

## Article

# Study of Photodegradation of Organic Solar Cells Under Brazilian Climate Conditions

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**Abstract:** The increasing technical and economic viability of photovoltaic solar energy technologies includes modules with organic photovoltaic (OPV) cells, which have shown significant efficiency increases, reaching 20% for research devices. This study investigated the photodegradation and associated loss mechanisms in OPV devices under tropical conditions in Brazil. The electrical and optical characteristics of the modules were correlated with chemical and structural changes when exposed to sunlight. Electrical parameters were monitored over time on external test benches and measured in solar simulators, while changes in the optical transmission and absorption of the films were analyzed. Scanning electron microscopy, energy-dispersive spectroscopy, and Fourier-transform infrared spectroscopy were used to study the physical and chemical properties of the materials. We found that photodegradation causes bond breakage in the active layer, altering the carbon structure and consequently reducing the module's output power. The primary reasons for the activation and progression of this mechanism are high temperature and elevated solar irradiance. Therefore, we demonstrate that understanding these mechanisms is essential for the development of more sustainable OPVs in tropical climates.

**Keywords:** solar energy; photodegradation; organic photovoltaics (OPV)



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## 1. Introduction

Rapid global population growth and escalating environmental challenges, including climate change and the depletion of essential resources such as water and food, are driving the urgent need for sustainable solutions [1]. One of the most critical areas in addressing these issues is the development of clean, renewable energy technologies that can meet the increasing global energy demand while minimizing environmental impacts [1–4]. Solar photovoltaic (PV) energy, along with wind and hydropower, is among the leading solutions to the energy transition. In 2023, solar PV installations surpassed 1.6 terawatts (TW) globally [1,4,5], underscoring its pivotal role in the shift towards sustainable energy [1–5].

Although silicon (Si) modules (predominantly) and thin-film cadmium telluride CdTe dominate the commercial solar PV market, research into advanced photovoltaic technologies has gained considerable momentum in the past decade. Certainly, hybrid organic–inorganic perovskite technologies are currently the primary focus of research. However, recent advances in organic photovoltaic (OPV) performance have attracted some attention. OPV is valued for its low-cost production, flexibility, lightweight design, and environmentally friendly materials. Research into OPV cells began in the 1980s, but interest in

this technology surged in the early 2000s due to its potential cost and specific application advantages [2].

OPV efficiency remained modest during the 2000–2018 timeframe [6], as shown in Figure 1. However, in 2018–2019, OPVs experienced a turning point, with rapid increases in the performance of laboratory devices. Currently, OPV devices have achieved performance with research cells validated at 20% efficiency [6,7].

