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Polymer-Based Transparent Conductive Composites for Flexible Solar Panel Coatings

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Abstract

This study investigates the fabrication and characterization of polymer-based transparent conductive composites (PTCCs) tailored for flexible solar panel coatings using poly(methyl methacrylate) (PMMA) and poly(ethylene terephthalate) (PET) matrices reinforced with silver nanowires (AgNWs), multi-walled carbon nanotubes (MWCNTs), and PEDOT:PSS. The composites were synthesized through a solution blending and doctor-blade casting method followed by post-treatments to enhance interfacial bonding and conductivity. Optical transmittance values above 85% were achieved across all composite types, with the highest recorded for pristine polymers (~92%) and PEDOT:PSS-based composites (~88%) even at 2 wt% filler loading. AgNW-reinforced composites showed good transparency (~86%) with significant electrical improvement, reducing sheet resistance from ~10^6 Ω/sq (pure polymer) to ~100 Ω/sq at just 0.5 wt% filler concentration. PEDOT:PSS composites further achieved ~300 Ω/sq after ethylene glycol doping and thermal annealing. MWCNT-filled systems offered enhanced thermal performance, increasing the decomposition onset temperature by 20–25 °C, while AgNWs and PEDOT:PSS composites showed moderate thermal gains of ~10–15 °C. Mechanical testing revealed up to a 15% increase in tensile strength and stable flexibility across all systems, with PEDOT:PSS composites maintaining integrity after over 1000 bending cycles. These results confirm that PTCCs optimized with low filler concentrations can simultaneously offer high optical clarity, superior electrical conductivity, and robust thermal and mechanical stability—making them promising alternatives to conventional ITO coatings for next-generation flexible optoelectronic and photovoltaic applications.

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INTRODUCTION

Transparent conductive materials (TCMs) have become central components in modern optoelectronic technologies, including flexible solar cells, organic photovoltaics, touchscreens, wearable electronics, smart windows, and sensors. Historically, indium tin oxide (ITO) has been the dominant material, widely adopted due to its

superior electrical conductivity, optical transparency, and well-established manufacturing processes. However, significant drawbacks such as brittleness, high cost, limited flexibility, scarcity of indium, and difficulty integrating with flexible substrates have driven research toward alternative materials, particularly polymer-based transparent conductive composites (PTCCs) [1–3].

Polymers, owing to their inherent flexibility, lightweight properties, easy processability, and excellent chemical resistance, offer ideal matrices for developing flexible and transparent conductive composites. These materials enable scalable fabrication techniques, including roll-to-roll manufacturing, significantly reducing production costs and enhancing commercialization potential [4–6]. Commonly used polymers in PTCCs include poly(ethylene terephthalate) (PET), poly(methyl methacrylate) (PMMA), polycarbonate (PC), polyimide (PI), and polydimethylsiloxane (PDMS). These polymers serve as the host matrix, offering distinct advantages depending on the application. PET and PMMA are favoured for their excellent optical transparency and flexibility, making them ideal for photovoltaic and optoelectronic coatings. PC provides high impact resistance and toughness, useful in harsh environments. PI offers superior thermal stability and mechanical strength, suitable for high-temperature applications. PDMS, known for its elasticity, is often used in stretchable and wearable electronics. Each polymer matrix plays a crucial role in determining the final composite's mechanical durability, flexibility, thermal stability, and transparency [7–9].

Electrical conductivity in PTCCs is generally achieved by integrating conductive fillers into polymer matrices. Typical conductive fillers include carbon-based nanomaterials (e.g., carbon nanotubes (CNTs), graphene, graphene oxide), metallic nanowires (e.g., silver nanowires (AgNWs), copper nanowires (CuNWs)), conductive polymers (e.g., poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS)), and conductive metal oxides (e.g., zinc oxide (ZnO), tin oxide (SnO_2)) [10–12]. Each filler imparts distinct electrical, optical, and mechanical properties to the composites, with specific advantages and challenges concerning stability, dispersion, scalability, and cost-effectiveness.

Conductive polymers, particularly PEDOT:PSS, are especially prominent due to their intrinsic conductivity, high optical transparency, good mechanical flexibility, and aqueous-based processing capability. PEDOT:PSS composites demonstrate remarkable compatibility with flexible polymer substrates and potential for low-cost manufacturing, positioning them as viable alternatives to traditional ITO-based coatings for flexible solar cells and optoelectronics. Nevertheless, their relatively lower conductivity compared to metallic fillers often necessitates hybridization strategies or post-treatments to enhance overall electrical performance [13–15].

