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Article

Thermal Stability of EVA Nanocomposites for Solar Cell Encapsulation

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Abstract: The long-term reliability and performance of photovoltaic (PV) modules largely depend on the thermal stability and durability of encapsulation materials that protect solar cells from environmental and thermal degradation. Ethylene–vinyl acetate (EVA) is widely used as a solar cell encapsulant due to its excellent optical and mechanical properties; however, its thermal stability and resistance to degradation remain critical challenges under prolonged operating conditions. Although EVA-based nanocomposites have been investigated for solar cell encapsulation, limited studies have systematically examined how different nanoclay fillers and processing conditions influence the thermal stability and encapsulation efficiency of EVA materials. This study aims to optimize the thermal stability of EVA nanocomposites by incorporating different inorganic fillers mica, montmorillonite (MMT), and vermiculite, at varying concentrations and milling cycles. An 8% EVA solution was prepared and blended with these fillers to evaluate their effects on the thermal and structural properties of the nanocomposite materials. Thermal characterization using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) revealed noticeable changes in melting temperature, glass transition temperature, and thermal degradation behavior. The incorporation of nanofillers improved the thermal stability of the EVA matrix and influenced its crystallinity and mechanical properties. The optimized EVA nanocomposite demonstrated enhanced thermal resistance and improved durability compared with neat EVA, although a slight reduction in encapsulation efficiency was observed. These findings provide valuable insights into the formulation and optimization of EVA nanocomposites for solar cell encapsulation, contributing to the development of more thermally stable and durable encapsulation materials for sustainable photovoltaic applications.

Keywords: EVA; MICA; Thermal Stability; Encapsulation; Thermogravimetric Analysis; Nanocomposite.

1. Introduction

The rapid pace of industrialization and population growth has led to a substantial increase in global energy consumption in recent decades. Fossil fuels remain the leading source of energy, meeting the majority of the world's energy needs [1], [2]. The heavy reliance on these finite petroleum resources is causing significant environmental harm and health issues. The urgency of finding alternate, sustainable energy sources is highlighted by this circumstance. Solar energy is the most abundant renewable energy source, and photovoltaic (PV) technology is starting to emerge as a viable and affordable alternative [3]. The operational reliability of PV technologies, both conventional and advanced, is a critical component in their adoption. Outdoor systems are expected to survive for 25–30 years [1]. However, the performance of PV systems is influenced by the environmental and climatic conditions of their deployment sites, which could limit the technology's potential for widespread commercialization.

The commercialization of solar technology relies heavily on the performance and durability of photovoltaic (PV) cells, which are the foundation of PV modules and play a critical role in determining their effectiveness [4], [5]. PV cells experience considerable degradation in their morphological and structural integrity, optical absorption, and optoelectronic properties due to extended outdoor exposure. This degradation negatively impacts the module's performance and energy output [6]. Encapsulation has proven to be a reliable method for enhancing the operational stability of PV cells, as it protects them from environmental stressors that can lead to degradation, such as moisture, UV light, oxygen, and temperature fluctuations. Additionally, encapsulation bolsters the cells' mechanical resilience against external forces [7]. Ethylene-vinyl acetate (EVA) copolymer has been the predominant encapsulating material in most studies exploring various encapsulation techniques to date. However, EVA degrades quickly when exposed to environmental factors, which diminishes the power output efficiency of PV modules. Consequently, the scientific community has devoted substantial effort to investigating novel strategies to improve the aging resistance of EVA encapsulant films, including the incorporation of antioxidants, UV absorbers, and photo stabilizers [7].

In today's world, the imperative to transition away from traditional fossil fuels, which pose significant environmental and health risks due to their high pollution and carbon dioxide emissions, has become increasingly urgent. Simultaneously, the need to harness energy from renewable sources and adopt practices that minimize harm to the environment and human well-being has become a pressing priority [8], [9]. Renewable energy recovery techniques that harness the power of tides, wind, and solar radiation are particularly promising. Among these, the development of solar photovoltaic (PV) systems for efficient energy recovery is a crucial area of research. As global energy demand is expected to increase steadily, reaching approximately 778 exajoules (EJ) by 2035, the importance of advancing solar PV technology cannot be overstated [10]. In response, Green Power (Catania, Italy) is developing an innovative device aimed at efficient energy recovery: a highly reliable bifacial glass-glass heterojunction photovoltaic module. This advanced heterojunction technology, which combines crystalline and amorphous silicon, offers high performance and efficiency in energy recovery, even under extreme weather conditions [11]. Encapsulant materials play a pivotal role in PV module manufacturing and installation, and selecting the appropriate ones is crucial to ensure the effective shielding of active PV elements, resulting in enhanced performance and extended lifespan. Encapsulant polymer-based materials must provide robust protection for PV modules against humidity, oxygen, and other gases while also being transparent, flexible, and offering strong adhesion to both glass and solar cells [12]. Several encapsulant materials have demonstrated suitability for industrial applications, including polydimethylsiloxane (PDMS), polyethylene vinyl acetate (EVA), polyvinyl butyral (PVB), thermoplastic polyolefins (TPO), and polyolefin elastomer (POE), among others [13]. Among these, EVA is considered the optimal polymer material for PV encapsulation when balancing cost and performance. To enhance EVA's environmental resilience, stabilizers and crosslinking agents are incorporated [13]. However, even with these additives, EVA degrades upon exposure to sunlight [13]. Among these, EVA is considered the optimal polymer material for PV encapsulation when balancing cost and performance. To enhance EVA's environmental resilience, stabilizers and crosslinking agents are incorporated [13]. However, even with these additives, EVA degrades upon exposure to sunlight. Acetic acid is produced as EVA breakdown proceeds, causing encapsulant yellowing, which eventually impairs the PV module's performance [13].