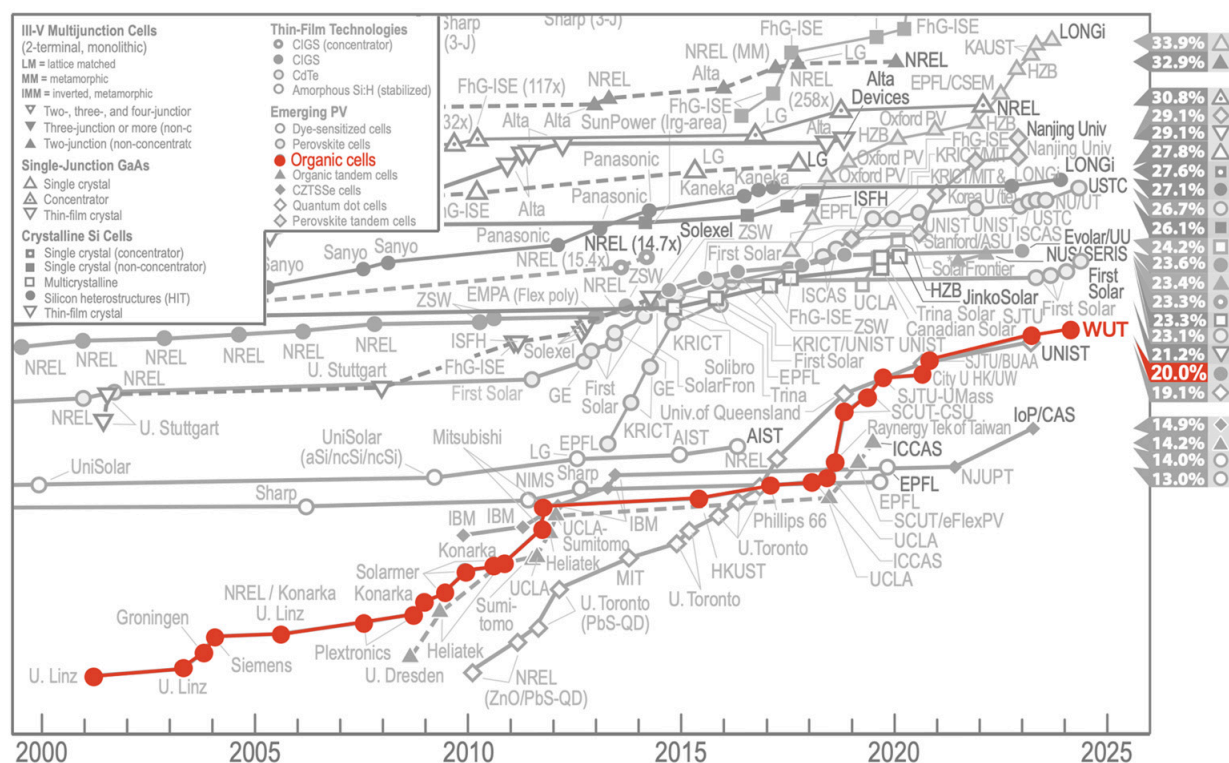


**Figure 1.** Portion of the NREL efficiency chart, highlighting OPV research solar-cell performance advancement from 2000 to the present. The organic cells are shown in color on the chart, with the other technologies muted in gray (defined in the inset). The recent (2025) record, the first confirmed 20%-OPV device by Wuhan University of Technology, is included [7]. (Chart adapted from [6].)

This recent efficiency increase has sparked greater interest in this technology, as well as its impact on perovskite solar cells [8]. However, determining the reliability and lifespan of OPV devices remain challenging. Various reliability aspects need to be considered, but degradation from solar radiation and environmental exposure are crucial and are the focus of our research [9–14].

The physics involved in the photovoltaic conversion and the structural differences between organic and inorganic solar cells are significantly distinct. Unlike conventional inorganic solar cells, OPV devices use molecular or polymeric light absorbers that result in localized excitons (analog to particles composed of bound electron–holes pairs). The absorber is used in conjunction with an electron acceptor, such as fullerene, which has a molecular energy state that facilitates electron transfer. After photon absorption, the resulting exciton migrates to the interface between the absorber material and the electron acceptor material. At this interface, the energy discrepancy between the molecular orbitals provides the driving force sufficient for separating the exciton, thus creating free charge carriers (electrons and holes). The physics and chemistry related to OPV materials and devices have been extensively studied in the literature [8–27].

Interest in OPV modules has been maintained primarily due to their competitive cost and flexibility in physical and electro-optical formats. This has made the technology ideal for use in the built environment, an energy sector that has not yet had significant

photovoltaic energy integration. The absorption bands of OPV can be adjusted to match the desired spectrum, allowing for the production of various colors. Additionally, the transparency of OPV can be adjusted, ranging from fully transparent to semi-transparent, allowing for the control of light levels passing through the window. The format of OPV allows it to be integrated into buildings (BIPV—Building Integrated Photovoltaic), providing great value to this field, as seen in examples in Figure 2. Its other applications are mainly niche, such as interior/exterior lighting, electricity augmentation in vehicles, energy windows, and ornamental structures. Commercial OPVs have demonstrated initial life efficiencies compatible with these applications. However, to compete in major photovoltaic energy markets, challenges still need to be resolved regarding adequate stability and lifespan.

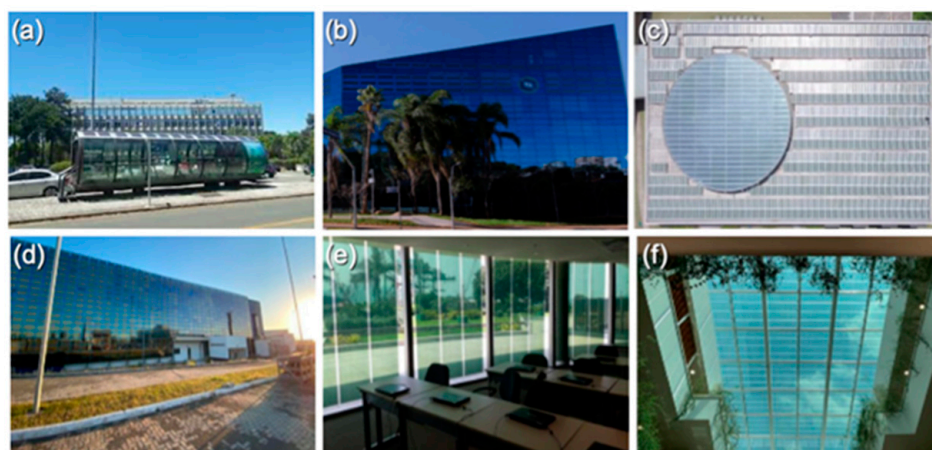


**Figure 2.** Examples in Brazil of applications of OPV modules in buildings for electricity generation: (a) rapid transit station in Curitiba (PR); (b) TOTVS office building in São Paulo (SP); (c) roof integration at Natura; (d) facade of the CAO A building; (e) office of Petrobras; and (f) skylight of the Morumbi shopping mall. Images by [22].