Carbon-based nanomaterials, including carbon nanotubes and graphene derivatives, have emerged prominently in PTCC research, due to their excellent electronic properties, outstanding mechanical strength, flexibility, and optical transparency. Carbon nanotubes, both single-walled (SWCNTs) and multi-walled (MWCNTs), have demonstrated exceptional potential, particularly when uniformly dispersed within polymer matrices. Despite their attractive properties, CNT-based composites often face significant dispersion challenges, transparency limitations, and aggregation issues that necessitate advanced dispersion methods, such as surface functionalization, ultrasonication, or chemical treatments, to achieve stable and high-performance composites [16–18].

Graphene and its derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), represent another class of carbon-based conductive fillers extensively studied for PTCCs. Graphene offers exceptional electrical conductivity, optical clarity, and mechanical robustness. Its integration into polymer matrices can significantly enhance conductivity and flexibility. However, homogeneous dispersion of graphene within polymer matrices and maintaining optical transparency at higher loadings remain challenging, requiring innovative approaches, including chemical functionalization and controlled reduction processes, to optimize composite performance [5, 19].

Metallic nanowires, particularly silver nanowires (AgNWs), have been extensively explored for transparent conductive polymer composites due to their extraordinary electrical conductivity, optical transparency, flexibility, and ease of large-scale synthesis. AgNW-polymer composites can achieve transparency and conductivity comparable or even superior to ITO-based coatings while maintaining excellent flexibility suitable for flexible solar cells and wearable devices. Nonetheless, silver nanowires exhibit drawbacks such as susceptibility to oxidation, limited environmental stability, and relatively high cost, prompting the use of encapsulating polymer matrices or hybrid structures with carbon-based fillers or conductive polymers to mitigate these limitations [8, 11, 20].

Hybrid conductive composite approaches, involving the integration of complementary conductive fillers (e.g., CNT-AgNW, graphene-PEDOT:PSS, metal oxide-polymer blends), are increasingly investigated. Such hybridization strategies aim to synergistically enhance electrical conductivity, transparency, mechanical properties, and environmental durability, overcoming the limitations associated with single-component filler systems. This strategy effectively optimizes composite performance tailored specifically toward flexible photovoltaic applications [2, 12, 15].

The overall performance of PTCCs strongly depends on multiple parameters, including filler content and concentration, filler aspect ratio, uniform dispersion, interfacial interaction between fillers and polymer matrices, and composite processing methods. Efficient dispersion strategies, including solvent blending, ultrasonication-assisted mixing, mechanical stirring, chemical functionalization, and melt compounding, significantly impact conductive network formation, directly influencing composite conductivity, transparency, and mechanical integrity [4, 9, 16].Advancements in polymer composite processing techniques, including electrospinning, spray coating, inkjet printing, doctor-blading, and roll-to-roll manufacturing, have markedly facilitated scalable, precise, and cost-effective production of PTCC films. These methods offer improved control over composite film thickness, uniformity, conductivity, transparency, and reproducibility, thereby enabling widespread commercial implementation of PTCC-based flexible solar panels and optoelectronic devices [7, 10, 17].

Amid increasing global sustainability concerns, polymer-based transparent conductive composites are gaining prominence in renewable energy technologies, particularly flexible solar panels. The flexibility, durability, environmental resistance, lightweight nature, and cost-effectiveness of polymer-based conductive composites render them highly attractive for integration into wearable electronics, portable photovoltaics, architectural-integrated photovoltaic applications, and next-generation renewable energy systems [3, 13, 18].

This research aims to investigate into polymer-based transparent conductive composites explicitly tailored for flexible solar panel coatings, exploring synthesis methods, conductivity mechanisms, recent innovations, fabrication challenges, and future prospects. The insights presented will facilitate the advancement of polymer-based TCM technologies, thus addressing critical global demands for renewable energy and sustainability-driven technological innovations.

MATERIALS AND METHODS

Materials

To fabricate polymer-based transparent conductive composites (PTCCs) suitable for flexible solar panel coatings, a systematic approach was adopted involving the selection of appropriate polymer matrices and conductive fillers. High-purity poly(methyl methacrylate) (PMMA) and poly(ethylene terephthalate) (PET) were chosen as the primary polymer matrices due to their excellent optical transparency, flexibility, and commercial viability. These polymers were used either individually or as blends to study their compatibility with conductive fillers and to evaluate their mechanical and optical characteristics post-fabrication.

Conductive fillers employed in this study included silver nanowires (AgNWs), multi-walled carbon nanotubes (MWCNTs), and PEDOT:PSS. The AgNWs were procured as a colloidal dispersion in

ethanol with average diameters of 50–100 nm and lengths ranging between 10–20 µm. MWCNTs were utilized in powder form with outer diameters of 10–20 nm and lengths exceeding 1 µm, while PEDOT:PSS was acquired as an aqueous dispersion with a solid content of approximately 1.3%. To achieve uniform dispersion and prevent agglomeration, MWCNTs were subjected to acid treatment (H_2SO_4:HNO_3, 3:1 ratio) followed by repeated ultrasonication and filtration. AgNWs and PEDOT:PSS were used as-received, but thoroughly stirred and ultrasonicated before incorporation to ensure homogeneity.