Advances in polymer science have significantly influenced the design of polymer encapsulants over time. The development of enhanced polymer composites, incorporating inorganic or carbon fillers, has led to improved gas and moisture barrier properties, resulting in superior performance. These composites are utilized to encase electrical equipment, protecting it from environmental damage. One category of smart polymers, known as photo-responsive polymers, is engineered to respond to sunlight or UV radiation. Due to their rapid curing time and the ability to form cross-linking network structures upon exposure to light, photo-responsive polymers are extensively utilized in electronics for applications including adhesion, sealing, potting, gasketing, and encapsulation [14], [15]. Inspired by the outstanding performance of these polymers, researchers have directed their efforts towards developing innovative and state-of-the-art polymer encapsulants that offer enhanced operational longevity and durability.

Initially, graphene oxide (GO) was added to the EVA matrix as an anti-aging additive to lower the photo-oxidation and photo-degradation of EVA encapsulants. GO was present in concentrations ranging from 0.25% to 2.0% by weight. Out of all of them, only the composite film containing 0.25% GO demonstrated adequate optical clarity and a moderate 20.4% loss of solar irradiance, making it appropriate for use in solar power modules. Another study used acid-functionalized graphene nanoplatelets (GNP) to reinforce EVA to increase the longevity of PV cells. The study also looked at the impact of different GNP concentrations on the thermo-mechanical, barrier, and optical properties of the EVA composite film [16], [17].

A melt-compounding procedure in a micro-compounder was utilized to include a commercial-grade acid-functionalized GNP into the EVA matrix using two distinct mixing techniques: direct mixing and solution mixing. The weight-based GNP concentrations that were evaluated varied from 0.001% to 1.0%. An EVA composite film with 0.1% GNP and greater tensile strength of roughly 26.09 MPa was created using the direct mixing method. To develop encapsulants for bifacial heterojunction photovoltaic modules, [18] proposed blending mixtures of polyethylene vinyl acetate (EVA) and polyolefin (PO) with stabilizers such as metal deactivators, UV absorbers, and crosslinking agents. The results showed that a blend of EVA/PO at a 75/25 wt/wt% ratio, containing stabilizers and a crosslinking agent, exhibited superior mechanical properties, optical qualities, and durability compared to plain EVA, indicating that even low concentrations of polyolefins have a beneficial impact. Furthermore, the photooxidation resistance of the EVA/PO blend at a 75/25 wt/wt% ratio, which includes stabilizers and a crosslinking agent, is comparable to that of pure EVA.

This suggests that the blend is a strong candidate for use as an encapsulant material in bifacial PV modules. [19] developed graphene oxide (GO) for use in EVA/GO nanocomposite films, and the results showed that these films exhibited enhanced mechanical properties and a highly water-resistant morphological structure. [20] also utilized graphene oxide (GO) to improve the moisture barrier properties of polyimide, reducing the water vapor transfer rate (WVTR) significantly from 181 g/m^2/day to 31 g/m^2/day with the addition of just 0.001 wt% GO. Furthermore, it was discovered that the optical transparency of the polymer film, which stayed at 95%, was unaffected by this small amount of GO. In a recent investigation by [21], examine the functions of reduced graphene oxide (rGO) and graphene oxide (GO) in ethylene propylene diene monomer (EPDM) and nitrile rubber (NBR). The results showed that reduced graphene oxide works better with NBR rubber than it does with less polar EPDM. This is probably because the graphene oxide sheet's surface has hydroxyl and carboxylic groups.

[22] study on the effect of graphene nanoplatelets (GNP) on the mechanical properties of epoxy resin, found that the tensile strength and modulus of the polymer could increase by up to 20% with the addition of just 0.1 wt% of graphene. Furthermore, they observed that graphene platelets provided a stronger reinforcing effect than carbon nanotubes. [23] investigated the impact of GNPs on the thermal properties of low-density polyethylene (LDPE) and found that adding approximately 1–5% of GNPs raised the polymer's decomposition temperature from 426°C to a range of 435–442°C. [24] used a solution-based method to produce EVA/GNP composites. Testing showed that incorporating 3 phr (parts per hundred resin) of GNPs resulted in the highest achievable tensile strength for the composite. Additionally, the electrical conductivity of the EVA/GNP composites increased by ten orders of magnitude after two hours of GNP application. This significant improvement was attributed to the excellent dispersion of GNPs within the EVA matrix, which led to the formation of an interconnected and continuous network throughout the composites. The study also demonstrated that GNPs could act as barrier-enhancing fillers for EVA, as the addition of 3 phr of GNP reduced oxygen permeability through the EVA film by 31%.

This research project aims to showcase the advancements made to enhance the reliability of EVA as an encapsulant for PV modules. Recent developments in polymeric encapsulants for the long-term durability of PV devices have focused on improving the properties of EVA nanocomposites through solution blending and examining the effects of inorganic fillers on the material's characteristics, to create a composite material suitable for encasing solar cells. This work encourages further investigation into the formulation and discovery of PV encapsulants that offer high performance in terms of durability and oxidative resistance while remaining cost-effective. Additionally, the properties and performance of commercial EVA were proposed, along with a suggestion for a comparative study.

This paper is organized as follows. Section 2 presents the methodology, Encapsulation requirement, and experimental analysis. Section 3 Results and discussion. Section 4 presents the conclusion and future works.

2. Methodology

Mechanical specifications for photovoltaic module encapsulants are crucial in addressing the mechanical stress experienced by solar cells during thermal cycling. Crystalline solar cells, for instance, often require high-temperature annealing (>80°C) to produce a quality of the crystalline film on TCO-coated glass or polymer substrates. This process induces mechanical tension between the layers. While glass and inorganic materials have low coefficients of thermal expansion (about 10×10^{-6} °C^{-1}), the crystalline, organic, and polymeric layers experience mechanical stress as they cool, leading to tensile stress, delamination, cracking, and eventual moisture infiltration and degradation. The encapsulant material needs to have a low elastic modulus to reduce tension between layers to mitigate these problems. The storage modulus, or elastic modulus, is a crucial factor in this scenario. As temperature increases, the storage modulus typically decreases, indicating the glass transition temperature, a phase transition from crystalline to amorphous. PV module thermal cycle tests usually cover a temperature range of -40°C to +85°C. Nevertheless, phase shifts within the range of -20°C to -10°C can lead to shear tension between layers, posing a risk to solar cell integrity [25]. To withstand impacts like hail, the encapsulant must possess a tensile strength exceeding 20 MPa.

