NImpact of Desert Conditions on the Microstructural and Structural Proprieties of Ethylene -Vinyl Acetate (EVA) in Solar Energy

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Abstract

This comprehensive study delves into the degradation of Ethylene-Vinyl Acetate (EVA) in solar panels under arid, desert conditions. Employing techniques like Scanning Electron Microscopy (SEM), Fourier Transform Infrared (FT-IR) Spectroscopy, and X-Ray Diffraction (XRD), we observed a marked increase in crystallization within EVA layers, with rates of 46% above and 36% below the cells, surpassing the usual range of 25-33%. SEM analysis revealed significant carbonaceous particle deposition and crevassing in the sun-exposed EVA layer, impacting the efficiency of light transmission to the photovoltaic cells. Moreover, XRD and FTIR analyses detected the formation of novel compounds such as NH_4^+ and Si-O, indicating complex chemical changes. These findings highlight the need for materials better suited to withstand harsh desert environments, crucial for improving the durability and efficiency of solar panels in such challenging conditions.

Keywords: Solar Panels, EVA Degradation, Desert Conditions, Photovoltaic Efficiency, SEM Analysis, FT-IR Spectroscopy, X-Ray Diffraction, Material Science, Crystallization and Environmental Stressors

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Introduction

The advent of solar energy stands as a beacon of hope in the quest to surmount the global energy crisis and combat the escalating challenges posed by climate change [1]. In this context, Algeria emerges as a pivotal player, endowed with the unique geographical bounty of the Sahara Desert's intense sunlight, thus positioning itself as a hub for solar energy exploitation, driving economic growth, energy security, and environmental sustainability [2].

The Algerian desert regions, characterized by their abundant sunlight and expansive, underpopulated landscapes, present an ideal setting for solar energy harnessing [3]–[6]. Adrar, a southern Algerian region, is particularly noteworthy, boasting an impressive solar potential exceeding 2,000 kWh/m^2 annually [7]. However, the harsh desert conditions, marked by extreme temperatures and dust, pose significant challenges to the functionality and longevity of conventional solar cells, thereby impacting their operational lifespan.

Accordingly, a plethora of research endeavors have been dedicated to examining the impact of climatic conditions on solar panel performance in desert environments. Younce Mohammed et al. [8] identified the hot and dry climate of desert regions as a particularly challenging environment for photovoltaic (PV) panel performance. The extremities of climate, such as intense heat and pervasive dust, impose strains on standard solar cells, jeopardizing their long-term reliability and operational lifespan. Furthermore, the study highlights that major degradation mechanisms encompass both physical and chemical alterations of the materials, leading to premature failures or the emergence of undesired physical defects. Notably, common failure modes in this domain include the discoloration of the EVA encapsulant and delamination above the cell.

Z. Kherici et al. [9] discuss the implications of heat and thermal stress on PV installation performance and reliability in hot desert climates, highlighting the relationship between the degradation of polymeric components in crystalline silicon PV modules and climatic conditions.

Understanding the causative factors of PV panel degradation in desert climates is imperative for devising effective mitigation strategies. Concurrently, the exploration and development of new materials and technologies resilient to harsh desert conditions is a burgeoning field of research.

The schematic architecture of a typical commercial crystalline silicon (c-Si) PV module is illustrated in Figure 1. This conventional module comprises a front cover glass, EVA encapsulant, serially connected Si cells, a back sheet, edge sealant, and an aluminum frame. The EVA encapsulants in PV modules generally incorporate various additives, such as peroxide (as a curing agent), UV absorbers, UV stabilizers (like hinder amine light stabilizer, HALS), phosphonite (as an anti-oxidant or radical scavenger), and silane coupling agents to reinforce adhesion at the EVA-glass interface [10].