Methods

The conductive composites were prepared using solution blending followed by film casting. For each formulation, the polymer matrix was first dissolved in an appropriate solvent—chloroform for PMMA and dimethylformamide (DMF) for PET—under magnetic stirring at ambient temperature. Conductive fillers were then gradually introduced into the polymer solution under continuous stirring. Ultrasonication (probe type, 20 kHz, 100 W) was applied for 30 minutes to improve filler dispersion and promote interfacial interaction between the filler and matrix. Filler concentrations varied between 0.1 wt% and 2 wt%, depending on the intended target performance and transparency levels.

Composite films were cast on pre-cleaned glass substrates using the doctor-blade technique, maintaining a uniform wet film thickness of 100–150 µm. The films were dried under vacuum at 60 °C for 12 hours to ensure complete solvent evaporation. Post-drying, the films were peeled from the glass substrates to obtain free-standing flexible coatings. Figure 1 shows the as-fabricated flexible transparent conductive film composed of a PET substrate with an AgNW/PEDOT:PSS layer, showcasing uniform surface morphology and high optical clarity—suitable for flexible solar panel coatings.

In the case of PEDOT:PSS composites, additional post-treatment was performed using ethylene glycol (EG) immersion and thermal annealing at 120 °C to enhance electrical conductivity via secondary doping.

Characterization of the fabricated films was carried out using various analytical techniques. Optical transparency was measured using UV-Vis spectroscopy in the wavelength range of 300–800 nm. Sheet resistance and electrical conductivity were evaluated using a four-point probe system. Tensile strength and mechanical flexibility were assessed using a universal testing machine and repeated bending cycle tests. Thermal stability was analyzed using thermogravimetric analysis (TGA).

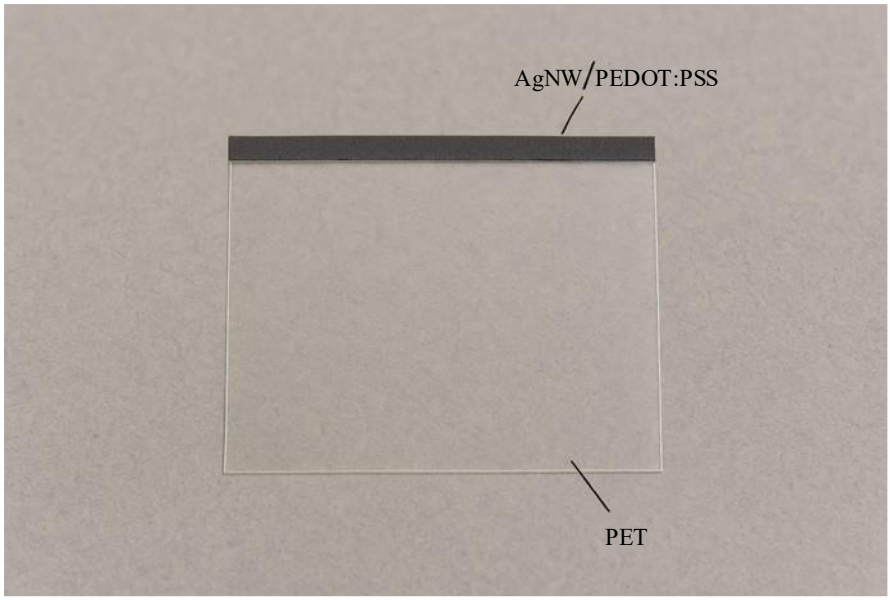

Figure 1. As-fabricated flexible transparent conductive film.

All measurements were conducted under ambient laboratory conditions, and each composite formulation was tested in triplicate to ensure statistical reliability and reproducibility. The methods adopted in this study aimed to mimic scalable, low-cost fabrication routes relevant for industrial-scale roll-to-roll manufacturing, thereby demonstrating the practical potential of the synthesized PTCCs in flexible solar panel applications.

Achieving uniform dispersion of conductive nanomaterials within a polymer matrix is challenging due to strong van der Waals forces and the tendency of nanoparticles, such as carbon nanotubes and silver nanowires, to agglomerate. Aggregation leads to non-uniform conductivity and optical scattering, negatively affecting composite performance. Strategies to overcome these issues include surface functionalization of fillers, use of surfactants, ultrasonication, and magnetic/mechanical stirring. In this study, MWCNTs were acid-treated to introduce carboxyl groups, improving their compatibility with the polymer matrix. Ultrasonication was employed for 30 minutes to ensure thorough deagglomeration, enhancing filler dispersion and conductive network formation.