The primary objective of this research is to establish a comprehensive correlation between the electrical parameters of OPV devices and the chemical and structural changes occurring within the active materials due to photodegradation. By monitoring key electrical parameters such as open-circuit voltage ( $V_{OC}$ ), short-circuit current ( $I_{SC}$ ), fill factor (FF), and maximum power output ( $P_{max}$ ), in conjunction with advanced material characterization techniques, this study seeks to provide insight into the fundamental degradation pathways in OPV materials. Moreover, this work aims to identify the critical environmental stressors that contribute most significantly to the degradation process, thus informing strategies to enhance the reliability and operation of OPV technologies in tropical climates.

Ultimately, the findings from this research could pave the way for the development of more robust and efficient OPV modules, facilitating their broader adoption in regions with challenging environmental conditions, such as Brazil. The successful integration of OPV technologies into the global energy market would not only diversify the portfolio of renewable energy solutions but also support the transition towards more sustainable and resilient energy systems, particularly in urban environments where flexible, lightweight, and adaptable solar technologies are increasingly in demand.

## 2. Materials and Methods

For this study, a set of five mini modules (in this paper, we use the terms module or mini module for the samples of this study) with organic solar cells (OPVs), as illustrated in Figure 3, were used and specifically provided by ONINN (Innovation Center), a partner in this work. These test structures have solar cells with standard commercial geometries, interconnections, and encapsulations.

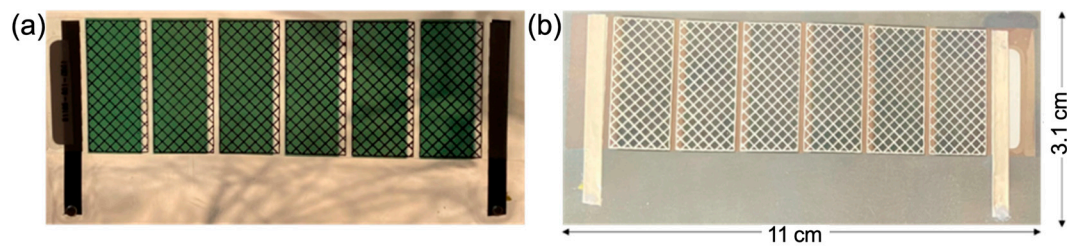


**Figure 3.** (a) Front view of the OPV mini module; (b) rear view of the OPV mini module used in this study.

The generic cross-section of the solar cells is shown in Figure 4. The OPV modules were manufactured using the standard commercial roll-to-roll (R2R) process [10,22,23]. The modules consist of six solar cells connected in series with an active area of  $21.6 \text{ cm}^2$ , encapsulated with UV-curable epoxy between flexible barrier films with a water vapor transmission rate (WVTR) of the order of  $10^{-3} \text{ g/cm}^2/\text{day}$ . Details on the material and module manufacturing can be found in [22].

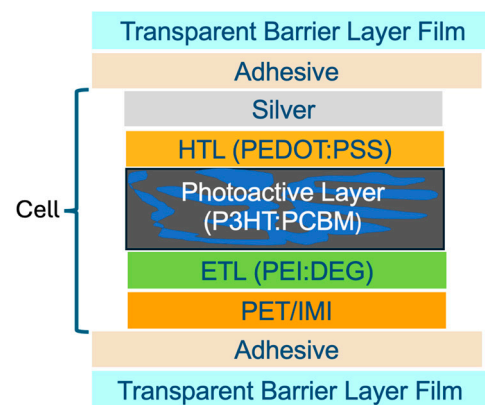


**Figure 4.** Cross-sectional representation of the standard OPV device.

The research flowchart is presented in Figure 5. Six mini modules with similar I–V characteristics were provided for this study by [22]. Two modules were used for initial characterization (Modules 5 and 6). Four of these solar mini modules (Modules 1–4) were selected for the degradation test protocol, which involved exposure on external test benches under existing tropical conditions for 30, 60, 90, and 120 days.

The four selected OPV mini modules for the degradation test protocol were mounted on test benches at the Energy Studies Group laboratory of the Pontifical Catholic University of Minas Gerais (GREEN PUC Minas), linked to the Polytechnic Institute of PUC Minas (IPUC), located in the city of Belo Horizonte in Minas Gerais.

One mini module (Module 6) was chosen as a reference and initially subjected to evaluation of its optical transmission/absorption, as well as destructive tests to establish the initial chemical and compositional properties of the active layer. The electrical characteristics of each exposed mini module on the benches were initially measured under standard test conditions (STCs) of the solar simulator belonging to ONINN before the exposure period.

The characterization techniques included the following:

- **Electrical Characterization:**  
The measurement of the I–V characteristic curves before the exposure of the OPV modules was performed in a solar simulator under standard test conditions (Figure 6), recording the main parameters: open-circuit voltage ( $V_{oc}$ ), short-circuit current ( $I_{sc}$ ), fill factor (FF), maximum power ( $P_{max}$ ), maximum voltage and current ( $V_{max}$ ,  $I_{max}$ ), conversion efficiency, and series and parallel resistance ( $R_{series}$ ,  $R_{shunt}$ ). [Instrument—Wacom Solar

Simulator, model WXS-156S-10, class AAA with a silicon (Si) reference cell under AM 1.5G filter].