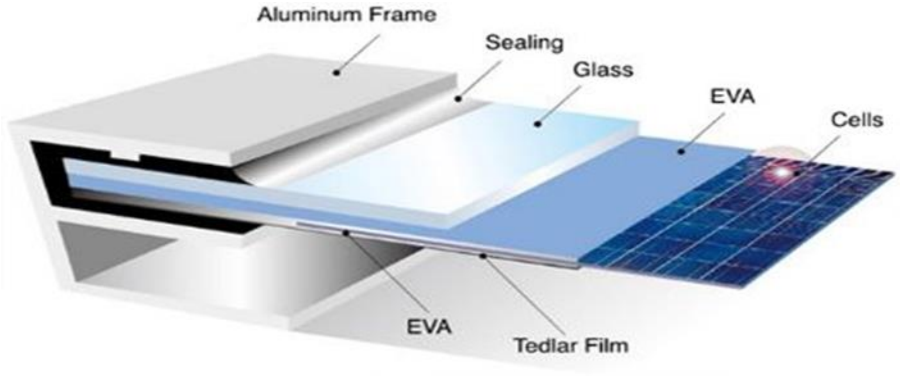

Figure 1: Multilayered Architectural Configuration of the Photovoltaic Module

The encapsulation materials fulfill several fundamental functions [11], including:

- Providing structural support and positioning of the solar cell throughout the manufacturing, handling, storage, installation, and operation phases.

- Ensuring and maintaining optical coupling between the solar cell and glass, with minimal solar radiation transmittance loss over the module's operational lifespan.

- Protecting the solar cells and circuit components from environmental degradation.

- Maintaining electrical insulation between solar cells and circuit elements throughout the module's lifespan.

- Preserving the integrity of the electrical circuit to generate the requisite current and voltage under light exposure.

Table 1 encapsulates the salient bulk properties of an encapsulant [12].

Bulk properties			
Chemical	Mechanical	Optical	Electrical
Resistant to photo induced reactions	- Tensile strength	- Clarity	- Insulation
- Moisture, gas and water absorption	- Elongation	- Transmissivity	- Low Leakage Currents
- Oxidation-Degradation product-induced	- Gel content - Adhesion		- Dielectric Properties

reactions

- Interface reactions

In this study, we investigate the degradation of EVA encapsulants in several c-Si PV modules exposed outdoors for approximately 17 years in Adrar using SEM, Fourier transform-infrared (FT-IR) spectroscopy and XRD analyses. The SEM analyses reveal cracks, inhomogeneities, and stacking on the sun-exposed side of the EVA sample, alongside distortions relative to the opposite side of the photovoltaic cell. X-ray analyses indicate an increased crystallization percentage in the upper layer of EVA compared to the lower layer. Furthermore, FTIR analyses detect a chemical reaction and the formation of new compounds such as $NH_4^+$and Si-O, predominantly in the top layer of EVA.

2-Exprimental

The multi-faceted analysis of Ethylene-Vinyl Acetate (EVA) utilized in the fabrication of deteriorated photovoltaic panels was meticulously carried out employing a suite of analytical techniques. The particle size and morphological characteristics were rigorously examined utilizing a Zeiss DSM 960A Scanning Electron Microscope, which operated at an accelerating voltage of 20 kilovolts. Complementary to this, the phase composition of the samples was discerned by X-ray Diffraction using an ADRX Benchtop diffractometer housed in Ontario, Canada. This analysis harnessed Cu-Kα radiation (λCu = 0.15418 nm) and the results were interpreted against the established databases ICDD (PDF-2, 2014) and COD-2021. The structural parameters of the EVA material were refined via HighScore Plus software (version 3.0.4), which leveraged the Rietveld refinement technique for precision. In parallel, Fourier Transform Infrared Spectroscopy was employed to scrutinize the vibrational spectra of the EVA compounds, using an Agilent Cary 600 Series FTIR spectrometer based in Springvale, Australia. This apparatus operated over a spectral range extending from 4000 to 400 cm^{-1} and incorporated baseline correction against a KBr spectrum to ensure heightened accuracy of the spectroscopic data.