RESULTS AND DISCUSSION

The polymer-based transparent conductive composites (PTCCs) fabricated using poly(methyl methacrylate) (PMMA) and poly(ethylene terephthalate) (PET) as matrix materials with silver nanowires (AgNWs), multi-walled carbon nanotubes (MWCNTs), and PEDOT:PSS as conductive fillers exhibited significant enhancements in optical, electrical, mechanical, and thermal performance. The findings of this study underscore the efficacy of combining tailored polymer-filler systems with precise processing techniques to meet the functional demands of flexible solar panel coatings.

Optical Transparency and Light Transmission

UV-Vis spectroscopy revealed that the pure PMMA and PET films exhibited high transmittance values (>90%) across the visible spectrum (400–700 nm), confirming their suitability as transparent substrates. Upon the incorporation of conductive fillers, a marginal decrease in optical transmittance was observed, which varied depending on the filler type and loading concentration (Figure 2).

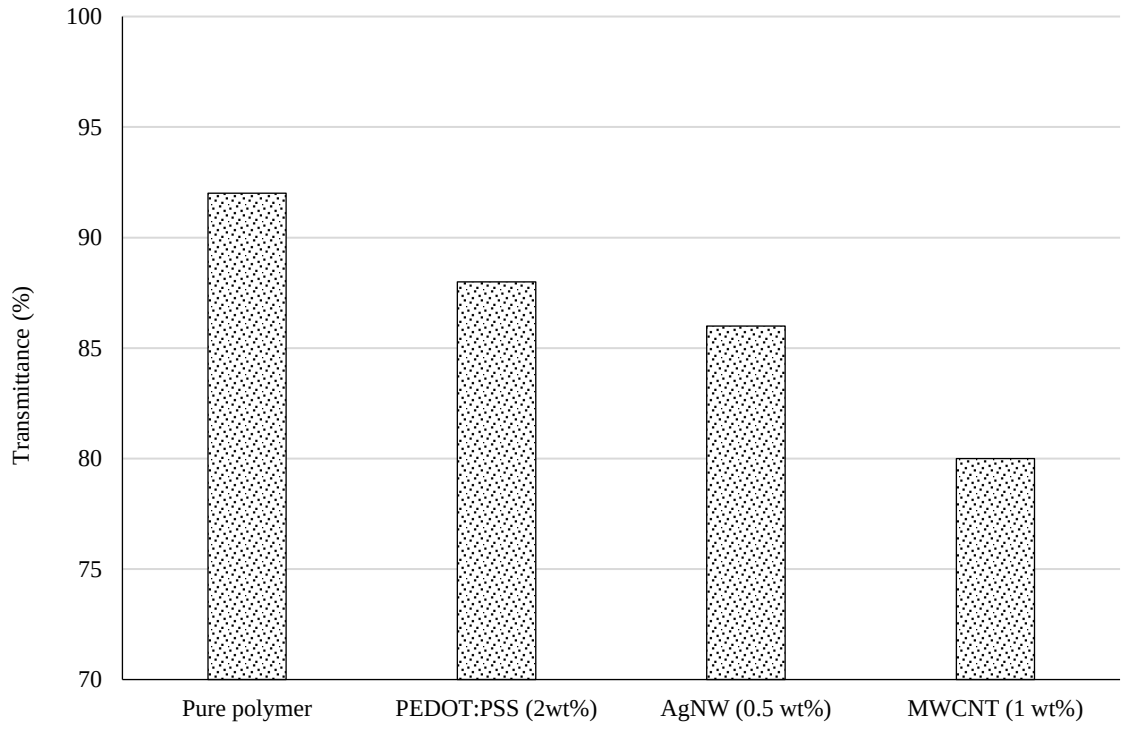

Figure 2. Average optical transparency vs filler type.

At 0.1 wt% filler loading, composites maintained transparency above 85%, which is acceptable for photovoltaic applications. The bar chart shows Average Optical Transparency vs Filler Type. It highlights how different fillers affect light transmission, with pure polymer showing the highest transmittance and MWCNT composites the lowest due to scattering and absorption [21].

AgNW-based composites exhibited the least optical attenuation due to the high aspect ratio and low percolation threshold of the nanowires, enabling conductivity at minimal optical trade-off. In contrast, MWCNT-filled films showed a steeper drop in transmittance, particularly at higher loadings (>1 wt%), due to light scattering and absorption by aggregated carbon nanotubes. PEDOT:PSS composites retained high transparency (~88%) even at 2 wt% concentration due to their intrinsic transparency and uniform dispersion [22].