- Scanning electron microscopy/energy dispersive X-ray spectroscopy (EDS): For measurements of the physical properties and elemental analysis of the active layer. [Instrument—JEOL model JSM IT300 (Peabody, MA, USA)].
- Infrared Spectroscopy (IR)—Attenuated Total Reflectance (ATR): Information on the presence or absence of specific functional groups as well as the chemical structure and bonding of organic materials. [Instrument—Bruker Alpha model equipped with a single reflection diamond ATR with a scan range of  $400\text{ cm}^{-1}$  to  $4000\text{ cm}^{-1}$ ].

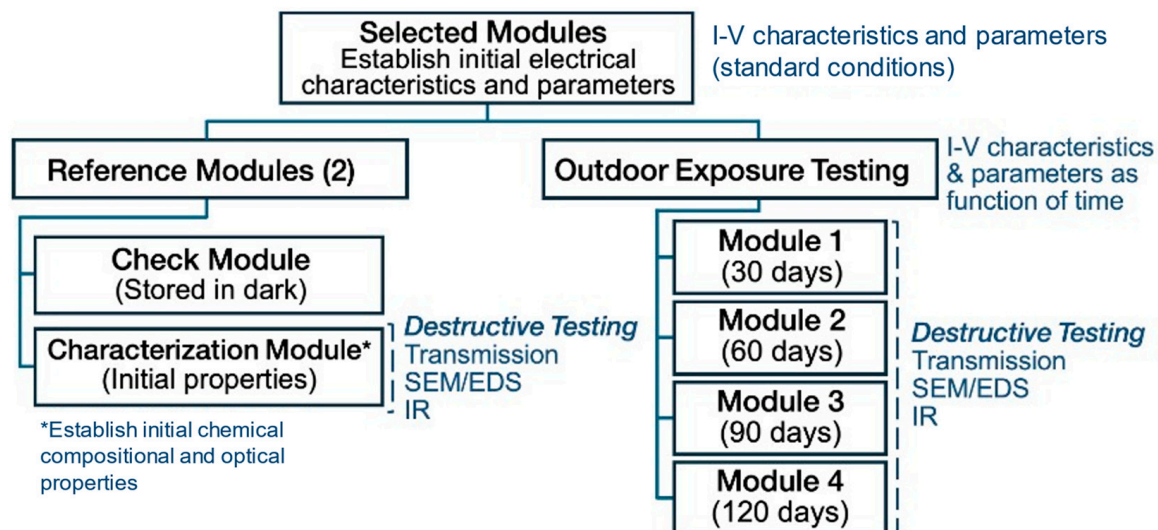


**Figure 5.** Research flowchart defining the project progression and characterization. The study began with a selection of 6 modules based on their similarity in I-V characteristics and related parameters. One module (“Characterization Modules”) was used to establish the initial optical and chemical/compositional properties of the photoactive layer. A “Check Module” was kept isolated to efficiencies and in case any of the exposure test modules needed substitution. Four modules were used for the outdoor exposure testing defined in Section 2.

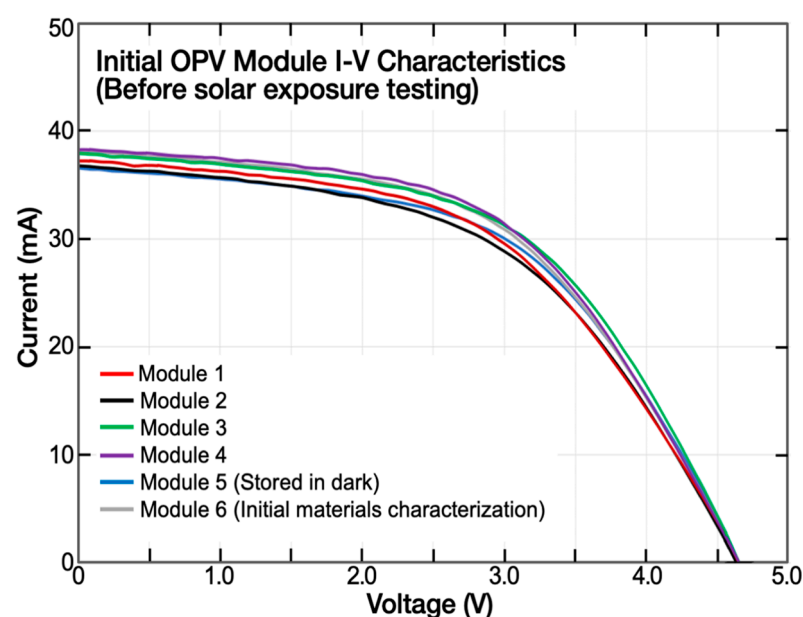


**Figure 6.** Initial I-V characteristics of the OPV modules indicating the similarity of the initial electrical behavior.