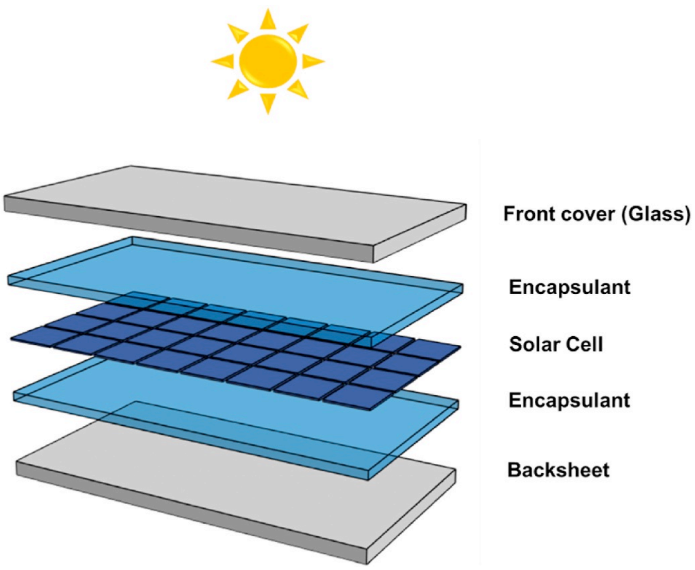

Figure 1. Diagrammatic representation of a silicon photovoltaic module enclosed.

Table 1. Properties of EVA.

Properties	**EVA**
Encapsulation	142 ^{0}C, 650 Mba
Time Condition	25 mins
Transmittance	92%
Young Modulus	11MPa
Harmful by product	Acetic acid
Glass Transition Temperature (T_g)	< -41^{0}C
Hydrolysis	No hydrolysis at 80 ^{0}C
Thermal Oxidation	Stable above 82 ^{0}C
Deterioration brought on by UV	No wavelength > 322 nm
Gel composition following curing	> 69%
Processing Temperature	169 ^{0}C
Liquidity Mechanics	50 ^{0}C

Additionally, the encapsulant system, comprising the glass and encapsulant, must pass standardized hail impact tests (FM 44787) to be commercially viable. Moreover, the encapsulant material should exhibit high creep resistance, which is often superior in cross-linked polymers compared to non-cross-linked ones. Cross-linking slows down the ingress of moisture and oxygen into the device and stabilizes the layer stack, enhancing its durability.

2.1. Encapsulation requirements

Encapsulation techniques for silicon photovoltaics are well-established, and the requirements for encapsulant materials are less stringent than those used in organic electronics. However, device degradation in crystalline solar cells remains a significant challenge that is not yet fully understood or managed. Consequently, encapsulating the entire device is currently the best approach to support the rapid commercialization of crystalline solar cells and address the device degradation issue. crystalline solar cells require encapsulant materials that are chemically compatible with every layer of the solar cell. As a result, these materials must be carefully chosen, taking into account the more intricate and particular degradation mechanisms that occur in these solar cells. The aforementioned material properties can be obtained by a variety of characterization techniques, including oxygen transmission rate (OTR), water vapor transmission rate (WVTR), tensile strength measurement (TSM), dynamic mechanical analysis (DMA), Fourier transform infrared spectroscopy (FTIR), and surface and volume resistivity tests.

Since the early 1980s, EVA (ethylene-vinyl acetate) has been the preferred material for manufacturing encapsulating films, with EVA film used in over 80% of photovoltaic (PV) modules [26]. EVA's prominence in the PV industry is attributed to its advantages, including low cost, ease of processing, high transparency, excellent chemical and electrical resistance, outstanding light transmittance, flexibility, and superior melt fluidity. In photovoltaic applications, EVA grades can contain up to 33% vinyl acetate by weight, combined with curing agents, UV absorbers, and photo and thermal antioxidants. Table 1 displays the characteristics of EVA used for PV module encapsulation. Despite its excellent encapsulation properties, EVA is subject to aging due to photothermal-induced polymer breakdown. UV absorption turns the polymer yellow or discolored, which lowers encapsulation efficiency and transparency. EVA's degradation behaviors have been investigated; Figure 1 depicts the main degradation process.

A primary objective of the TFE (Thermal Film Encapsulation) is to minimize the damage caused to crystalline solar cells (CSCs) by the encapsulation process and materials. It is evident that conventional encapsulation methods, such as heat stress, UV curing, and high pressure, can harm PSCs and lead to a loss of power conversion efficiency (PCE) after encapsulation. Typically, hot melt adhesive films used in lamination-encapsulation are easy to process as they are non-sticky at room temperature. These thermoplastic materials form a robust bond with the solar cell, glass, and other layers once subjected to heating, laminating, and curing processes. Temperature and pressing force are two crucial elements in a standard encapsulation procedure, with a recommended encapsulation temperature of approximately 80°C.

2.2. Thermal analysis

Thermogravimetric analysis (TGA) was employed to evaluate the weight composition and thermal stability of the EVA films, using the NETZSCH TGA 209-F3 model.

Pure Eva Sample *EVA/Toluene Solution* *Dried Fillers*

Figure 2. Material samples used for the experiment.

Figure 3. Mould on heated water jar setup.

Each sample, weighing approximately 10 mg, was heated in a nitrogen atmosphere from 25°C to 800°C at a rate of 20°C per minute. Additionally, differential scanning calorimetry (DSC) was used to assess the glass transition temperature (Tg), melting temperature (Tm), and crystallinity of the polymer composites. The DSC analysis was performed with a NETZSCH DSC 204-F1 model, also in a nitrogen atmosphere, with sample sizes around 10 mg. The temperature increased at a rate of 10°C/min over a range from -50°C to 200°C.