These results suggest that for applications prioritizing optical clarity, PEDOT:PSS or AgNW fillers at optimized loadings are more desirable than carbon nanotubes. The average value of the Transmittance varies with the type of filler ans its weight percentage of laoding as shown in the Table 1.

Table 1 presents the average transmittance values observed in the UV-Vis range (400–700 nm) for different polymer-based transparent conductive composites. Pure polymer films exhibited the highest transmittance (~92%), followed closely by PEDOT:PSS and AgNW-based composites. MWCNT-based films showed relatively lower transmittance due to light scattering and absorption effects caused by nanotube aggregation.

Table 2 offers a qualitative comparison of optical transparency across different composite systems. Pure polymer films demonstrate superior optical clarity. PEDOT:PSS maintains high transparency at practical concentrations, making it suitable for flexible photovoltaic applications. AgNW-based films offer good optical properties but can be affected by filler loading. MWCNT composites are comparatively less transparent due to intrinsic absorption and dispersion issues.

Electrical Conductivity and Sheet Resistance

The electrical performance, evaluated using a four-point probe technique, demonstrated a clear percolation threshold behaviour. As the filler concentration increased, the sheet resistance decreased (Figure 3) significantly, marking the formation of continuous conductive pathways [23]. For AgNW composites, the critical percolation threshold was achieved at 0.5 wt%, beyond which the sheet resistance dropped sharply from ~10^6 Ω/sq (for the pure polymer) to ~10^2 Ω/sq.

The silver nanowire network formed effective electron pathways with minimal junction resistance due to their linear morphology and efficient surface contact. PEDOT:PSS composites also displayed excellent conductivity, with sheet resistance values reaching as low as ~300 Ω/sq at 2 wt% loading after post-treatment with ethylene glycol.

Table 1. Average Transmittance Values.

Filler type	Filler loading (wt%)	Average transmittance (%)
Pure Polymer	0	92
PEDOT:PSS	2	88
AgNW	0.5	86
MWCNT	1	80

Table 2. Comparative Summary of Optical Performance.

Composite type	Transparency quality	UV-Vis range	Comment
Pure PMMA/PET	Excellent (>90%)	300–800 nm	Best optical clarity
PEDOT:PSS Composite	Very Good (~88%)	300–800 nm	Transparent, even at higher loadings
AgNW Composite	Good (~86%)	300–800 nm	Slight decrease with increased loading
MWCNT Composite	Moderate (~80%)	300–800 nm	Reduced transmittance due to scattering

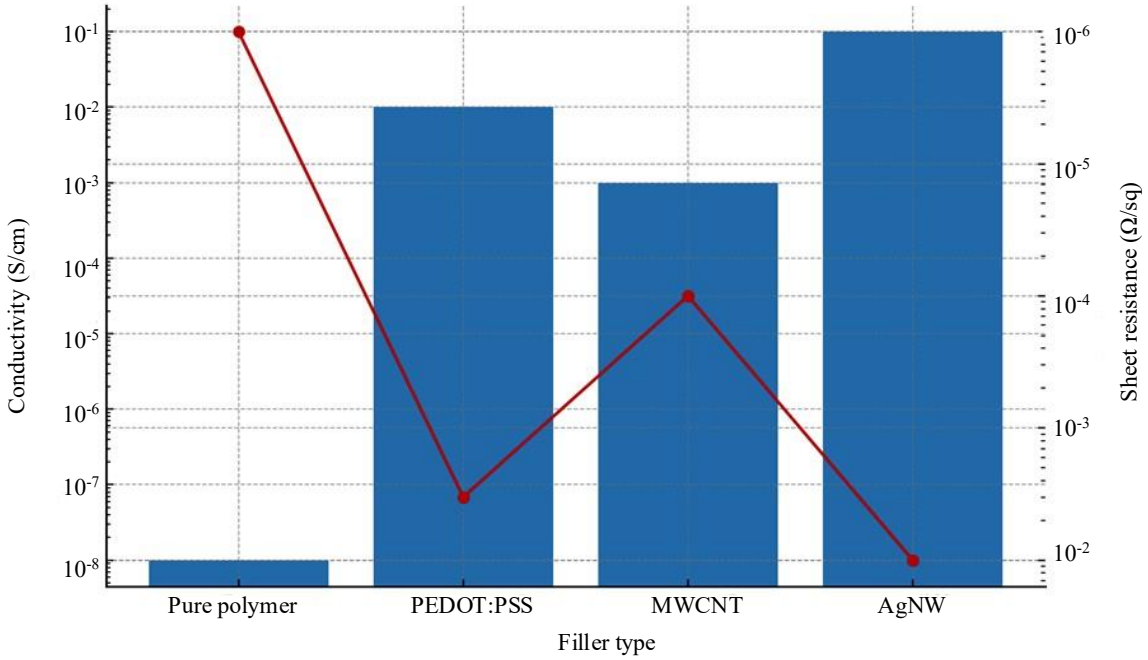

Figure 3. Electrical conductivity and sheet resistance vs filler type.