3-Results and Discussion

3.1- Scanning Electron Microscopy (SEM) Analysis

Subsequent to the elucidation of Ethylene-Vinyl Acetate (EVA) degradation via Fourier Transform Infrared (FTIR) and X-Ray Diffraction (XRD) analyses, which established pronounced degradation of the EVA layer situated above the solar cells compared to that beneath, a comprehensive SEM investigation was embarked upon. This examination scrutinized the degradation phenomena of the EVA from two distinct perspectives: the sunlight-exposed surface and the cell-facing surface beneath, utilizing varying imaging resolutions (1 mm, 20 µm, and 10 µm).

Figure 2 encapsulates the SEM microstructural analysis of EVA from degraded solar panels, delivering a granular view into the morphological alterations imposed by environmental and operational stresses. This analysis is instrumental in decoding the degradation mechanisms and assessing the resilience of the EVA, a critical determinant of the photovoltaic module's durability and functional capacity.

A 1 mm-resolution SEM scan disclosed a generalized darkening on both surfaces, indicative of mechanical degradation. At increased magnifications, chemical degradation signatures become evident, particularly on the upper, sunlight-exposed layer. Conversely, the cell-facing layer exhibits less severe deterioration, appearing relatively unscathed at the same scanning resolution, with minimal evidence of mechanical or chemical degradation.

At a heightened resolution of 20 µm, the sunlight-exposed side reveals widespread, non-uniformly distributed black particles, presumed to be carbonaceous in nature, interspersed with significant crevassing. These particles, by virtue of their reflective and heat-absorptive properties, pose a considerable threat to EVA efficiency, potentially compromising light transmission to the PV cells and elevating cell temperatures, which may precipitate cell damage.

In stark contrast, the SEM analysis of the cell-facing side, while still displaying dispersed black particles, is notably devoid of fissuring, showcasing greater compactness and homogeneity.

Further scrutiny under 10 µm magnification unveils a marked speckle-like discoloration alongside a dense congregation of particles and pronounced gaps on the sun-facing side. These dark regions and particulate matter are implicated in significant light blockage, curbing light penetration and dispersion into the PV cell relative to the cell-facing side.

High-resolution SEM imaging distinctly reveals exacerbated weathering effects, characterized by surface discoloration and particulate interference with light transmission on the sun-facing side. This degradation is markedly catalyzed by the intense solar irradiation typical of the Algerian desert, particularly in Adrar. The resultant EVA discoloration severely impedes light access to the underlying photovoltaic cells, thereby diminishing their electrical output and exacerbating the rate of material degradation.

