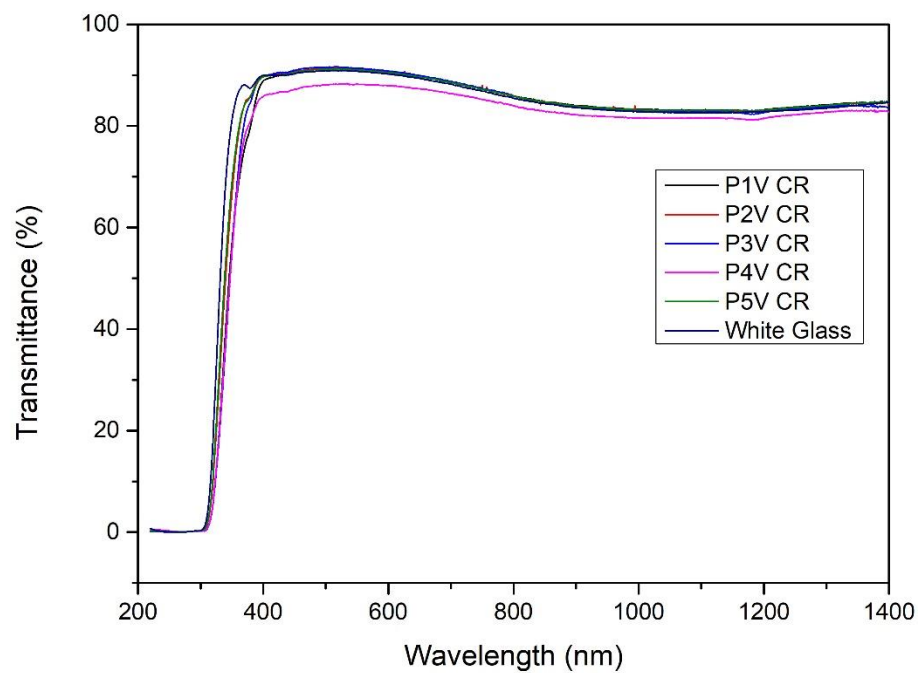
After the resin had cured, a visual inspection was performed in accordance with the IEA-PVPS (Köntges *et al.*, 2014) protocol, which confirmed satisfactory uniformity of filling and a reduction in the visibility of grooves. The results of the UV–Vis spectroscopy analyses are shown in Figures 1 and 2, indicating that no significant variations occurred in the optical properties of the samples when comparing the pre- and post-simulation states of defects and subsequent repair. The tests further revealed that groove formation by abrasion led to a slight decrease in the transmittance of the grooved glass. This allows us to observe that the efficiency of photovoltaic modules can be affected by degradation resulting from weather conditions such as rain, intense solar radiation, wind, temperature fluctuations, humidity, and hail. This behavior confirms that surface defects alter the interaction of electromagnetic radiation with the material, leading to additional scattering and absorption, as described by Koester *et al.* (Koester *et al.*, 2022), who identify fissures and microcracks as critical factors in the degradation of the optical performance of photovoltaic modules.

Figure 1- UV-Visible spectroscopy results for resin-free grooved glass samples.



Source: The author's own work.

Figure 2 - UV-Visible spectroscopy results for glass samples with grooves and with resin.



Source: The author's own work.

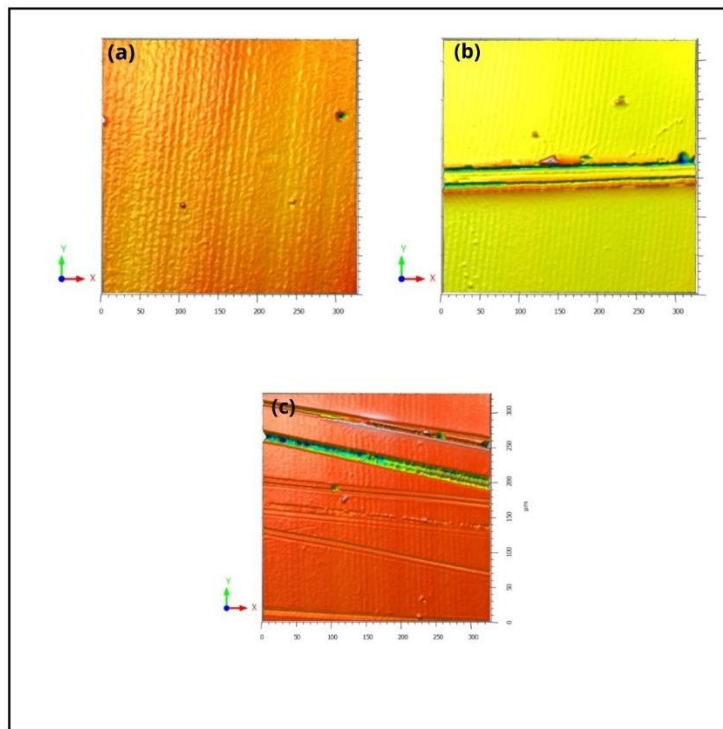
This approach enabled us to quantify the impact of simulated defects and the effectiveness of repair processes on the optical properties of the samples. Previous research indicates that UV–Vis absorption in vitreous materials is influenced by intrinsic factors, such as electronic configuration and the presence of dopants, as well as by extrinsic factors, including surface imperfections (Ehrt, 2002).