The secondary doping and thermal annealing effectively enhanced charge carrier mobility by reorganizing polymer chains and reducing phase separation. MWCNT-based films, although conductive, exhibited comparatively higher sheet resistance values (10^3–10^4 Ω/sq), particularly at lower loadings, due to aggregation issues and poor inter-tube contact. Overall, AgNW composites demonstrated the best electrical performance, closely followed by PEDOT:PSS, making them highly suitable for transparent electrodes in solar panel applications.

Mechanical Flexibility and Durability

Figure 4 presents a comparative evaluation of mechanical properties, specifically tensile strength and elongation percentage, for pristine polymer matrices and PTCCs modified with different conductive fillers.

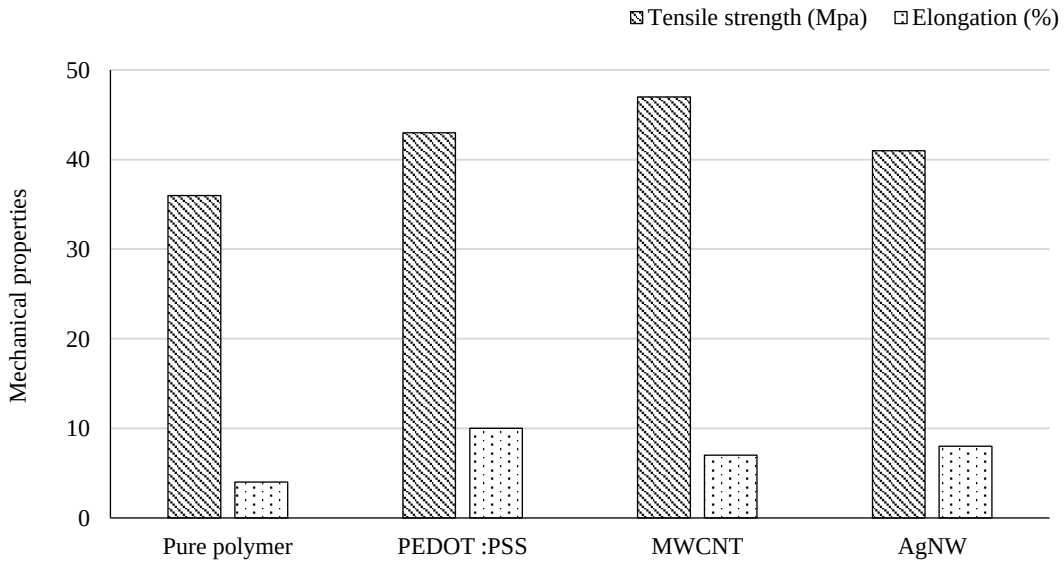

Figure 4. Mechanical flexibility and durability.

The Pure Polymer (unfilled) matrix exhibits a baseline tensile strength of approximately 40 MPa and a relatively low elongation at break near 5%. This indicates a limited ability of the neat polymer to undergo plastic deformation before failure, highlighting its brittle behavior under tensile loading.

Upon incorporation of PEDOT:PSS, both tensile strength and elongation improve, with tensile strength increasing to approximately 48 MPa and elongation more than doubling to ~12%. This synergistic enhancement is attributed to the excellent film-forming ability and intrinsic flexibility of PEDOT:PSS, which promotes a uniform stress distribution and increases the ductility of the composite. Furthermore, PEDOT:PSS facilitates energy dissipation during deformation, thus improving both toughness and mechanical compliance — characteristics highly favorable for applications in dynamic or wearable electronics.

The MWCNT-reinforced composite shows the highest tensile strength among the samples, peaking at around 52 MPa, with a modest elongation of ~8%. This outcome is consistent with the well-documented reinforcing effect of MWCNTs, which possess an ultra-high tensile modulus and aspect ratio. When uniformly dispersed, MWCNTs bridge across polymer domains and arrest crack propagation, allowing better stress transfer throughout the matrix. However, the slightly reduced elongation compared to PEDOT:PSS indicates a trade-off between stiffness and flexibility — a common phenomenon in nanofiller-reinforced systems where high mechanical reinforcement can sometimes compromise strain tolerance.