2.3. Preparation of Test Samples

A furnace was used to dry a jar containing a blend of three dry fillers: montmorillonite, mica, and vermiculite. In a separate process, 8% EVA was dissolved in toluene solvent and heated to 60°C for 24 hours to achieve uniform homogeneity. Meanwhile, a glass sheet was coated with ceramic material to create a circular mold for casting. A heater was used to warm a water bath to 40°C to ensure moderate and steady heating of the solution, preventing it from becoming gelatinous before casting, as illustrated in Figure 2. To secure a proper cast and prevent premature evaporation of the toluene, a white sheet of paper was placed over the surface of the setup.

A crucial factor in the casting process was the material of the mold. It is essential to use a mold material whose chemical properties do not react with EVA due to its unique characteristics. In this study, a ceramic mold mounted on a glass base was used. This setup prevents interaction between the glass composition and EVA, facilitating easy removal of the mold after casting with minimal stress as shown in Figure 3. The mold used in this investigation had a diameter of 70 mm.

Various techniques, such as Response Surface Methodology (RSM), Orthogonal Design of Trials, and Plackett-Burman (PB) design, are employed for optimal planning. In this study, the Taguchi approach, also known as the Orthogonal Design of Experiments, was utilized. The Taguchi methodology is a novel and efficient approach that requires the minimum number of experiments necessary for optimization, making it a valuable tool. By utilizing this comprehensive experimental strategy, researchers can swiftly determine the ideal conditions for their study, resulting in improved performance outcomes and reduced time and financial expenditures. Previous studies by [27] have demonstrated the efficacy of this method. Table 2 shows the factor levels selected based on references and practical experience [28]. It is important to acknowledge that component interactions were not considered in this study. The research employed an orthogonal experimental design (L9 (34)) to investigate the individual effects of four factors - platelet amount, type, ball milling, and casting thickness - on nine samples, with each factor having three levels. The factor levels are represented by the numbers "1, 2, 3." The experiments were conducted in a randomized order to minimize bias. To accurately determine the number of platelets required for

Figure 4. A sample mixer and vial set were employed for the experiment.

Figure 5. Stages of mould casting.

Table 2. Formulation of Experiment Parameters.

No	Platelet amount (%)	Platelet's type	Ball-milling min x run	Casting thickness
1	4	Mica	10 x 1	1
2	4	Vermiculite	10 x 2	2
3	4	Montmorillonite	10 x 3	3
4	6	Mica	10 x 2	3
5	6	Vermiculite	10 x 3	1
6	6	Montmorillonite	10 x 1	2
7	8	Mica	10 x 3	2
8	8	Vermiculite	10 x 1	3
9	8	Montmorillonite	10 x 2	1

each sample, it is crucial to refer to the material design formulation table using the Taguchi method, which specifies the platelet amount as a percentage. For this study, the standard was 8% EVA in a 100% solution. Thus, the solution used in this investigation contains 8% EVA.

A number of experimental techniques were conducted prior to the development of an effective methodology for solution blending. First, the filler material was combined with the full gramme of solution. After mixing, it was found that the filler material did not completely mix with the solution because there is not enough filler in the mixture to mix it evenly. In order to obtain a homogeneous mixture, the subsequent actions were performed.

1) To combine the solution, 35 grammes of EVA/Toluene solution were taken.
2) 10% of the EVA solution was added to dry clay (filler) in the reflux mixer vial set using a spatula and mount in the mixer.

3) The mixer is set up to operate for the right amount of time and cycles.
4) Following the cycle's conclusion, the residual 90 % of the EVA Solution was added to the vial's refluxed solution along with filler, and the mixture was again stirred in the mixer for ten minutes.

The SPEX SAMPLE PREP 8000M Mixer was the mixer/mill utilized in this investigation as shown in Figure 4. There are two balls in the vial set that are 12.7 mm and 11.6 mm in diameter. The fillers, used in small amounts, didn't fully dissolve when mixed with the complete solution. To address this, a small amount of solution was required for proper mixing with the filler material. Therefore, pre-mixing with 10% of the EVA solution was crucial for achieving uniform dispersion.

After combining the solutions, the composites were moulded while being heated gradually and steadily. Initially, the solution was poured at room temperature. It was found that before the mould cures (forms), the solution turns jelly. After experimenting with a range of temperatures, it was found that the solution moulds perfectly at 40°C when slow, continuous heating is provided by placing a water jar over the heater as shown in Figure 5. To cast the mould, the following procedures were followed.

1) Each mould receives 7 grammes of the refluxed solution; 10 grammes were used for thickness 2 and 12 grammes for thickness.
2) To prevent the toluene from evaporating too quickly, the mould surface is coated to regulate its evaporation.
3) For the entire three hours that the arrangement was under constant observation, the mould solidified completely.
4) To prevent material damage, the casted mould is carefully removed from the mould surface.
5) After cleaning, the mould is ready for a new casting.

The mechanical properties of the film cast were evaluated using an Instron Universal Testing Machine to test the composites, which were prepared by moulding them into 70mm circular shapes via a solution mixing procedure.

Combining SEM with energy-dispersive X-ray spectroscopy (EDS) analysis offers a powerful non-destructive analytical approach for determining the elemental composition of materials. This technique involves exposing a sample to a focused electron beam, which stimulates the emission of characteristic X-rays from the sample's atoms. By detecting and analyzing these X-rays, EDS can identify and quantify the elements present in the sample, providing valuable insights into their relative abundance.

Preventing moisture intrusion is vital to extending the lifespan of solar cells. To accomplish this, an encapsulant and edge sealer are typically used together to prevent moisture ingress through the edges. The ASTM E96 calcium test can measure the water vapor transfer rate (WVTR), a key performance indicator. This study used the water method specified in ASTM E96 to calculate WVTR. It is important to note that this study did not account for component interactions. Additionally, Aclar is not suitable for use as an edge seal material due to the same limitations that preclude its use as an encapsulant. By employing this method, solar panels can potentially increase their useful life by 10 to 15 years.

The melt flow index (MFI) of the blend was determined using the MP600 model extrusion plastometer, with a 2.16 kg weight applied. A 7g sample was placed in the heating chamber at 190C, where it took 5 minutes to melt and reach thermal equilibrium. The molten material was then extruded through the die, and samples were collected every 90 seconds. The average weight of five consecutive slices was calculated and converted to MFI. All values were recorded.

