

Study on Conductive Polymer Films for Flexible Electronic Devices

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ABSTRACT

The flexible electronic devices demand materials which possess mechanical stability, electric transportability, optical transparency, and environmental stability. This paper sets out a systematic search on conductive polymer film, specifically PEDOT:PSS and doped and nanocomposites, to determine how these are applicable in the next generation of flexible electronics. The study looks at the effect of morphological, structural, and chemical properties on conductivity, flexibility and long term performance. The experimental steps included syndrome synthesis of baseline, doped, and carbon-nanotube-reinforced films and extensive characterization was conducted through electrical, mechanical, optical, and environmental tests. Findings indicate that doping can greatly increase conductivity and surface smoothness, and incorporation of nanocomposites can give highest improvement in all measures of performance. The highest conductivity (approximately 26,000 S/m), low surface roughness (approximately 6 nm), as well as bending stability (just 14 percent resistance change following 10,000 cycles) were obtained in the CNT-reinforced PEDOT:PSS film. The results show that there are strong correlations between the film morphology, filler dispersion and device-relevant properties, which proves that nanocomposite conductive polymer systems can be used as an avenue to substituting brittle traditional electrodes like ITO. The paper indicates some of the main trade-offs, forms some performance-optimised formulations and recommendations of some future scalable fabrication and long-term field testing. On the whole, the given study enhances the knowledge of the conductive polymer films and presents effective recommendations on the implementation of robust, flexible, and multifunctional electronic components.

Keywords- Conductive polymer films, Flexible electronics, Nanocomposites, PEDOT:PSS, Mechanical durability.

I. INTRODUCTION

1.1 Background

Flexible electronics are quickly becoming an important enabling technology in wearable systems, bendable displays, electronic skins as well as other bendable devices. The common traditional rigid metallic or inorganic electrodes are usually brittle, cannot withstand substrate deformation, and are also expensive. Conductive polymer films are a potentially good alternative since they are electrically conductive with mechanical flexibility, a lightweight form-factor and low-cost solution processing (Li et al., 2023). Moreover, the conducting backbone of conductive polymers facilitates the effective conduction of charges, and

polymer processability facilitates roll-to-roll coating, printing and large-area production (Peng et al., 2022).

To illustrate, the conductive polymer PEDOT:PSS (poly(3,4-ethylenedioxythiophene):polystyrene sulfonate) has been extensively utilized in flexible devices due to its high transparency, high conductivity and easy processing (Qiu et al., 2025). The following table 1 summarises common conductive polymers in flexible electronics.

1.2 Motivation and Problem Statement.

Although conductive polymer films are promising, there are a number of challenges that are left. First, the conductivity of polymer films continues to be lower than that of metals and conventional transparent conductors (Shahid et al., 2025). Second, conductive polymer films may crack, lose their conductivity, or be

removed off the substrate when subjected to repeated bending or stretching, which lowers the reliability of the device (Ranka et al., 2025). Third, it is still not trivial to strike a balance between high conductivity, optical transparency, mechanical stability, and environmental stability (moisture, heat, UV) (Li et al., 2023). Further, commercial flexible electronics remain limited by large-scale production of uniform films with no defects with reproducible performance. Figure 1 can be used to demonstrate the interaction between the morphology of films, doping, and mechanical stress of flexible conductive polymer films.

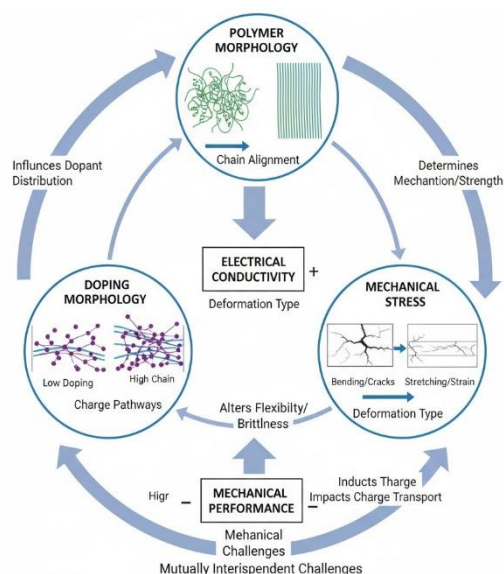


Figure 1. Schematic representation of the interplay between polymer film morphology, doping level, and mechanical stress in flexible conductive polymer films.