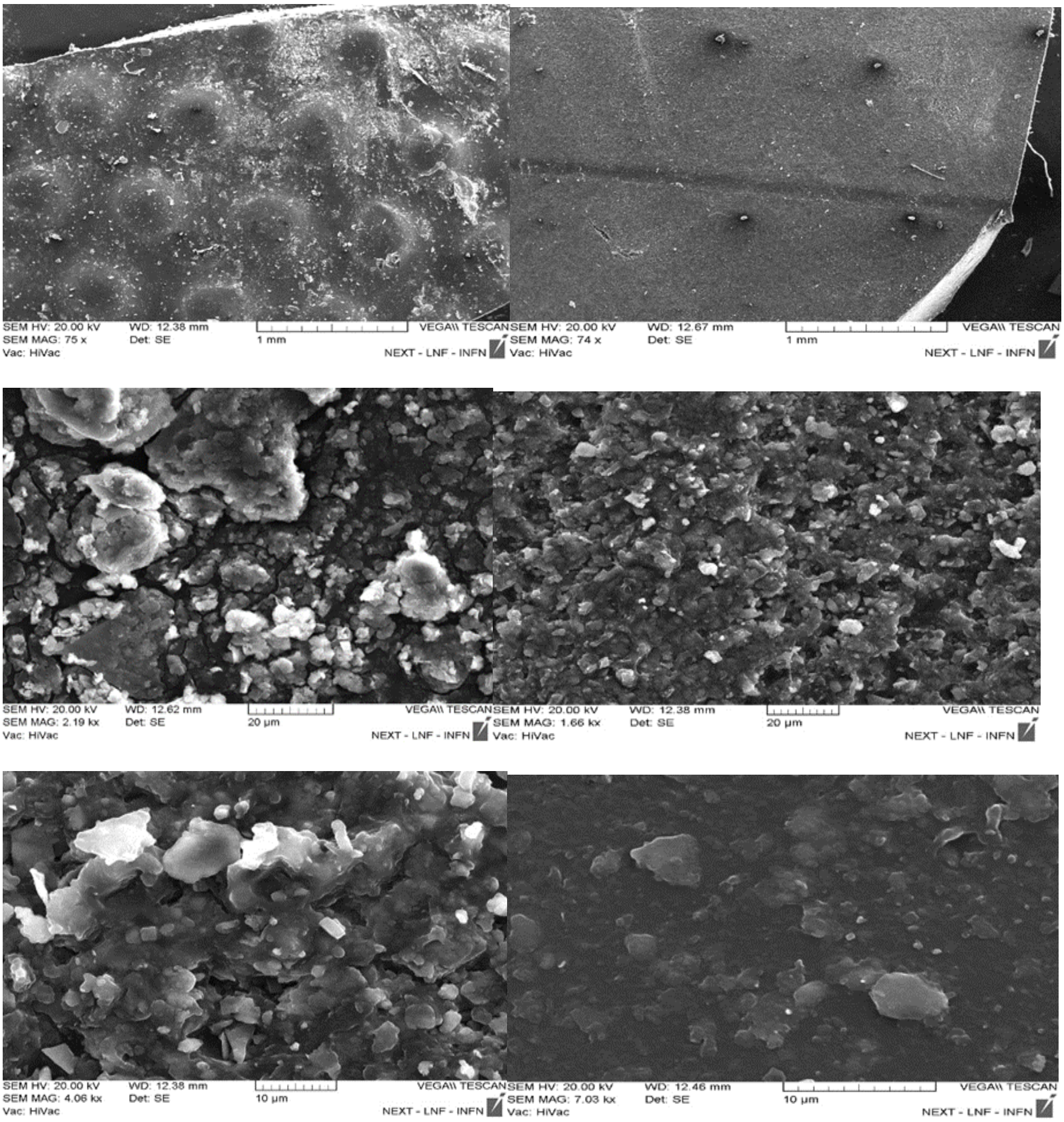

Figure 02: SEM microstructure Investigation of EVA Degradation in Solar Panel Construction

3.2- X-Ray Diffraction (XRD) Evaluation

In our extended investigation into the aging effects on ethylene vinyl acetate (EVA) copolymer layers within solar panels deployed in the Adrar region for 17 years, a notable escalation in crystallinity was observed. The X-ray diffraction (XRD) technique was employed to ascertain the crystallization levels of EVA layers situated both above and beneath the photovoltaic cells (refer to Figure 3). This assessment revealed a crystallization rate of 46% in the EVA layer atop the cells, a marked increase from the 36% crystallinity detected in the lower layer adjacent to the cells. These crystallinity rates significantly exceed the conventional threshold of 25-33%, which is deemed optimal for enduring solar encapsulation.

Crystallinity percentages were precisely quantified utilizing the formula:

$Xc = (Ac / (Ac + Aa)) \times 100\%$ .... (1)

Where:

-Ac denotes the area of the crystal peaks, discerned by the integration of sharp diffraction peaks denoting the polymer's crystalline zones.

-(Aa) corresponds to the area of the amorphous halo, deduced by integrating the broad halo in the XRD patterns, indicative of scattering from the disordered chains in the polymer's amorphous state.