The TM4000Plus Tabletop Microscope was employed to study the foam structures of the EVA/Filler blends via scanning electron microscopy (SEM). Sample pieces were sectioned and then imaged using SEM at magnifications of 100x and 500x. Furthermore, SEM analysis was conducted to characterize the filler particles' size and shape. The microscope was operated in secondary electron mode at 1 kV to obtain high-resolution SEM images.

3. Discussion of Results

The objective of this study was to evaluate how the addition of nanocomposite fillers influences the encapsulation performance of EVA for solar irradiance and to assess the dispersion of these fillers within the EVA polymer matrix. An 8% EVA solution dissolved in toluene at 60°C was used, which was then combined with various nanocomposite fillers, such as mica, montmorillonite, and vermiculite, in different percentages and milling cycles. The study also explored the effects of milling cycles and filler concentrations on the properties of the films. To characterize the resulting material, the study analyzed its morphology, processability, mechanical properties, and permeability. The following testing methods will be employed in a series of experiments to gather the required data from the film samples: Water Vapor Transmission Rate (WVTR), Tensile Test, Melt Flow Index (MFI), Energy Dispersive X-ray Spectroscopy (EDS), and Scanning Electron Microscopy (SEM).

3.1. Scanning electron microscope

A series of analyses known as SEM is carried out on film samples that are cast in the Low/Variable Pressure (VP) mode. Since the substance being examined is nonconductive, this mode was selected. This stops the electrons from forming and charging. When the primary

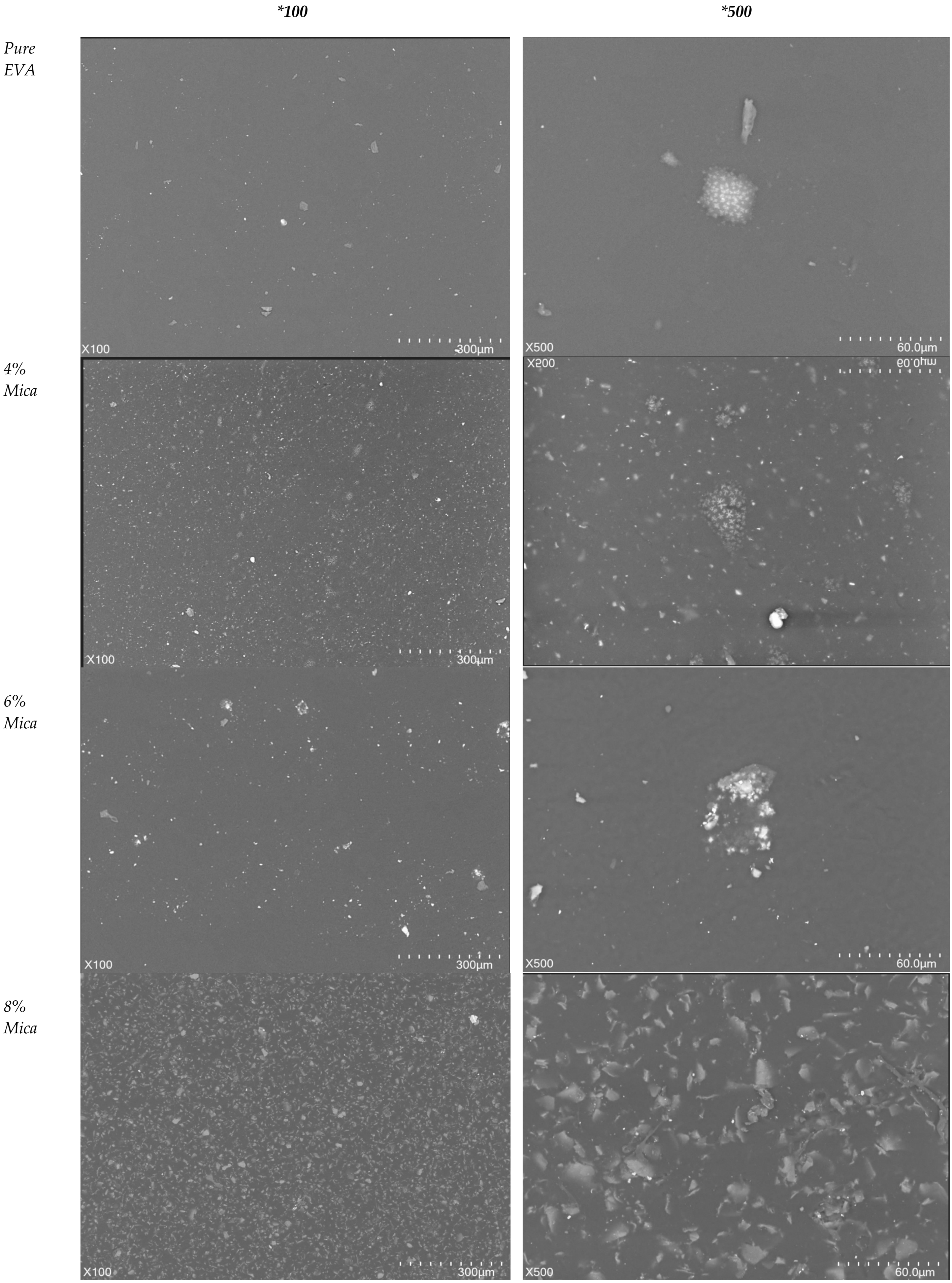

Figure 6. Different concentrations of Nano-composite EVA and Mica.

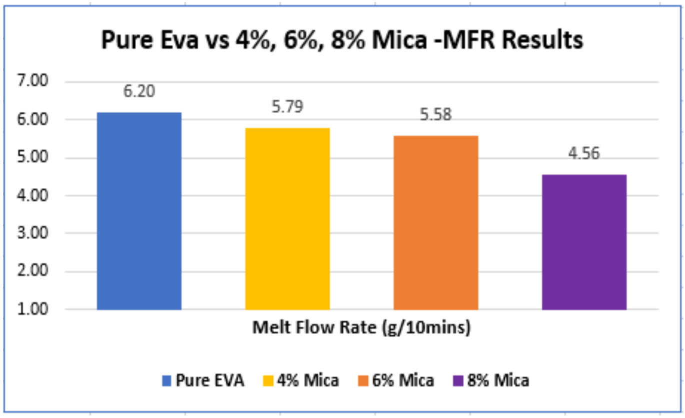

Figure 7. Melt Flow Mica.