Profilometry Results

The surface roughness images obtained by profilometry are presented in Figure 3, demonstrating an increase in the three-dimensional roughness (S_a) of the samples with increasing abrasion caused by sanding, as expected. These observations are consistent with the results presented in Figure 4, including the mean values and standard deviations, suggesting good agreement between the qualitative and quantitative analyses. This behavior was anticipated, since the proposed treatment aimed to promote the filling of surface grooves by the resin without compromising the optical properties of the material.

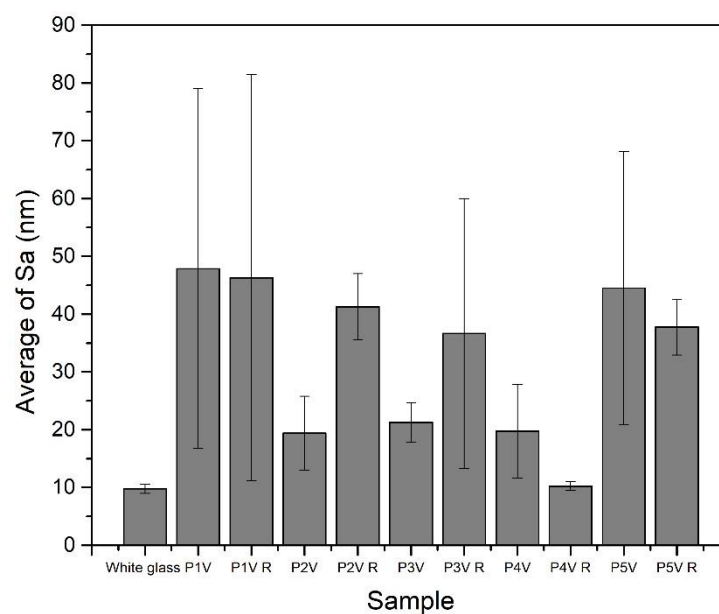
Specifically, for the samples coated with resin, a slight reduction in roughness values was observed, with $S_a = 46.3$ nm for P1V CR and $S_a = 37.8$ nm for P5V CR. This decrease in roughness was expected, as the resin was able to partially fill the grooves produced by the abrasive sanding process.

Figure 3 - Images from the profilometry analysis (a) White glass sample; (b) P1V sample; (c) P5V sample.



Source: The author's own work.

Figure 4 - Results of average and standard deviations of Sa from profilometry analyses.



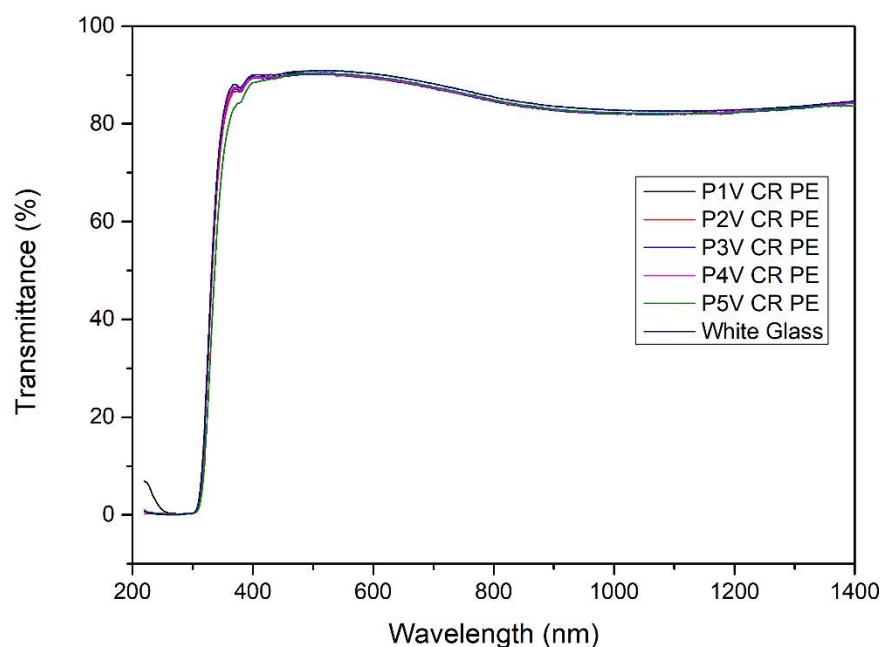
Source: The author's own work.