### 3. Results

The focus is on the correlation of changes in the electrical characteristics of the mini modules with the measured values of the optical, compositional, and chemical properties of the organic active layer. This provides direct indications of the underlying causes of photodegradation of the OPV modules after prolonged exposure under tropical climatic conditions.

#### 3.1. Initial Electrical Characterization of Mini OPV Modules

Initially, the I–V curves of the OPV modules were measured before external exposure, as shown in Figure 6.

Following the test protocol of the flowchart (Figure 5), the electrical characteristics were recorded as a function of exposure time on external benches, with measurements on the OPV modules (1–4) at the end of each period at 30, 60, 90, and 120 days. These I–V curve results are shown in Figure 7 for each of the OPV modules. During the first 30 days, the OPV modules remained relatively stable, but the evaluations of the I–V parameters indicated the onset of photodegradation. The summary of the effects of exposure time related to the I–V curves in Figure 7, listing the main device parameters, is presented in Table 1.

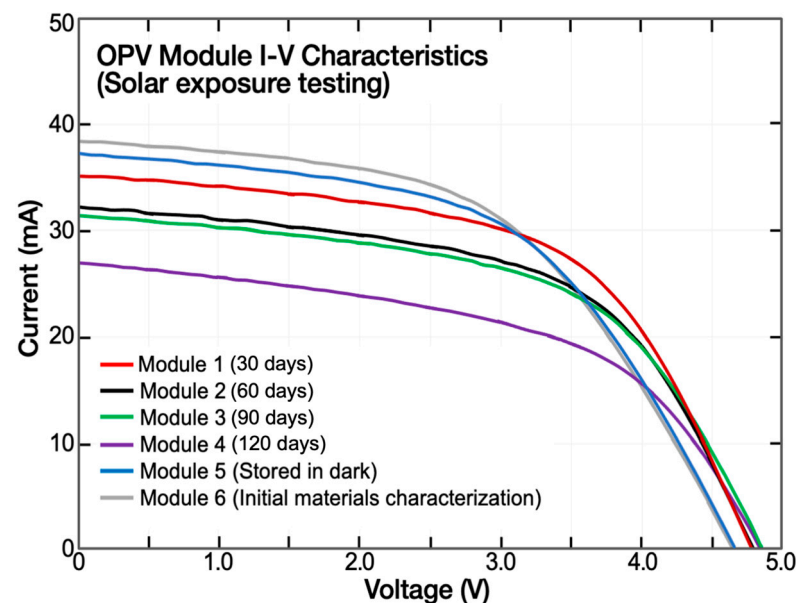


**Figure 7.** I–V characteristics of OPV modules as a function of the exposure time (initial time through 120 days). The initial I–V data for the characterization module (Module 6) and the check module (Module 5) are included for comparison.

**Table 1.** Measurements of OPV module data after the exposure period showing degradation.

| Module Electrical Parameters | Module 1 |             | Module 2 |              | Module 3 |              | Module 4 |              | Module 5 (Stored in Dark) |   | Module 6 (Initial Sample Characterization) |   |
|------------------------------|----------|-------------|----------|--------------|----------|--------------|----------|--------------|---------------------------|---|--------------------------------------------|---|
|                              | Initial  | 30 Days     | Initial  | 60 Days      | Initial  | 90 Days      | Initial  | 120 Days     | Initial                   | - | Initial                                    | - |
| $P_{\max}$ (mW)              | 89.98    | 94.89 (+8%) | 88.88    | 85.57 (−1%)  | 94.26    | 83.67 (−11%) | 94.22    | 67.24 (−29%) | 90.21                     | - | 92.64                                      | - |
| $V_{\max}$ (V)               | 3.04     | 3.46 (+15%) | 3.11     | 3.49 (+13%)  | 3.16     | 3.51 (+11%)  | 3.16     | 3.51 (−11%)  | 3.14                      | - | 4.66                                       | - |
| $I_{\max}$ (mA)              | 29.45    | 27.40 (−7%) | 28.12    | 24.55 (−13%) | 29.80    | 23.88 (−20%) | 29.80    | 23.87 (−20%) | 28.73                     | - | 38.10                                      | - |

Table 1. Cont.