- The cumulative scattering area beneath the XRD curve encompasses both the crystalline peaks and the amorphous halo (Ac + Aa).

The derivation of the crystalline area (Ac) as a proportion of the total area yields the crystallinity percentage (Xc) of the semi-crystalline polymer. This metric facilitates a quantitative crystallinity comparison across varied EVA samples and processing conditions.

The pronounced crystallinity within the EVA, particularly in the layer overlaying the photovoltaic cells, is a point of concern. Such heightened crystallization may lead to EVA discoloration, which in turn impedes the transmission of light to the photovoltaic cells, thereby reducing electrical output. Concurrently, the increase in crystallinity can compromise the material's inherent flexibility, elevating the risk of fissuring. Ultimately, such degradation may permit moisture ingress into the cells, fostering an environment conducive to corrosion.

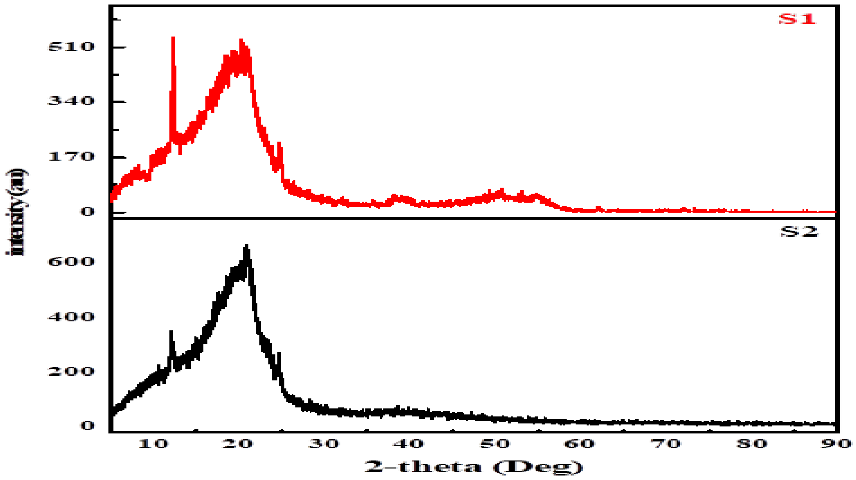

Figure 3: XRD Patterns of EVA Degradation in Photovoltaic Panels

3.3- Spectroscopic Analysis via FTIR

Fourier Transform Infrared (FTIR) spectroscopy emerges as an unparalleled technique in analytical chemistry, renowned for its exceptional sensitivity and precision in identifying trace elements within a matrix. It adeptly differentiates among various functional groups and bonding scenarios, providing a rich spectrum of molecular intelligence. Such precision and depth have established FTIR spectroscopy as an indispensable tool in the realm of mineralogical analysis.

The wide-ranging applications of FTIR spectroscopy extend to its aptitude for characterizing crystalline arrays, amorphous structures, and complex organic matrices. This comprehensive technique affords a holistic view of the materials being scrutinized.

Within the context of solar technology, FTIR spectroscopy provides valuable insights into the molecular intricacies of photovoltaic systems. In our specific study, the EVA layers encapsulating a solar cell, subjected to the harsh climate of Adrar for 17 years, were interrogated across the 400-4000 cm-1 spectral range. The resultant spectra, as delineated in Figure 04, divulge the molecular composition and structural transitions of the EVA, both above and below the solar cell. The array of spectral peaks and valleys render an intricate portrait of the chemical and structural shifts experienced by the EVA components.

Through meticulous spectral analysis, we can infer potential degradation mechanisms, identify possible contaminants, and conjecture about the remaining service life of these photovoltaic modules. This insight underscores the significance of FTIR spectroscopy in evaluating the durability and efficacy of materials used in solar energy systems.