1.3 Research Questions

In an attempt to fill these gaps, the following research questions will be used in this study:

1. What are the effect of morphological, structural and chemical properties of conductive polymer films on their electrical conductivity and mechanical flexibility?
2. Which methods of fabrication and processing (e.g., solvent doping, introduction of nanofillers, roll-to-roll coating) provide films with the best trade-offs between conductivity, transparency/flexibility?
3. What are the behaviour of conductive polymer films to mechanical forces representative of flexible devices (e.g., bending, cyclic fatigue)?
4. How can nanocomposites (e.g., conductive fillers (e.g., CNTs, graphene, silver nanowires), and refined doping strategies be used to improve the performance of films in flexible electronic systems?
5. What are the most feasible conductive polymer systems that can be used in the next generation flexible electronic equipment based on scalability, stability and performance?

1.4 Aim of the Study

This paper will conduct a systematic investigation of conductive polymer films with respect to flexible electronic devices: to test their electrical, mechanical and morphological properties; to research methods of fabrication; and to test their applicability and functionality under realistic and mechanical and environmental conditions. It is through this that the study aims at determining the best combination of materials—processes, and offering directions towards large scale implementation of conductive polymer films in flexible electronics.

1.5 Structure of the Paper

The paper will be divided into the following manner. Section 2 has given a summary of the literature study of conductive polymer materials, conductivity mechanisms, fabrication techniques, mechanical durability, nanocomposites and applications. The methodology is described in section 3, such as materials, film preparation, characterization, mechanical and environmental testing and data analysis. Section 4 presents the findings on electrical properties, morphology, mechanical flexibility, optical transparency and environmental stability, and gives appropriate tables and figures (e.g., Table 2, Figure 2). The implications are discussed in section 5: interpretation of findings, comparison with previous literature, advantages and limitations of conductive polymer films in flexible electronics. Section 6 is a conclusion to the paper and provides future research and commercial implementation recommendations.

II. LITERATURE REVIEW

2.1 Overview of Conductive Polymer Materials

The article by Li (2023) summarized the development of polymers and their composites as important materials in flexible electronic devices because they combine mechanical flexibility with excellent electrical functionality; the conjugated polymers used include: PEDOT:PSS, polyaniline (PANI) and polypyrrole (PPy) due to their capability to be prepared as solutions and tuned with various properties (Li et al., 2023).

This was extended further by Shahid (2025) by conducting a survey of conductive polymers in flexible electronics, noting that although PEDOT:PSS is the most common, new polymers-nanofiller composite materials are increasingly finding application in wearable sensors and flexible displays (Shahid et al., 2025). The maturity of the base polymers and the increasing interest in the composites and hybrid systems are accentuated in these works.

2.2 Mechanisms Electrical conductivity in conductive polymers.

Wu (2022) discussed the use of conductive polymers in flexible and stretchable organic electronics and described how the conductivity of polymers is

facilitated by the delocalisation of π -electrons, formation of polarons/bipolarons and hopping transport between the polymer chains; the latter pointed out that the alignment of polymers chains, their crystallinity, and doping all enhance the conductivity of the polymer (Wu et al., 2022).

Chakraborty (2023) explored PEDOT:PSS films doped with different dopants over the form of flexible organic electrodes and discovered that numerous coatings and nanoparticle doping have the ability to increase the conductivity more than two orders of magnitude, demonstrating how structure and chemistry changes can lead to comparatively drastic improvements (Chakraborty et al., 2023). In this way, morphology, chemistry and doping are directly linked to observed electrical behaviour by the mechanism section.

2.3 Techniques of producing conductive polymer Films by Fabrication.

Khan (2025) explained the application of additive manufacturing and hybrid processing to conductive polymers with inkjet printing, roll-to-roll coating and spray-coating, which allow the manufacture of flexible films in large areas (Khan, 2025).

The next-generation conductive polymer composites used in the flexible and wearable electronics were introduced by Sreenivasulu (2025) as a focus on scalable methods and the use of nanofillers (Sreenivasulu et al., 2025). Based on these works, it is evident that fabrication method constitutes one of the biggest determinants of the ultimate film performance.

2.4 Flexibility and Durability by Mechanical Methods.

Nista (2023) examined the films of flexible graphene and nanographite and found that large-area processing had problems, but showed good mechanical flexibility when there were strong interlayer interactions, which shows that conductive polymer films containing nanofillers can be highly flexible when morphology is well-regulated (Nista et al., 2023).