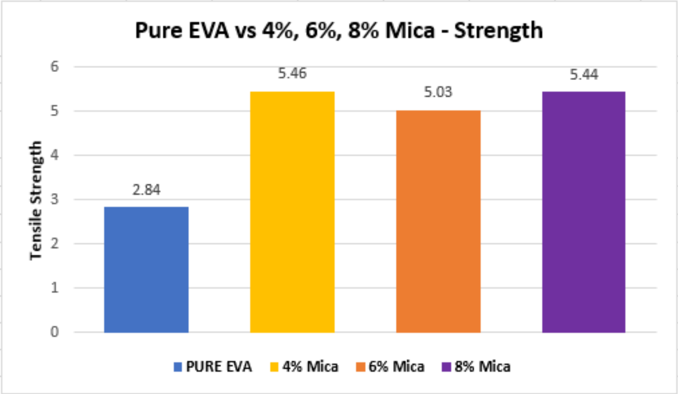

Figure 8. Mica- Strength.

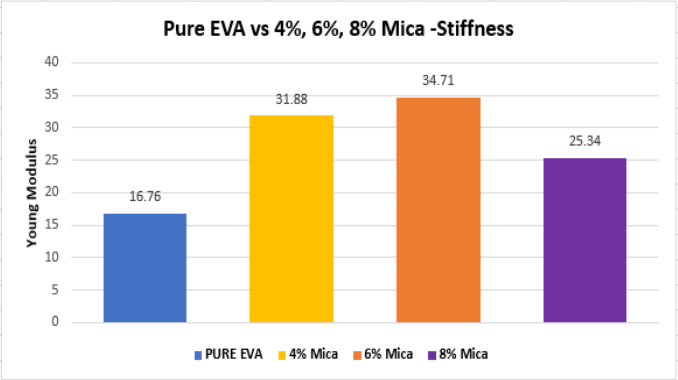

Figure 9. Mica-Stiffness.

electrons reflect off the specimen surface, the Backscattered electrons (BSE) detector produces an image. Because of their increased activity, they will be able to enter the specimen more deeply and contribute to the creation of its compositional data. To achieve consistent results, the microstructure and dispersion of various EVA nanocomposite material concentrations were analyzed using Scanning Electron Microscopy (SEM). SEM was employed to observe and visualize alterations in surface morphology that might influence the outcomes. This technique allows for a qualitative evaluation of surface physical changes by examining particle size, shape, and distribution/dispersion. The SEM analysis for the 4% and 8% Mica composites, as depicted in Figure 6, reveals several regions of particle aggregation and agglomeration, which act as stress concentrators. It was observed that these aggregated nanofillers increase water permeability at the clay/polymer interface by creating more pathways for water ingress, thereby reducing tortuosity.

3.2. SEM-EDX (Energy dispersive X-ray diffraction)

When paired with Scanning Electron Microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS) serves as a powerful, non-destructive analytical technique for determining and quantifying the elemental composition of materials. This method involves directing a focused electron beam at a sample, causing its atoms to emit characteristic X-rays. By detecting and analyzing these emitted X-rays, EDS can identify the elements present in the sample and their relative concentrations. The SEM-EDS analysis was conducted using a Hitachi TM4000Plus tabletop microscope, operating at a working distance of 17 mm and an accelerating voltage of 15.00 kV. The SEM-EDS images were captured from locations similar to those used for the SEM images. EDS provides both semi-quantitative and semi-qualitative elemental data, making it a versatile tool for various applications. This technique is widely used across various fields, including materials characterization, biomedical research, and environmental contamination studies. The characterization of the components reveals that EVA is the predominant substance in the samples, indicated by a high oxygen content. This oxygen primarily originates from EVA, and as the percentage of nanocomposite filler increases, the oxygen content decreases. Vermiculite follows this trend, with 6% Mica and MMT showing a slight deviation. The EDS spectrum also indicates a significant presence of silicon (Si) in the MMT filler. Si was found to have the highest chemical composition in MMT, and this composition increases as the filler fraction in the material rises. Overall, the EDS spectrum effectively displays the elemental composition of each sample. Factors such as time and the number of milling cycles could influence this composition. A well-dispersed solution provides a clearer understanding of the sample's primary elemental makeup.

3.2.1. Melt Flow Index (MFI)

Melt Flow Index (MFI) tests were conducted to evaluate the materials' processability and melt viscosity or flow resistance. Another important aspect of these tests is understanding how variations in blending affect the composite fillers. The material with the highest MFI value is the easiest to process. As the filler content in the material increases, viscosity decreases, which is influenced by the ratio of EVA to nanocomposite filler. For this experiment, a weight of 2.16 kg and a 90-second duration were used. The Melt Flow Rate (MFR) data is presented in Figure 7. The EVA/Mica nanocomposite exhibited a consistent trend as the filler proportion increased. It was observed that adding filler results in a reduction in melt flow rate, and this reduction remains consistent as the filler quantity increases. To gain a deeper understanding of the materials' processability, the percentage composition of each filler type was also analyzed. The results showed that vermiculite exhibited higher processability at 4% compared to Mica and MMT. At 6%, Mica was more processable than both vermiculite and MMT, while at 8%, MMT outperformed both Mica and vermiculite in terms of processability. It is important to consider how different milling cycles each lasting ten minutes affect the Melt Flow Rate (MFR) outcomes for each filler type and their respective percentages. Vermiculite demonstrated the highest MFR value during the second and third milling cycles, indicating a higher melt flow index compared to Mica and MMT.