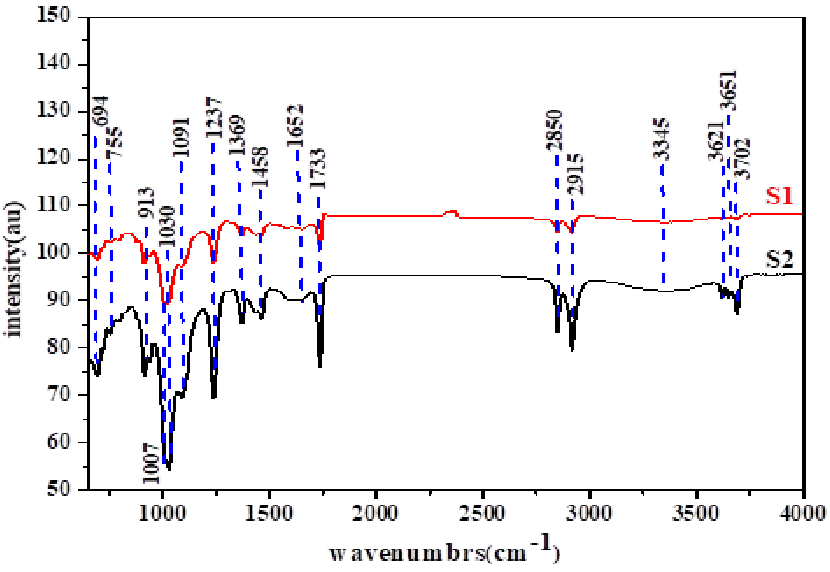

Figure 4: FTIR Spectra of Degraded Solar Panel EVA Samples.

The meticulous examination of spectral data, illustrated in Figure 4 and elaborated upon in Table 2, has uncovered a series of distinct absorption characteristics within the EVA layers encapsulating the aged solar cells. A prominent band situated at approximately 694 cm^{-1}, consistently recognized in prior research and spectral databases, is identified as indicative of C–H stretching vibrations, a signature trait of organic compounds [13]. Moreover, a subtler band around 755 cm^{-1} is discernible, which is consistent with additional C-H stretching vibrations [14].

The absorption peak at 914 cm^{-1} further substantiates the presence of CH functional groups [15]. The spectral feature observed at 1030 cm^{-1} is attributable to C-O structures[16][17], whereas the peak at 1091 cm^{-1} is suggestive of Si-O-CH_3 vibrations, often associated with siloxane or silicone-like materials [18]. The absorption at 1237 cm^{-1} is likely derived from C-O-C bending movements within the molecular framework of the polymer [18]. A notable feature at 1368 cm^{-1} delineates the presence of CH_3 groups interlaced within the EVA structure [15][19]. Concurrently, the peak at 1652 cm^{-1} is indicative of C=O stretching vibrations, which could signal ketones or other carbonyl-containing entities [19].

A discernible peak at 1733 cm^{-1} is particularly telling, denoting the carbonyl functional groups and underscoring the potential inclusion of organic impurities or carbonate species within the examined layers [20][19]. The spectral bands emerging at 2850 cm^{-1} and 2915 cm^{-1} resonate with the asymmetric and symmetric C-H (or CH_2) stretching vibrations, denoting the potential integration of organic compounds or hydrocarbons within the EVA matrix [19].

Furthermore, the distinct band at 3345 cm^{-1} corroborates the presence of hydroxyl (OH) groups [k]. The spectral markers identified at 3621 cm^{-1} and 3651 cm^{-1} could be associated with silanol (SiOH) groups [21], which might reflect interactions between the EVA and the solar cell components. Lastly, the signal at 3702 cm^{-1} is indicative of OH groups, which could be attributed to moisture absorption or hydrolysis reactions [22]. These findings provide a nuanced understanding of the chemical alterations and potential contaminant inclusions within the EVA layers, which are critical to assessing the material's integrity and performance within solar panel applications.

Table 2: Band Assignments in EVA Infrared Spectra from Degraded Solar Panels.