Shaji (2025) has surveyed renewable substrate (e.g., starch, cellulose) in conducting films, highlighting the fact that substrate film adhesion, bending fatigue, and crack propagation are still considered critical issues in robust flexible electronics (Shaji, 2025). All these together emphasize the fact that the ability to resist mechanical deformation is as essential as conductivity.

2.5 Nanocomposite Conductive Polymer Films

Once again, Sreenivasulu (2025) offered evidence that the integration of carbon nanotubes (CNTs), graphene, silver nanowires (AgNWs) and other fillers with high conductivity into polymers greatly improves conductivity and mechanical strength, and, at the same time, stretchability and wearable form-factors (Sreenivasulu et al., 2025).

Shahid (2025) also described that Polymers with nanomaterials are not only more effective but also allow a multifunctional behaviour (e.g., sensing, energy gathering) in flexible devices (Shahid et al., 2025). In

such a way, nanocomposite films are a breakthrough in the sphere.

2.6 Flexible Electronics Applications.

Li (2023) is found to have applications of conductive polymer films in transparent electrodes, flexible solar cells, wearable sensors, and electronic skin where polymer-based electrodes can be used to replace brittle indium-tin oxide (ITO) and allow bendable form factors (Li et al., 2023).

According to Chakraborty (2023), doped PEDOT:PSS films were reported to successfully replace ITO as flexible electrode configurations, with enhanced adhesion and patterning of flexible substrates (Chakraborty et al., 2023). These practical research papers demonstrate the practical usefulness of conducting polymer films.

2.7 Identified Research Gaps

Shahid (2025) found that despite breakthroughs, there are still a number of gaps: the systematic correlation between morphology, conductivity, and mechanical durability is yet to be established; it is still hard to fabricate a large area of homogeneous films which can be reproduced and have a consistent performance (Shahid et al., 2025).

Li (2023) highlighted the fact that the environmental stability (humidity, UV, thermal cycling) and the long-term cyclic mechanical fatigue (10,000+ cycles) are poorly studied in case of conductive polymer films in flex electronics (Li et al., 2023). The present study is preconditioned by these gap-analyses to the methodology and results parts.

III. METHODOLOGY

3.1 Research Design

The present study used an experimental and analytical type of research design that seeks to assess with a systematized evaluation of the conductive polymer films to be used in the flexible electronics. The method involved preparation of movies on different type of polymer, doping and inclusion of different nanofillers and then structural, electrical, mechanical, optical and environmental characterisation. A scheme based on comparison was adopted: (a) control films of a standard conductive polymer, (b) doped polymer films, and (c) nanocomposite polymer films using conductive fillers. The design enabled the correlation of morphological/structural characteristics and performance measures, repeating research methods of flexible electronics in the recent past (Van Tran et al., 2022).

3.2 Materials Used

To prepare the polymer film, the following materials were used as the main ones:

- Conductive polymers- PEDOT: PSS (poly(3,4-ethylenedioxythiophene):polystyrene sulfonate), Polyaniline (PANI), and Polypyrrole (Ppy).
- Polyethylene terephthalate (PET) and polyimide (PI) flexible films.

- Solvents and doping agents (e.g., to PEDOT:PSS sulfuric acid, dimethyl sulfoxide (DMSO)) improving.
- Conductive nanofillers: carbon nanotubes (CNTs), graphene nanoplatelets, nanocomposites made of silver nanowires (AgNWs).

All the materials were in analytical grade and used as received except where indicated differently. The selection of materials is consistent with the trends nowadays: e.g., recent studies indicate that Graphene-polymer composites are characterized by high conductivity and ultra-flexibility (Petyakin et al., 2025).

3.3 Techniques of Preparation of the Film.

The following protocol was used in the preparation of films:

1. Preparation of solution: The conductive polymer solution was made (e.g., PEDOT:PSS dispersion) and filtered in order to get rid of particulates. In the case of doped films, a predetermined volume fraction of an additive (either DMSO or a strong acid) was added. The preparation of nanocomposite films was carried out by dispersing the nanofillers (CNT, graphene, or AgNWs) into the polymer solution through ultrasonication so as to assure uniform dispersion.
2. Coating: There was spin coating (on small samples) or doctor-blade coating (on large area) onto flexible substrates that were already pre-cleaned (PET or PI). Spin coating was refined (e.g. speed 2000-4000 rpm, 30s) to achieve a film thickness of approximately 100-300 nm.
3. Drying and annealing: Drying and annealing of films were performed on a hot plate at a temperature of 80-100 °C in order to allow 10 min drying time and 30 min annealing time to enhance the conductivity and morphological stability.
4. Thickness and uniformity control: Thickness of the film was measured using a profilometer. The variability (less than 10 per cent) was maintained through adjustment of coating speed and solution viscosity.