| Module Electrical Parameters | Module 1 |                 | Module 2 |                 | Module 3 |                 | Module 4 |                 | Module 5<br>(Stored in Dark) | Module 6<br>(Initial Sample Characterization) |   |
|------------------------------|----------|-----------------|----------|-----------------|----------|-----------------|----------|-----------------|------------------------------|-----------------------------------------------|---|
|                              | Initial  | 30 Days         | Initial  | 60 Days         | Initial  | 90 Days         | Initial  | 120 Days        | Initial -                    | Initial                                       | - |
| V <sub>OC</sub> (V)          | 4.67     | 4.78<br>(−6%)   | 4.64     | 4.79<br>(+3%)   | 4.65     | 4.88<br>(+3%)   | 4.65     | 4.87<br>(−3%)   | 4.68                         | 3.06                                          |   |
| I <sub>SC</sub> (mA)         | 37.28    | 34.88<br>(−6%)  | 36.78    | 31.92<br>(−13%) | 37.90    | 31.12<br>(−13%) | 30.73    | 29.14<br>(−2%)  | 36.57                        | 30.30                                         |   |
| FF (%)                       | 50.91    | 56.89<br>(+12%) | 50.79    | 56.01<br>(+10%) | 53.40    | 55.26<br>(+3%)  | 52.87    | 52.78<br>(−2%)  | 52.87                        | 52.16                                         |   |
| Efficiency (%)               | 4.1      | 4.4<br>(+7%)    | 4.0      | 4.0 (0%)        | 4.4      | 3.9<br>(−11%)   | 4.4      | 3.1<br>(−29%)   | 4.2                          | 4.3                                           |   |
| R <sub>series</sub> (Ω)      | 45.3     | 33.95<br>(−25%) | 43.5     | 36.73<br>(−16%) | 38.8     | 41.2<br>(+6%)   | 40.7     | 48.36<br>(+19%) | 42.2                         | 41.85                                         |   |
| R <sub>shunt</sub> (Ω)       | 1079.8   | 1088.8<br>(+1%) | 1008.4   | 1009.0<br>(0%)  | 1138.4   | 1143.1<br>(−8%) | 1297.40  | 781.1<br>(−40%) | 1104.5                       | 1143.7                                        |   |

### 3.2. Initial Active Layer Characterization

Physicochemical analysis techniques were used to identify any changes in the OPV active layers of the modules as a function of exposure times on external benches and the established electrical parameters (Table 1). The reference characterization module established the initial properties of the layer for these comparisons.

To investigate the molecular nature and any changes in the bonds and chemical structure of the organic layer, Fourier-Transform infrared spectroscopy (FTIR or IR) was used to evaluate the material. Figure 8 summarizes the results, showing IR (absorbance) as a function of the wavenumber for the set of initial and exposed active layers in the modules.

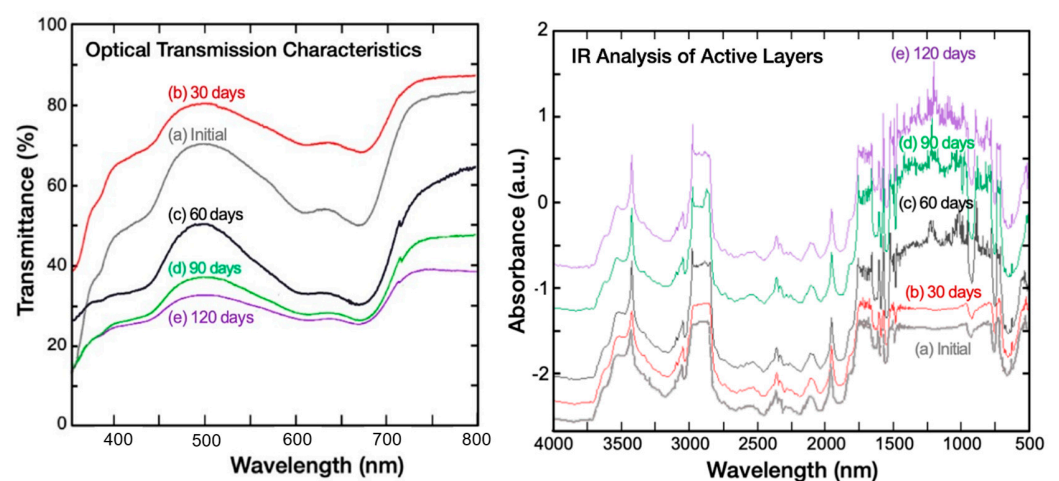


Figure 8. Optical transmission (left) and IR (right) analyses of active layers: (a) initial conditions; (b) after 30 days; (c) 60 days; (d) 90 days; and (e) 120 days.

## 4. Discussion

### 4.1. Electrical Characterization of OPV Mini Modules on an External Test Bench

Three performance stages of OPV modules can be identified from the electrical characteristics presented in the I–V curves. In the first stage, the modules showed a moderate power gain during the initial 30-day exposure period. This improvement can be attributed to the reduction in recombination facilitated by internal defect rearrangements and changes in the active layer morphology of the OPV solar cell (Figure 4); this is consistent with observations by the authors of [9,10], who also reported increased charge carrier mobility

and reduced defect density during the early stages of exposure solar irradiance. These morphological rearrangements, driven by sunlight, improve charge transfer between molecules in the active layer, corroborating the findings from [24,25], where similar behavior was noted for molecules with MoO<sub>3</sub> layers under high temperatures.