Wavenumber (cm^{-1})	Assignement
694	C-H
755	C-H
913	C-H

1030	C-O
1091	Si-O-CH_3
1237	H-O-H
1368	C-O-C
1652	C=C
1733	C=O
2850	CH_2
2915	CH_2
3345	O-H
3621	Si-O-H
3651	Si-O-H
3702	OH

Figure 5 presents an In-depth analysis of the FTIR spectra from samples S1 and S2, representing the EVA layers situated above and below the solar cell respectively, has elucidated a series of distinct vibrational bands, each signifying specific molecular constituents. The comparison between S1 (above-cell EVA) and S2 (below-cell EVA) revealed notable differences in their spectral profiles:

1. Si-O Bands: At S1, a band at approximately 802 cm^{-1}, and at S2, a band around 796 cm^{-1}, were observed. This marginal disparity in the band positions is indicative of the presence of Si-O linkages, as corroborated by the literature [23].

2. C=O and C-O Indications: New bands emerging at S1 around 874 cm^{-1} suggest the presence of C=O groups [13]. Additionally, bands at S1 near 1318 cm^{-1} and 1438 cm^{-1} are potentially indicative of C-O bonds [24][25].

3. CH3 Vibrational Features: The presence of bands at S1 (~1456 cm^{-1}) and S2 (~1460 cm^{-1}) with a slight distinction between them points to the existence of CH3 groups, aligning with established spectroscopic data [18].

4. H-N and NH_3^+ Presence: Furthermore, the emergence of new bands at S1, specifically at 1538 cm^{-1} and 2344 cm^{-1}, may signal the presence of H-N [26] and ammonium ions (NH_3^+) [27], respectively.

5. OH Group Identification: The spectral feature at S1 around 3747 cm^{-1} is likely representative of OH groups, adding to the complexity of the molecular landscape within the EVA layers [28].

This comprehensive spectral comparison between the above-cell and below-cell EVA layers underscores the nuanced chemical alterations that occur in these materials over time. The presence of these specific bands reveals significant insights into the molecular changes and potential degradation pathways in the EVA layers, essential for understanding their impact on the overall performance and longevity of the solar panels.