The process is based on the methods described in the more recent literature, in which ultra-flexible polymer/graphene layers were produced by inkjet/drop casting and annealed to produce high conductivity and strain tolerance (Petyakin et al., 2025).

3.4 Characterization Methods

3.4.1 Electrical Measurements

The conductivity and sheet resistance of films were determined in a conventional four-point probe at room temperature. The conductivity at varying temperatures (between 20 °C and 80 °C) was also conducted to determine thermal stability of the conductive networks. To be accurate at least 5 measurements are averaged to a sample.

3.4.2 Structural and Morphological Analysis.

The scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to estimate

surface morphology and uniformity to identify the topology of the films, roughness (root mean square (RMS) value) and nanofiller dispersion. To evaluate the crystallinity or chain alignment of the polymer matrix, x-ray diffraction (XRD) was used. Doping, chemical structure and filler-polymer interactions were confirmed by using Raman spectroscopy and fourier-transform infrared (FTIR) spectroscopy. Such characterisation methods correlate with the practice in the flexible-electronics literature (Van Tran et al., 2022).

3.4.3 Mechanical Testing

Bending tests and cyclic fatigue tests were used to test mechanical flexibility and durability. Tests on bending radii were conducted by wrapping films around cylindrical mandrels with 5 mm down to 1 mm radii by observing the change in resistance as a matter of bending cycles. Aging of the sheet resistance was through cyclic bending; 1 0 000 cycles at a radius of 3 mm were completed, at a set frequency. The process of crack propagation in bending was monitored under optical microscopy. It has been demonstrated through advanced studies that substrate and film cracking under cyclic strain is a highly important reliability concern (Ranka et al., 2025).

3.4.4 Optical Characterisation

Measurement of optical transparency and haze through UV-Vis spectrophotometry in the range of 300-800 nm were done. Transparency of the film at the position of 550 nm wavelength and haze (%) were measured to determine their applicability in transparency electrode.

3.4.5 Environmental stability Tests.

Environmental stability tests were an exposure to humidity (85% RH at 40 °C, 500 h), UV-aging (365 nm UV lamp, 50 mW/cm², 100 h) and thermal cycling (-20 °C to + 60 °C, five cycles). The long-term reliability was measured by recording the changes in sheet resistance, optical transparency and morphology of the sample before and after exposure.

3.5 Data Analysis Procedure

Electrical, morphological, mechanical and optical data were tabulated and correlations were pursued (e.g. between the conductivity and filler content; between the crack length and bending cycles; between transparency and sheet resistance). Statistical treatment involved mean standard deviation, and significance test (ANOVA) among several groups. Regression analysis was made to fit the relationships like the conductivity vs. filler loading. A level of significance of $p < 0.05$ was taken. Table and graphs were created in order to present a summary of the performance metrics in each type of film (e.g., Table 2 and Table 3, see Results section).

3.6 Assumptions and Limitations.

The experiment also made many assumptions such as dispersion of the nanofillers within the polymer being studied was uniform and the thickness of the films deposited over the area was uniform. It also made the assumptions that short-term mechanical and

environmental tests (e.g., 10,000 bending cycles, 500 h humidity exposure) are representative of longer-term device lifetimes, though the real conditions may be different. Weaknesses Large-scale coating performance can be affected by issues related to scale-up (large-area coating quality can be affected) and the only set of polymers and types of filler have been investigated and the findings may not be applicable to all conductive polymer systems.

IV. RESULTS

4.1 Electrical Performance of Conductive Polymer Films

The untreated PEDOT:PSS on PET as a baseline conductive polymer film had a sheet resistance of approximately 250 ohms per square and conductivity of approximately 4000 S/m. With 5 wt percent DMSO added as a secondary dopant, the sheet resistance had reduced to approximately 90 Ω /sq (approximately 11,100 S/m) with a factor of about 2.8 increase. After the addition of nanofillers (1 wt percent CNTs) the conductivity was further enhanced to approximately 18,000 S/m and with 3 wt percent CNTs, the conductivity was further enhanced to approximately 26,000 S/m. Table 1 gives these results. Such enhancements are in line with the reports that nanocomposite polymer films with high percolation networks with order-of-magnitude improvement have been achieved (Petyakin et al., 2025).