Results After Aging Tests

According to the results of the UV–Vis spectroscopy analysis presented in Figure 5 for the samples after the aging period, no significant variations in transmittance values were observed over the 240 h exposure period. This indicates that the resin used for repairs retains its properties and does not alter the optical performance of the glass. The total hemispheric transmittance values were calculated from transmittance data obtained through UV–Vis spectroscopy, combined with integral calculation results (Çengel, 2012) and climatic data from the city of João Pessoa-PB provided by PVlighthouse (pvlighthouse, 2025). All total hemispheric transmittance values are presented in Table 2.

The transmittance values of the samples after the aging period were around 85%, consistent with the literature. According to Kong (Kong *et al.*, 2025), glasses with transmittance above 70% exhibit relatively high transparency in the wavelength range of 520–570 nm. Zhang *et al.* (Zhang *et al.*, 2025) studied samples of ordinary glass and glass doped with CeO_2 , both of which showed transmittance values above 85% in the wavelength range of 400–800 nm.

Figure 5 - UV-visible spectroscopy results for the samples after aging.



Source: The author's own work.

These results corroborate studies such as those by Overend and Louter (Overend and

Louter, 2015) who evaluated the effectiveness of resins in automotive glass repairs and demonstrated that, although the original strength and transparency are not fully restored, the technique is effective in mitigating the impact of defects. Applied to the photovoltaic context, this approach may represent a viable alternative to complete module replacement.

Experimental findings indicate that the technique employed has the potential to extend the lifespan of photovoltaic modules with surface glass defects, reducing the need for immediate disposal while promoting both environmental and economic benefits. This outcome aligns with the considerations of Curtis (Curtis *et al.*, 2021), who emphasize the importance of circular economy strategies in the solar industry, extending system lifespans and reducing the demand for critical raw materials.

Table 2 - Total Hemispheric Transmittance Results for the samples.

Sample	Total Hemispheric Transmittance (%)	Sample	Total Hemispheric Transmittance (%)	Sample	Total Hemispheric Transmittance (%)
White glass	86,17%	-	-	-	-
P1V S R	87,79%	P1V C R	85,58%	P1V C R PE	85,62%
P2V S R	86,04%	P2V C R	86,05%	P2V C R PE	85,51%
P3V S R	82,22%	P3V C R	85,79%	P3V C R PE	85,36%
P4V S R	85,88%	P4V C R	83,37%	P4V C R PE	85,52%
P5V S R	84,32%	P5V C R	86,05%	P5V C R PE	85,23%

Source: The author's own work.

results and discussions of an article must be presented in a clear and organized manner, based on the data collected and the analyses carried out during the study. Initially, the results must be presented in an objective and concise way, using tables, graphs and statistics, if applicable, to highlight the main findings. Then, in the discussion section, the results should be interpreted in light of existing literature, highlighting similarities, differences and implications for theory and practice.

Furthermore, limitations of the study and possible directions for future research are discussed. It is essential that both the results and the discussion are based on solid evidence and that they contribute significantly to the advancement of knowledge on the topic addressed.

CONCLUSION

This study investigated the vitreous repair method in photovoltaic modules, inspired by procedures used in the automotive industry. The findings indicate that, following the repair process, structural recompositing of the samples was achieved, as evidenced by visual inspection confirming uniformity.

According to UV–Vis analyses of the resin samples before and after the aging period, the transmittance results showed no significant changes, demonstrating that the resin used does not alter the optical properties of the glass and may therefore aid in the repair of photovoltaic modules.

The experimental results presented in this article indicate that the repair technique studied demonstrates technical feasibility as a potential alternative to the premature replacement of damaged photovoltaic modules, contributing to extended lifespan and reduced waste generation in the sector. Moreover, the findings are consistent with circular economy and sustainability initiatives, which are regarded as fundamental to strengthening solar energy both in Brazil and worldwide.

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