3.2.2. Mechanical Properties

Mechanical properties are a vital aspect of solar cell encapsulation, contributing to panel stability and durability in challenging environments. Tensile testing is employed to assess the mechanical behavior of materials cast, yielding data on tensile strength (σ), elongation (EB), and elastic modulus (E) at maximum force. The experimental results demonstrate that the mechanical properties of the resulting materials are influenced by the type and amount of nanocomposite filler used, underscoring the need for careful filler selection and optimization to achieve optimal mechanical performance in solar cell encapsulation.

As shown in Figure 8, the tensile strength values and composition percentages of the fillers were recorded. Since the material is intended for use in encapsulating solar cells, the tensile strength was measured at maximum force to assess the material's elasticity before breakage or maximum strain, which is essential for understanding the sample's behavior. The Instron 3367 testing machine was used for this evaluation. The slight increase in elastic modulus observed in the nanocomposite filler results is attributed to the formation of filler platelets. Our data consistently demonstrate that nanocomposite filler samples exhibit higher elastic modulus and strength at maximum force compared to neat EVA samples. This is due to the increased stiffness of the inorganic clay, which is caused by its high aspect ratio and platelet structure.

A significant enhancement in mechanical properties, particularly stiffness, was observed in the EVA/Mica material compared to pure EVA, as shown in Figure 9. This finding suggests that a minimal addition of 4% mica is sufficient to improve the material's mechanical performance. While variations in mechanical properties may be attributed to factors such as blending cycle and sample thickness, as identified in our experiment design, the addition of mica filler is clearly effective in enhancing the mechanical properties of EVA.

3.2.3. Water Vapour Transmission Rate

The water vapor transmission rate (WVTR) measures the rate at which water vapor passes through an encapsulant material. This test adheres to the ASTM E96 standard and involves placing a sample film over a gravimetric cup containing 25 mm of water. The weight change of the cup is then monitored over time, while maintaining a specific pressure differential across the sample using the cup method. By controlling the temperature and relative humidity, the sample's water vapor permeability is measured, allowing for the calculation of WVTR parameters. The cup method can be conducted in two ways based on the same test principle: the water method, where water vapor exits the test cup, and the desiccant method, where water vapor enters the test cup. In this case, the water method was used. The mica-laden samples with 4%, 6%, and 8% filler showed the lowest and most stable permeability curves on the permeability graph, indicating that these samples performed best during the test. The permeability test results revealed that the 8% loaded sample initially showed promise but declined after 48 hours, ultimately finishing last. In contrast, the 4% loaded sample underperformed compared to pure EVA and reached a lower permeability saturation point. However, the 6% loaded sample consistently demonstrated the best performance throughout the test (Figure 10). Interestingly, the 4% loaded sample improved after 48 hours and finished satisfactorily. Despite being the least permeable, the 8% loaded sample failed to maintain consistency. These findings emphasize the need for experimental characterization and testing to optimize the performance of nanoplatelet-reinforced polymer composites. The WVT and Permeability graphs above demonstrate the effect of platelet percentage loading on the barrier permeability property of the nanocomposite samples.

Adding nanoplatelets to a polymer matrix can enhance barrier properties by reducing gas or liquid permeability. This is because nanoplatelets create tortuous pathways that hinder molecular diffusion. As nanoplatelet loading increases, barrier properties are expected to improve, and permeability should decrease. However, beyond a certain threshold, excessive nanoplatelet loading may lead to diminishing returns or even adverse effects due to issues like poor dispersion, agglomeration, or mechanical property degradation. While increasing nanoplatelet loading can generally improve barrier properties in a polymer matrix like EVA, the relationship is not necessarily linear, and an optimal loading percentage may exist to strike a balance between various properties. The Taguchi (L9) approach provided valuable insights by examining four components at three levels of analysis, offering varying perspectives depending on the characteristics of interest. However, the complex interplay between casting thickness, milling turn cycle, and filler percentage made it difficult to identify the top-performing

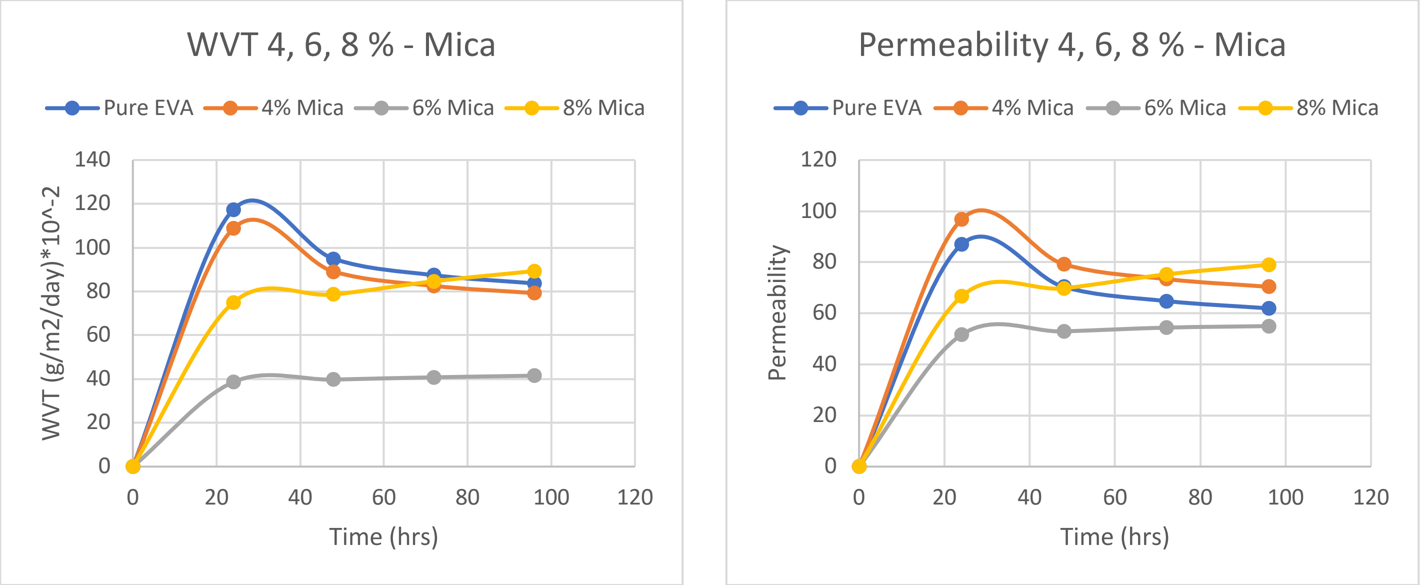

Figure 10. Mica WVT vs Time and Permeability vs Time.