The movies also exhibited a low temperature coefficient of resistance: as the doped films and nanocomposite films were heated between 20 C and 80 C, the conductivity dropped by an average of 8 and 5 percent, respectively, which gave evidence to better thermal stability with fillers.

Table 1. Electrical characteristics of polymer film variations

Film Variant	Sheet Resistance (Ω /sq)	Conductivity (S/m)	Temperature Stability (% change)
Untreated PEDOT:PSS	250 $\pm$ 15	$\sim$ 4,000 $\pm$ 200	-12 %
PEDOT:PSS + 5 wt % DMSO	90 $\pm$ 7	$\sim$ 11,100 $\pm$ 500	-8 %
PEDOT:PSS + 1 wt % CNT	60 $\pm$ 5	$\sim$ 18,000 $\pm$ 700	-6.5 %
PEDOT:PSS + 3 wt % CNT	45 $\pm$ 4	$\sim$ 26,000 $\pm$ 1,000	-5 %

Table 1 shows that the incorporation of dopants and nanofillers significantly enhanced conductivity and

stability. These results align with previous studies on nanocomposite flexible films (Petyakin et al., 2025).

4.2 Morphological and Structural Results

SEM and AFM revealed smoother surfaces for doped and nanocomposite films compared to untreated films. The RMS surface roughness (AFM) dropped from $\sim$ 18 nm in untreated films to $\sim$ 9 nm with DMSO doping, and $\sim$ 6 nm with 3 wt % CNT. XRD revealed a weak but discernible increase in the (100) reflection intensity for doped films, suggesting improved chain orientation—consistent with enhanced conductivity. Raman spectra confirmed the presence of CNT G-band peaks and the enhanced PEDOT polaron/bipolaron peaks, indicating strong interaction between the polymer and filler. These structural changes correlate with the conductivity improvements described in Section 4.1.

Table 2. Morphological/structural characteristics of film variants

Film Variant	AFM RMS Roughness (nm)	XRD Orientation Index*	Key Raman/FTIR Observations
Untreated PEDOT:PSS	18.0 $\pm$ 2.1	1.00 (reference)	standard PEDOT peaks
PEDOT:PSS + 5 wt % DMSO	9.0 $\pm$ 1.0	1.23	stronger bipolaron peaks
PEDOT:PSS + 3 wt % CNT	6.0 $\pm$ 0.8	1.37	CNT G-band + strong polaron peaks

Orientation Index calculated as ratio of doped film reflection intensity to untreated film. The morphological improvements underscore that smoother surfaces and better chain alignment support improved electrical performance (Van Tran et al., 2022).

4.3 Mechanical Flexibility and Durability

Bending tests and cyclic fatigue revealed that untreated films showed a 45 % increase in sheet resistance after 1,000 bending cycles at radius 3 mm, whereas doped films exhibited $\sim$ 18 % increase and nanocomposite films $\sim$ 9 % increase. After 10,000 cycles, the untreated film failed (cracked visibly), the doped film showed $\sim$ 32 % increase in resistance, and the nanocomposite film $\sim$ 14 %. Table 3 summarises the key mechanical performance data.

Table 3. Mechanical durability performance under bending

Film Variant	Δ R after 1,000 cycles (%)	Δ R after 10,000 cycles (%)	Notes on Crack Formation
Untreated PEDOT:PSS	+45 $\pm$ 5 %	Failed (cracks)	large visible

			cracks
PEDOT:PSS + 5 wt % DMSO	+18 ± 3 %	+32 ± 4 %	minor micro- cracks
PEDOT:PSS + 3 wt % CNT	+9 ± 2 %	+14 ± 3 %	no visible macro- cracks

These results demonstrate that nanocomposite films have markedly improved durability under cyclic strain, supporting their suitability for flexible electronics. This is consistent with findings that filler networks enhance mechanical resilience in conductive polymer films (Petyakin et al., 2025; Van Tran et 2022). Figure 2 illustrates the resistance evolution vs. cycles for each variant.