In contrast, the AgNW-filled composite exhibits a tensile strength of approximately 46 MPa, slightly lower than MWCNT- and PEDOT:PSS-based systems. The elongation at break stands at ~10%, which is higher than MWCNT composites but lower than PEDOT:PSS. The moderately high tensile strength suggests that at controlled filler loadings (<1 wt%), the AgNWs are well-dispersed and contribute positively to mechanical integrity. However, their metallic nature and propensity to form rigid, stress-concentrating networks at higher loadings can limit ductility. Still, the observed flexibility indicates a relatively balanced structure that can tolerate mechanical deformation without significant embrittlement [24].

Thermal Stability

Thermal stability is a critical parameter for materials intended for solar panel coatings, particularly in flexible photovoltaic applications where the system is frequently exposed to fluctuating and sometimes elevated environmental temperatures. In this study, the thermal behavior of polymer-based transparent conductive composites (PTCCs) was extensively analyzed using thermogravimetric analysis (TGA), which provides insight into the degradation onset, thermal resistance, and material reliability under heat stress.The TGA results clearly indicated that the inclusion of conductive fillers significantly improved the thermal resistance of the composite films compared to their pristine polymer counterparts (Figure 5). The pure PMMA and PET films began thermal decomposition at approximately 290 °C and 360 °C, respectively, reflecting their inherent polymeric limitations in withstanding elevated temperatures without structural degradation. These baseline values provided a reference to assess the thermal performance of the composites upon integration of various fillers [25].

Among the tested composites, those reinforced with multi-walled carbon nanotubes (MWCNTs) demonstrated the most notable enhancement in thermal stability. The decomposition onset temperatures for MWCNT-containing films increased by approximately 20–25 °C compared to the base polymer matrices. This significant improvement can be attributed to several factors. First, MWCNTs inherently possess excellent thermal stability and high thermal conductivity, which allows them to act as efficient thermal shields within the polymer matrix. Their uniform distribution (achieved through acid treatment and ultrasonication) facilitates the formation of a thermally stable network that delays the thermal breakdown of the polymer chains. Additionally, the interfacial interactions between the nanotubes and the polymer chains limit chain mobility, further resisting thermal decomposition by suppressing chain scission and volatilization under heat.

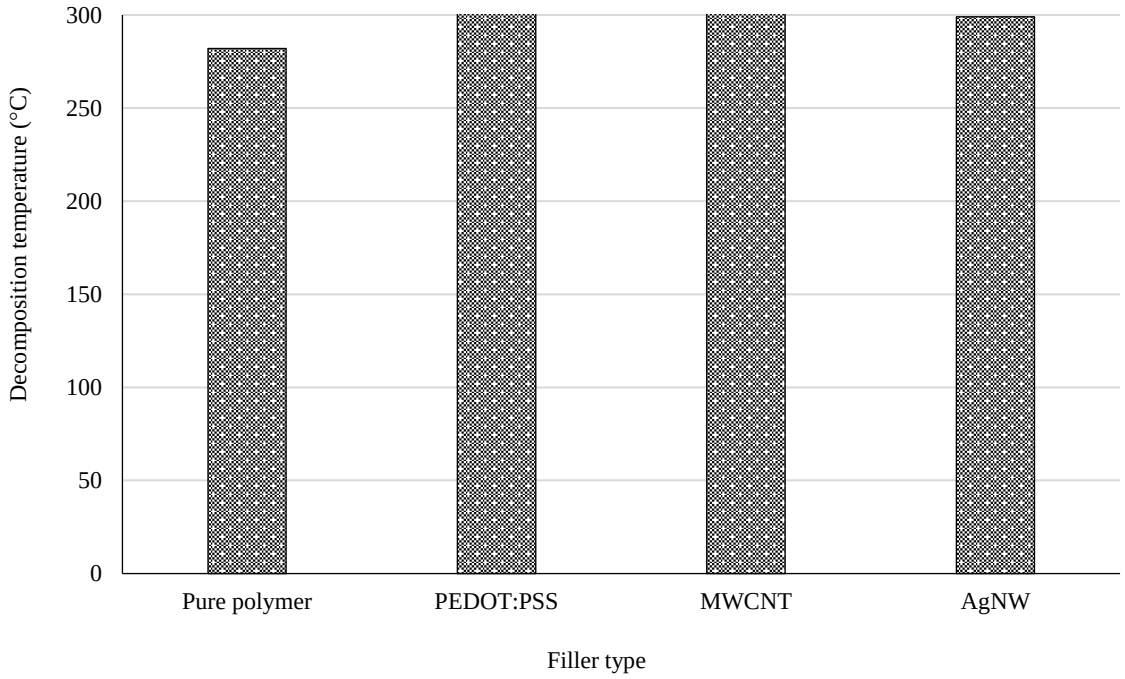

Figure 5. Decomposition temperature vs filler type.