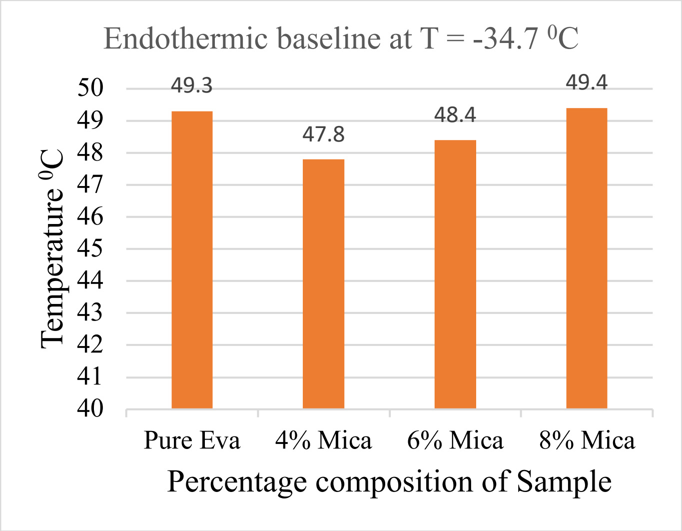

Figure 11. Effect of Mica Nanofiller Concentration on the Melting Temperature of EVA Nanocomposites.

Table 3. Comparison between encapsulated and raw monocrystalline PV cells.

Items	Before Encapsulated	After Encapsulated
Voltage	1.7V	1.72V
Current	5.2A	5.3A
Power	8.2W	8.32W
Solar Irradiance	1011w/m2	1032wm2
Efficiency	11.64%	12.22%

filler. Nonetheless, the addition of inorganic fillers consistently improved EVA's mechanical, morphological, and water barrier properties, regardless of test outcome variables. The material type and mould nature significantly impacted the results, emphasizing the need for a permanent mould to prevent solution spillage and produce high-quality films. Additionally, the operating temperature during film curing (forming) also played a crucial role in determining the film cast and resulting outcomes.

Figure 11 displays the Effect of Mica Nanofiller Concentration on the Melting Temperature of EVA Nanocomposites. The DSC analysis of pure EVA shows an endothermic baseline shift at approximately -34.7°C, corresponding to the glass transition temperature (T_g) of EVA rubber [29]. Additionally, an endothermic peak at around 47.3°C indicates the polymer's melting transition temperature (Tm). After compounding with graphene nanoplatelets MICA, the T_g of EVA remained relatively unchanged, while the Tm slightly increased, accompanied by a reduction in the enthalpy of melting. The crystallinity of pure EVA decreased from 10.28% to between 8.65% and 9.20% after blending with MICA. The literature suggests that adding nano-fillers to EVA can either increase or decrease its crystallinity. [30] observed minimal loss in EVA's crystallinity with MICA, whereas [31] reported a reduction in crystallinity with silica addition. The observed discrepancies may be due to differences in mixing techniques, filler types, and concentrations. The addition of MICA to the composite films did not substantially impact the weight loss percentage of EVA. Nonetheless, MICA blending improved EVA's thermal stability, as evidenced by the increase in de-acetylation temperature from 352°C to roughly 369°C and 365°C, respectively, using the master-batch and direct mixing methods. [30] also reported a similar effect, which was attributed to MICA's "heat sink effect," helping to dissipate heat within the polymer matrix.

After finalizing the encapsulation procedure for performance comparison, three monocrystalline solar cells were connected in series, and their baseline performance was measured in open air. Additional measurements were conducted following the encapsulation process. The average results are summarized in Table 3, showing the difference in efficiency between the two measurements. Specifically, the solar panel's efficiency increased from 11.64% before encapsulation to 12.22% after encapsulation. Although the epoxy lamination process led to a slight decrease in conversion efficiency, it significantly enhanced the solar cell’s resistance to weather and dirt, thereby improving its durability and extending its lifespan.

4. Conclusion and Future Work

The optimization of thermal stability in EVA nanocomposites significantly impacts their effectiveness as encapsulation materials for solar cells. This study has demonstrated that incorporating nanocomposite fillers such as mica, montmorillonite, and vermiculite into EVA can enhance its thermal stability and durability. The thermal analysis results revealed that these fillers influence the glass transition temperature, melting temperature, and overall thermal degradation of the EVA matrix. Although there was a slight reduction in encapsulation efficiency following the optimization process, improvements in thermal stability and resistance to environmental stressors are notable. The SEM images of the 4% and 8 % filler samples displayed notable agglomerates of clay layers, potentially caused by the exfoliation rate of the filler in the solution. Furthermore, the higher permeability of the samples was accounted for by the visible pathway in the images. Encapsulated solar cells exhibited enhanced resistance to weather and contaminants, leading to increased durability and extended lifespan. These findings underscore the potential of EVA nanocomposites in advancing solar cell encapsulation technology. Future work should focus on further refining filler concentrations and mixing methods to balance encapsulation efficiency with optimal thermal stability. Overall, this study provides a foundation for developing more robust and long-lasting encapsulation materials for photovoltaic applications.

5. Declarations

5.1. Author Contributions

Ganiyu Olamide Ogunsiji: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources; **Oluwaseyi Omotayo Alabi:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft; **Adeoti Oyegbori Laoye:** Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft; **Saidat Abisoye Salisu:** Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition; **Samuel Adekunle Dada:** Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

5.2. Institutional Review Board Statement

Not applicable.

5.3. Informed Consent Statement

Not applicable.

5.4. Data Availability Statement

No data availability.

5.5. Acknowledgment

Not applicable.

5.6. Conflicts of Interest

The authors declare no conflicts of interest.

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