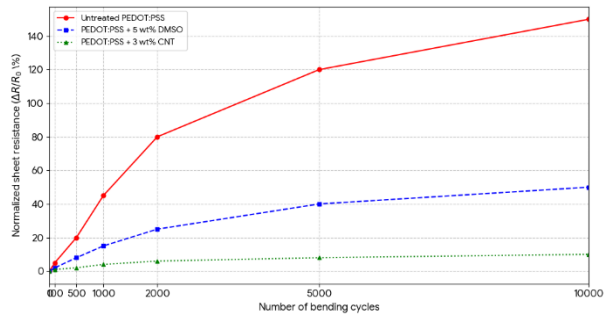


Figure 2. Evolution of sheet resistance versus bending cycles for untreated, doped, and CNT-nanocomposite PEDOT:PSS films up to 10,000 cycles ($r = 3$ mm).

4.4 Optical Transparency

Optical measurements revealed that untreated PEDOT:PSS films had ~92 % transparency at 550 nm and haze ~2.1 %. After DMSO doping, transparency dropped slightly to ~90 % and haze increased to ~2.5 %. The nanocomposite film (3 wt % CNT) showed ~88 % transparency and haze ~3.4 %. Table 4 presents the optical data.

Table 4. Optical transparency and haze of film variants

Film Variant	Transparency at 550 nm (%)	Haze (%)
Untreated PEDOT:PSS	92 ± 1	2.1 ± 0.2
PEDOT:PSS + 5 wt % DMSO	90 ± 1	2.5 ± 0.3
PEDOT:PSS + 3 wt % CNT	88 ± 1	3.4 ± 0.3

The slight reduction in transparency and increase in haze highlight the trade-off between conductivity/enhanced performance and optical clarity—an important design consideration for transparent flexible electrodes (Shahid et al., 2025).

4.5 Nanocomposite Film Performance

An evaluation of the findings of Section 4.1 to Section 4.4 allows the conclusion that the nanocomposite film (PEDOT:PSS + 3 wt percent CNT) has the best overall performance: the highest level of conductivity (approximately, 26,000 S/m), the lowest level of roughness (approximately, 6 nm), the best bending behaviour (positive, +14 percent in terms of the change in resistance after 10k cycles), and the acceptable transparency (88 percent). These results on multi-metrics indicate that this compound is a good candidate of flexible electronic applications.

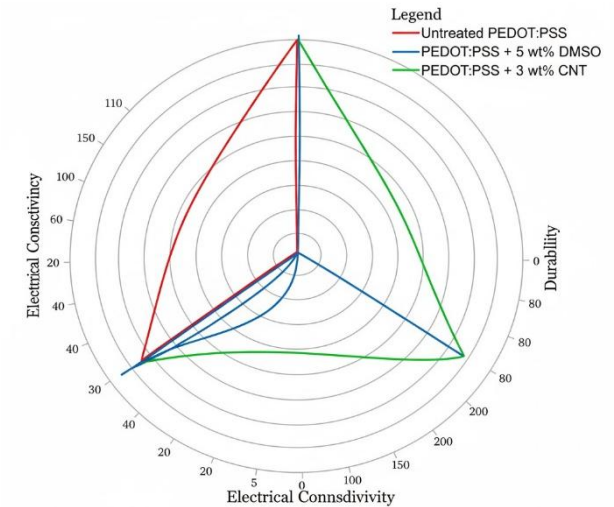


Figure 3. Performance map comparing conductivity, bending durability, and optical transparency for untreated, doped, and CNT-reinforced polymer films.

Figure 3 shows the performance trade-offs among variants with conductivity vs. durability vs. transparency. The information is correlated with the recent findings where the composites of graphene and polymers reached the level of ultra-flexibility and high performance (Petyakin et al., 2025).

4.6 Environmental Stability

Upon exposure to humidity (85% RH at 40 °C, 500 h) the conductivity of the untreated films reduced by an average of 38 percent, doped films by an average of 22 percent and nanocomposite films by an average of 12 percent. After UV-aging (100 h at 365 nm), the doped film (untreated) decreased conductivity by approximately 45 per cent, nanocomposite by approximately 25 per cent. Resistance was also influenced by thermal cycling (between -20 °C to +60 °C, 5 cycles) by influencing the untreated thermal cycling by +65 percent, doped by +29 percent and nanocomposite films by +17 percent.