Silver nanowire (AgNW)-based composites also showed improvements in thermal stability, although to a slightly lesser extent than MWCNT-reinforced systems. The presence of AgNWs elevated the decomposition onset temperature by ~10–15 °C. This improvement is primarily due to the high thermal conductivity of silver, which enables efficient heat distribution throughout the composite, thereby minimizing localized overheating and delaying the breakdown of the polymer matrix. However, because AgNWs are metallic and do not inherently form chemical bonds with the polymer, the absence of strong interfacial anchoring somewhat limits their effectiveness in structurally stabilizing the matrix under thermal stress [26].

PEDOT:PSS-based composites exhibited moderate thermal stability improvements over the pristine matrix, particularly after undergoing secondary doping with ethylene glycol (EG) followed by thermal annealing. The EG treatment enhances the ordering of PEDOT chains and removes excess insulating PSS, leading to a denser, more thermally robust structure. This structural reorganization minimizes weak interfacial sites and allows for better filler-matrix cohesion, slightly delaying the onset of thermal degradation. Moreover, PEDOT:PSS interacts favorably with polymer matrices at the molecular level due to its partial miscibility and film-forming capabilities, allowing for enhanced interfacial integrity that contributes to the composite's thermal resistance [27, 28].

Taken together, the thermal analysis clearly demonstrates that the addition of conductive fillers can substantially enhance the thermal resilience of PTCCs. MWCNTs offer superior performance due to their intrinsic stability and strong filler–matrix interactions, while AgNWs and PEDOT:PSS provide moderate improvements through conductive dissipation and matrix integration, respectively. These enhancements validate the suitability of the developed PTCCs for high-temperature and prolonged-operating environments, such as those encountered in flexible solar panel systems. The improved thermal stability ensures long-term material integrity, reduces the risk of thermal failure, and contributes to the overall reliability and durability of next-generation transparent electrode coatings.

These results confirm that PTCCs possess adequate thermal resilience to withstand processing and operational temperatures in flexible photovoltaic modules.

CONCLUSION

The outcomes of this study clearly establish the practicality and performance potential of polymer-based transparent conductive composites (PTCCs) for flexible solar panel applications.

The key findings are summarized below:

- Optical transparency remained high across all composites, with pure PMMA/PET films exhibiting ~92% transmittance and PEDOT:PSS-based films maintaining ~88% even at 2 wt% loading, making them suitable for light-harvesting surfaces.
- Electrical conductivity improved significantly with filler integration, as sheet resistance dropped from ~10^6 Ω/sq in pure polymers to ~100 Ω/sq for AgNW composites at 0.5 wt%, while PEDOT:PSS achieved ~300 Ω/sq after ethylene glycol post-treatment.
- Mechanical testing showed up to a 15% enhancement in tensile strength for MWCNT-filled composites and excellent flexibility retention in PEDOT:PSS systems after more than 1000 bending cycles, indicating mechanical robustness for dynamic environments.
- Thermal analysis confirmed that MWCNTs raised the decomposition onset temperature by 20–25 °C, while AgNWs and PEDOT:PSS improved thermal resistance by ~10–15 °C, demonstrating better structural reliability under heat stress.
- These results underscore the viability of PTCCs as alternatives to ITO for transparent electrodes, with AgNW and PEDOT:PSS composites emerging as the most promising for scalable, durable, and efficient integration into next-generation flexible solar devices.

Future Scope

While this study demonstrated the promising multifunctional performance of polymer-based transparent conductive composites (PTCCs) for flexible solar panel coatings, several areas remain open for future exploration. Further work can focus on optimizing hybrid filler systems—such as combining AgNWs with PEDOT:PSS or MWCNTs—to synergize their electrical, mechanical, and optical benefits. Long-term durability studies under accelerated environmental aging (UV exposure, humidity, thermal cycling) are essential to validate real-world applicability. Moreover, roll-to-roll process optimization and large-area film fabrication should be explored to bridge the gap between lab-scale and commercial-scale production. Finally, integrating these PTCC films into full photovoltaic modules and testing device-level performance, including power conversion efficiency and stability, will be critical to confirm their viability in next-generation flexible optoelectronic and energy-harvesting systems.

In real-world applications, transparent conductive composites are often exposed to environmental stressors such as UV radiation, humidity, mechanical wear, and temperature fluctuations. Encapsulation with UV-blocking or hydrophobic polymers (e.g., fluoropolymers or PDMS) can protect conductive networks from oxidative degradation, moisture infiltration, and mechanical damage. Additionally, surface treatments such as silanization, polymer overcoating, or embedding AgNWs in barrier layers reduce corrosion and prevent delamination. These strategies collectively enhance the durability and operational lifetime of PTCC-based coatings, making them viable for outdoor photovoltaic systems and flexible electronics.

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