In the second stage, beyond 60 days, a slow, linear degradation in  $P_{\max}$  was observed, returning the electrical parameters to their initial values. This aligns with [26], who found similar slow degradation rates in OPV devices during prolonged exposure under environmental conditions. The third stage (from 90 to 120 days) exhibited significant degradation in maximum power, with reductions of around 30% thereafter. This marked drop in efficiency, ranging from 2% to 3%, is likely due to thermal and photodegradation, phenomena that are similarly documented in various studies, including those by [14,27], who reported a substantial decrease in efficiency after prolonged thermal stress. The series resistance ( $R_{\text{series}}$ ) and shunt resistance ( $R_{\text{shunt}}$ ) corroborate these efficiency reductions.

#### 4.2. Active Layer Characterization

The most evident change occurs in the near-infrared regions, particularly between 750 nm and 1500 nm, following the initial 30-day stability period. The shifts to shorter wavelengths were correlated with the breaking of C-H and O-H bonds, altering the electronic properties of the organic materials, as also observed in studies by [10,26,28]. After 90 days, these changes became more pronounced, likely due to photo-oxidation, consistent with the findings from the authors of [27], who attributed similar shifts to photoinduced degradation in OPVs exposed to prolonged sunlight and high temperatures.

The exact composition of the donor polymer was not identified, making it challenging to draw more detailed conclusions. However, the degradation was not catastrophic, and the module continued to operate with about 30% power loss. This degree of degradation is in line with reports from Jiang et al. (2018) [25], who observed similar power losses in OPVs without efficient encapsulation and protective layers.

Morphological and elemental analysis of the active layer was performed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). The morphologies remained largely unchanged through 60 days of exposure, but after 120 days, micrometer-sized particles, including copper (Cu) and zinc (Zn), were observed in the layer. Their presence, as noted in previous studies (e.g., [13,24]), may be due to the diffusion of these metals into the active layer at high temperatures, potentially originating from soldering materials used after encapsulation.

This diffusion, likely exacerbated by thermal expansion differences between the transparent conductive oxide and the adhesive layer, was noted as a key factor in performance decline, which requires further investigation to confirm the sources of these impurities. The results are shown for the initial case and after 120 days of exposure in Figure 9b. The layer morphologies through 60 days of exposure were practically identical to the initial reference.

The EDS assay shows an expected elemental composition mainly composed of carbon (C) and oxygen (O), with low levels of sodium (Na), potassium (K), and calcium (Ca) contaminants. However, in the case of longer exposure, micrometer-sized particles are visualized with low levels of copper (Cu) and zinc (Zn). The layer was also examined in the cross-section, and the same levels of these two metallic impurities were detected. The origin is unknown since these elements are not part of the composition of any layer.

It is possible, however, that they are present in the busbar tape and soldering material made after encapsulation. Operations at higher temperatures may be responsible for the diffusion of particles through the active layer. This could also explain the detection of low levels of aluminum (Al). Alternatively, these metals may be components of the proprietary adhesive or transparent conductor and migrate through cracks in the solar cell layers due to the difference in thermal expansion between the transparent conductive oxide and the adhesive layer, which requires further investigation to determine the origin of these metallic components. It is also noteworthy that a physical change in the layer is observed (Figure 9)

at higher exposure times. This is due to the decomposition of the photoactive layer, as noted in the corresponding IR results.

The issues with the degradation of OPV cells and modules remain a concern [14]. However, commercial products mitigated the effects somewhat by including attention to encapsulation to minimize the ingress of moisture and oxygen into the module interior [14]. Additionally, UV inhibitors (films) have been incorporated into the module's surface to alleviate the interaction of this spectral component with the UV-sensitive organic layer. There has also been some success in embedding UV inhibitors in the adhesive layer. The benefits of stability are major. We tested a recent commercial mini module with advanced encapsulation and a UV inhibitor on the surface exposed to the sunlight. These results are shown in Figure 10 in comparison to the devices over the 120-day exposure (based on Table 1). Typical light soaking is observed in the first 20 days, but the device power is constant over the 120-day observation period. This mini module showed slow (less than 5%) loss over a 6-month period and improvement over the 25–30% mark for the devices in this study.