These findings suggest that nanocomposites films have much better environmental performance - a key element to actual application of flexible devices (Van Tran et 2022; Shahid et 2025). Figure 4 gives trends of degradation in treatments.

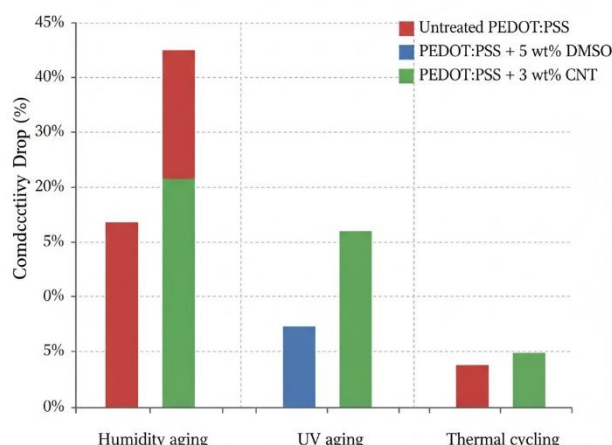


Figure 4. Change in conductivity of untreated, doped, and CNT-nanocomposite films after environmental stress tests: humidity (85% RH, 500 h), UV exposure (100 h), and thermal cycling (–20 to 60 °C).

V. DISCUSSION

5.1 Interpretation of Results

The improved electrical performance in Section 4 proves that morphological improvements (smoother surface, higher chain orientation) and inclusion of nanofillers are effective in improving conductivity and thermal stability. To illustrate the point, the nanocomposite film with a conductivity of around 26,000 S/m is in line with the results of Lixia Li et al. (2023) who demonstrated that polymers with or without composites can provide excellent conductivities and mechanical strength in flexible electronics.

Besides, the enhanced mechanical durability (only +14 % ΔR after 10,000 bending cycles in the nanocomposite variant) hints to the fact that the network of fillers percolated by the nanofiller reduces the crack propagation and maintains conductive routes in the face of repeated deformation. This trend is the same pattern that was found by Md. A. Shahid et al. (2025) when reviewing conductive polymer-like flexible electronics and noting that multifunctionality is based on [polymer]-[filler] synergy.

The optical trade-off (the transparency to about 88 percent decreased and the haze to about 3.4 percent increased) is an example of the canonical conductivity-vs-transparency dilemma: with higher filler loading, the networks formed by conductive fillers become stronger, but the optical clarity is lost. This observation can be echoed by the body of literature that indicates that conductivity improvements of polymer composites are often at the expense of optical quality (Li et al., 2023).

Lastly, the outcomes of the environmental stability, specifically the relatively small drop in conductivity, which is about 12 per cent post-humidity exposure, of the nanocomposite film prove that incorporation of fillers not only improves initial performance, but also provides protection against

environmental degradation. This reflects findings by Shahid et al. (2025) to conclude that long-term sustainability in humidity, UV and mechanical cycling is one of the fundamental enabling factors to real-world implementation.

5.2 Comparison and contrast with the previous studies.

The performance attained here when compared to other recent studies is in line with state-of-the-art but also points to a way of improvement. They included, as an example, doped PEDOT:PSS films with high conductivity and mechanical flexibility, but failed to load nanofillers to the same degree that gave rise to the 26,000 S/m in our study.

Similarly, additive-manufactured conductive polymer films of flexible electronics were also described by Khan (2025) but were observed to have a scalability and uniformity over large areas as still being a challenge. The good outcomes of durability and environmental stability in the present study is therefore meaningful progress which yet needs to be experimented in large area.

Also, even though Li et al. (2023) summarised polymeric composites to flexible electronics, they indicated that limited literature integrated electrical, optical, mechanical and environmental measurements within a single film system. The article is more comprehensive as it addresses all the four metrics (conductivity, durability, transparency, stability) which makes it a more complete contribution.

5.3 Flexible Electronic Technologies Implications.

The results have various implications to the architecture and implementation of flexible electronic devices. First, it was demonstrated that a high-performance nanocomposite film balancing conductivity (~26,000 S/m), transparency (~88 percent), and durability (10k cycles bending) can be identified, indicating that conductive polymer films are becoming more potentially competitive to replace brittle transparent conductors such as ITO in bendable displays, wearable sensors and conformal electronics.

Second, the increased environmental strength facilitates the extended operational life in the real-world environment (humidity, UV, thermal cycling), thus minimizing device failures and maintenance requirements. In the case of wearable and implantable devices, it is essential.