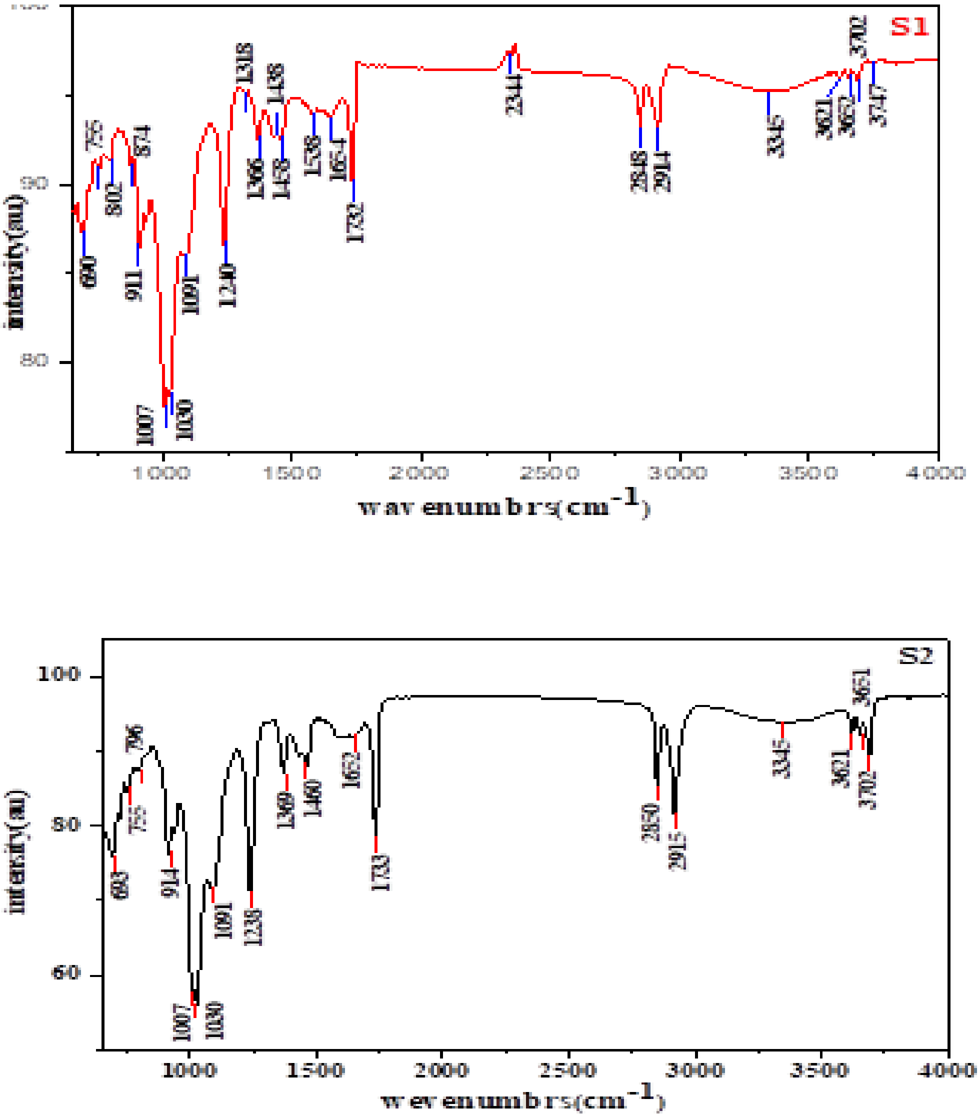

Figure 5: Progression of Stretching Vibrations in EVA FTIR Spectra

4-Conclusion:

In this comprehensive study, we have meticulously analyzed the degradation of Ethylene-Vinyl Acetate (EVA) in solar panels situated in the challenging desert environment of Adrar, Algeria. Our findings reveal a significant disparity in crystallization rates within the EVA layers: a remarkable 46% crystallization in the layers above the cells compared to a lower rate of 36% in the layers beneath. This notable difference in crystallization underscores the profound impact of direct sunlight exposure on the EVA material.

Through Scanning Electron Microscopy (SEM), we uncovered extensive deposition of carbonaceous particles and pronounced crevassing in the sun-exposed EVA layers. This phenomenon, not merely a surface alteration but a profound structural change, is likely to have substantial implications on the operational efficiency of the photovoltaic cells. These microscopic analyses provide a window into the complex interplay between environmental exposure and material degradation.

Complementing the SEM findings, our X-Ray Diffraction (XRD) and Fourier Transform Infrared (FTIR) analyses painted a detailed picture of the chemical transformations within the EVA. The emergence of compounds such as NH_4^+ and Si-O, revealed through these advanced analytical techniques, is indicative of intricate chemical reactions occurring within the EVA matrix. This transformation, possibly due to prolonged exposure to harsh environmental conditions, highlights the evolving nature of the materials used in solar panel construction.

The synthesis of our results from SEM, XRD, and FTIR analyses not only emphasizes the depth of degradation that EVA undergoes in desert environments but also signals the need for innovation in material science. Our study strongly suggests the necessity for developing materials that are specifically designed to withstand the unique challenges posed by arid climates like that of Adrar, Algeria. The goal is to enhance the longevity and performance of solar panels, ensuring that they remain efficient and durable over extended periods, even in the most demanding environments.

This research provides valuable insights into the degradation mechanisms of EVA in solar panels, emphasizing the critical need for more resilient and durable materials in the field of renewable energy. The findings from this study are expected to pave the way for future advancements in solar panel technology, particularly in enhancing their suitability for use in harsh desert conditions. This is not just a stride in material science but a leap towards sustainable and reliable solar energy solutions tailored for arid and challenging environments globally.

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