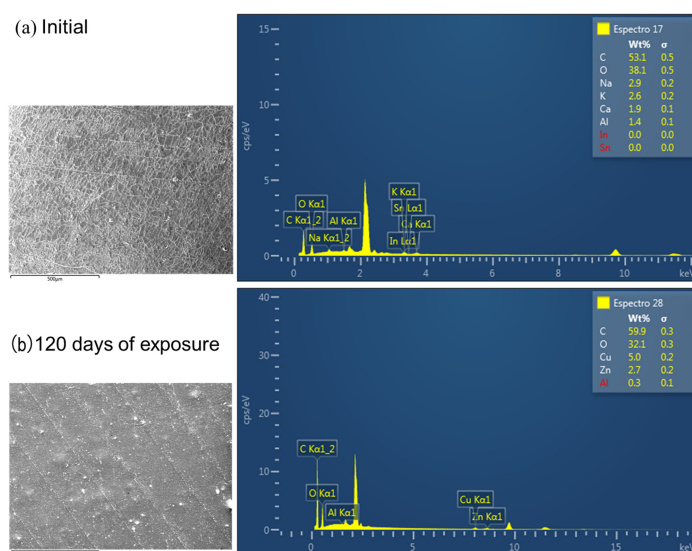


**Figure 9.** SEM and EDS in the organic photoactive layer: (a) initial condition; (b) after 120 days of exposure, degraded.

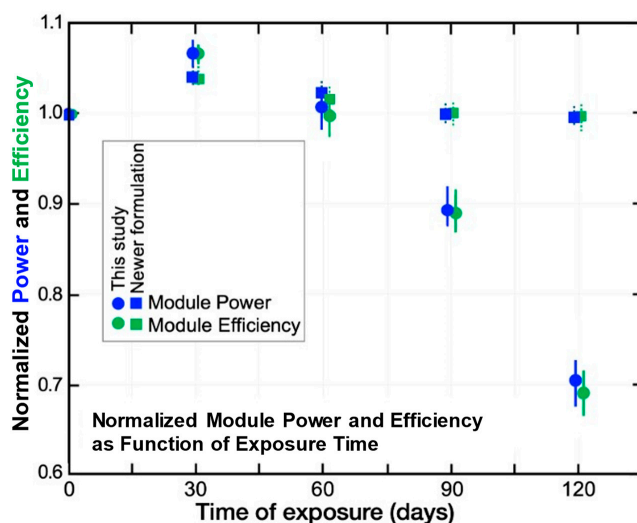


**Figure 10.** Normalized module power and efficiency as a function of the exposure times comparing modules from Table 1 (solid circles) with the improved module design. The lines indicate the measurement's uncertainty.

However, OPV stability remains a research focus. Recent advances in machine learning (ML) and artificial intelligence (AI) have provided a possible base to rapidly predict structures and compositions that would have suitable lifetimes. Initial successes have been demonstrated with OPC and hybrid perovskites [28–31], which could lead to the performance tipping point for these promising devices.

## 5. Conclusions

This study evaluated the performance and reliability of OPV materials and modules under Brazil's tropical climatic conditions. Modules with similar initial electrical characteristics were selected. A reference module was characterized for comparison, and a characterization module was used to establish the initial compositional and optical properties of the photoactive layer (destructive testing). The modules were subjected to typical local environmental factors, including high temperatures, humidity, solar irradiance, and UV exposure, and were monitored at 30-day intervals for a total of 120 days.

In the first 30 days, the modules displayed improved electrical parameters, with the maximum power increasing by 5% to 7%. This improvement is attributed to molecular rearrangements within the OPV active layer, reducing recombination and enhancing charge carrier mobility. These changes were correlated with decreases in series resistance and increases in the fill factor, effects like those observed in other thin-film PV technologies under light absorption.

From 30 to 60 days, the modules exhibited a slow linear decline in maximum power ( $P_{\max}$ ), with electrical parameters returning to initial values. IR analysis indicated some modifications in the C-H and O-H bonds, while the elemental composition remained largely unchanged compared to the initial reference module.

By the third stage (90 to 120 days), degradation became more pronounced, with power and efficiency decreasing by over 25%. IR analysis revealed further bond breakages, while elemental analysis detected Cu and Zn particles, likely caused by the diffusion of impurities at high temperatures. Despite the photodegradation, the modules continued to function, albeit with efficiency losses at about 25–30%, which may still be suitable for specific applications. A recent OPV module design with improved encapsulation and UV-inhibiting film on the module side exposed to the incoming radiation was tested, showing a significantly lower decrease in power output (none over the same 120-day period and less than 5% over a ~6-month period). This has indicated that the moisture and oxygen ingress and the UV are likely the major causes of the photoactive layer degradation that was observed. Further investigation into UV exposure and interface integrity is needed to improve OPV module stability in tropical climates.

This study focused exclusively on the organic photoactive layer, which is particularly susceptible to changes under tropical operational conditions. The degree of UV solar radiation exposure and the integrity of the interfaces under operational conditions also require further investigation, especially to ascertain the exact effects of the UV and temperature on the degradation of the organic layer. However, the observed photodegradation is not catastrophic, and the modules continue to operate with reduced but more stabilized performance, which would be satisfactory for some applications.

**Author Contributions:** Writing—original draft, L.P.Z.G.M.; Writing—review & editing, A.S.A.C.D., M.M.V., L.L.K. and G.A.S. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The original contributions presented in the study are included in the article.

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**Conflicts of Interest:** The author Gabriela S. Amorim is an employee of the company ONINN-Innovation Center. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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