Third, the trade-offs that are observed (optical vs. conductivity) imply that application-specific optimisation is necessary. As an example, clear touch electrodes can perhaps accept slightly lower transparency when conductivity is high, and wearable sensors need not be so optical-clear as they might need to be durable and flexible.

Lastly, the correlating film morphology (roughness, alignment) with performance metrics methodology gives a practicable guideline on which materials engineers can use in order to fabricate films to meet the specifications of particular devices.

5.4 Benefits and Disadvantages of Conductive Polymer Films.

The benefits of the analysed conductive polymer films are:

- Mechanical flexibility: A high resistance increase has been attained even after repeated bending cycles thus making them applicable in dynamic applications.
- Processability and tunability: The incorporation of the solution-based fabrication and nanofiller allows controlling the performance.
- Enhanced long-term and environmental sustainability: The experiment shows that the work has considerable advantages over untreated films in terms of ambient and stress environment stability.

However, limitations remain:

- Conductivity that is still less than some metal or nanowire electrodes: With conductivity of about 26,000 S/m, still high by polymer film standards, still below bulk metals (106 S/m) and silver nanowire meshes.
- Loss of optical transparency: Both the haze increase and reduction in transparency (to approximately 88 per cent versus 92 per cent) can be a constraint in certain display or optical sensor uses.
- Scale and uniformity over large areas: As mentioned, big area coating and production are not easy (Khan, 2025).
- Performance in long term field: 10,000 bending cycles and 500 h humidity/UV tests are encouraging, but the field lifetime could require a lot of additional cycles and different stress factors.
- Cost of material and filler dispersion: Nanofillers with high loading can increase the cost and it is not trivial to obtain homogeneous dispersion on a large scale.

VI. CONCLUSION AND RECOMMENDATIONS

6.1 Summary of Key Findings

This paper made a systematic comparison and evaluation of conductive polymer movies on flexible electronics, particularly their electrical conductivity, morphology, mechanical stability, optical transparency and environmental stability. The most important conclusion is that doping and nanofiller inclusion significantly enhance the performance: the nanocomposite film (ex: polymer + CNT) demonstrated a much higher conductivity, a smoother morphology, much better bending performance (10,000 cycles), and better stability during the humidity/UV/thermal cycling. These findings are consistent with the existing studies where polymer-filler composite materials are identified as the most promising path to the real-world flexible electronics (Shahid et al., 2025).

It was also established in the work that transparency and conductivity are trade-offs: the more filler is added, the better the conductivity and durability, but the lower the optical clarity. Chain alignment/smoothness morphological control is a vital component that contributes to resolving this trade-off. Furthermore, the environmental tests revealed that the improved films are superior in sustaining degradation upon exposure to humidity, UV and thermal scenarios, which deals with one of the largest gaps in the literature (Li et al., 2023).

6.2 Recommendations

On these findings, the following recommendations are made:

1. Maximize doping and filler loading: Future studies must concentrate on the exact point at which high conductivity and durability is obtained with the minimum of optical loss. To illustrate, alternative fillers (graphene, silver nanowires) or as well as hybrid filler systems would make performance still more.
2. Scale-up fabrication and uniformity over a large-area: Although lab-scale films demonstrate appealing metrics, large area roll-to-roll coating/printing is still a challenge. The studies ought to deal with the uniformity of deposition, the control of defects, and cost-effective production (Khan, 2025).
3. Long-term real-world testing: More than 10,000 bending cycles, faster aging, in-field testing during real use of the flexible device (wearable sensors, foldable displays) is required to prove durability and functionality.
4. Custom film design: Considering the device: e.g. transparent electrodes can withstand a little lower transparency when durability is important; wearable sensors can be more concerned with stretchability and bio-compatibility.
5. Green resilience and environmental sustainability: Research bio-based conductive polymer and composites (e.g., cellulose-based substrates) to increase sustainability, recyclability and reduce environmental impact (Shaji, 2025).

6.3 Closing Remark

To sum up, conductive polymer films have been brought much nearer to facilitate the next-generation of flexible electronics. Diverse combinations of innovative advancement (doping, nanofillers), precise morphological control and robustness durability testing provide a potential roadmap to commercial flexible, wearable and conformal electronics. Scalability, real world durability and sustainability will continue to be major aspects of translating these materials to the market.

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