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# CHAPTER 16

# PEDOT: PSS/Carbon Nanotube based polymer Nanocomposites for Advanced Electronic Applications

**Alina Solkar, Jignesh Mehta and Arvind Singh***

*Department of Physics, G. N. Khalsa College, University of Mumbai, NP Marg, Mumbai 400019 Maharashtra, India*

*Corresponding author Email:* arvind.singh@gnkhalsa.edu.in

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**Abstract:** PEDOT: PSS / Carbon nanotubes (CNT) nanocomposites have emerged as a versatile materials platform that synergistically combines the high electrical conductivity, mechanical robustness, and aspect ratio of CNT with the solution processibility, optical transparency, and mixed PEDOT: PSS. This review surveys the structure, property, processing relationships governing these hybrids, outlines interfacial engineering strategies that unlock ultra-high conductivities and stretchability, and evaluates performance across key device classes: transparent electrodes, flexible/stretchable interconnects, chemical and biological sensors, thermoelectrics, energy storage and conversion electrodes, electromagnetic interference (EMI) shielding, and bioelectronics. Particular emphasis is placed on percolation physics, secondary dopants, acid/post-treatment methods, morphology control, and printability. We summarize benchmarking figures of merit (conductivity, sheet resistance/optical transmittance, gauge factor, Seebeck



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coefficient, power factor, capacitance, and stability) and discuss reliability, environmental, and scalability considerations. Finally, we propose best-practice processing workflows and identify open challenges—including long-term hydration stability, junction resistance, alignment control, and sustainable manufacturing—that will shape next-generation soft, conformal, and eco-friendly electronics.

**Keywords**: PEDOT: PSS, carbon nanotube, nanocomposite, transparent electrode, flexible, EMI shielding.

## 1. Introduction

Conducting polymers and their hybrid nanocomposites have attracted considerable attention owing to their lightweight nature,[1] flexibility,[2] tunable conductivity and Optoelectromagnetic properties.[3] Among these, poly(3,4-ethylenedioxythiophene) :polystyrene sulfonate (PEDOT: PSS) stands out as a widely explored conducting polymer due to its high electrical conductivity (varies from 0.1 to >1000 S/cm depending on processing (additive, post treatment)), optical transparency(thin films are transparent in the visible region and suitable for transparent electrodes,[4] flexibility (unlike brittle metals e.g. ITO, PEDOT:PSS films are mechanically flexible), and stability in ambient conditions.[5]

However, the inherent limitations of PEDOT: PSS, such as moderate conductivity and sensitivity to environmental conditions, have motivated researchers to engineer hybrid nanocomposites with carbon nanotubes (CNT) and other polymers to achieve superior electrical, structural, and mechanical properties. Conductive polymer–nanocarbon hybrids are central to flexible and printed electronics. PEDOT:PSS offers aqueous dispersibility, excellent film formation, and ion-permeable conductivity,[6] while CNT provide exceptional intrinsic carrier mobility, thermal conductivity, and mechanical resilience.[7] When combined, the polymer can (i) disperse and stabilize CNT, (ii) bridge tube–tube gaps, and (iii) provide ion pathways, whereas CNT (i) lower percolation threshold, (ii) reduce series resistance by forming long-range networks, and (iii) toughen the matrix.[8] Achieving high performance requires deliberate control of the PEDOT: PSS:CNT ratio, dopants, acid/post-treatments, dispersion state, and processing.

## 2. Materials Fundamentals

### 2.1 PEDOT: PSS

It is the most widely studied conducting polymer known for its high transparency, flexibility and tunable conductivity, it is water-dispersible polyelectrolyte complex of conducting polymer PEDOT and the polyanion PSS, making it easy to process into thin films by solutions methods such as spin coating, printing and inkjet deposition. Because of its excellent electronic conductivity, mechanical flexibility, and biocompatibility, PEDOT:PSS is considered a key material for organic electronics, energy devices, and bioelectronics.[9]


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### 2.2 Carbon Nanotubes

Carbon nanotubes (CNT) are unique nanomaterials and have cylindrical structures which are made of carbon atoms arranged in a hexagonal lattice like a rolled-up sheet of graphene, discovered in1991 by Sumio Iijima.[10] The size of CNT in diameter is typically in the range of nanometre which is about 1-100 nm, whereas length can be around several micrometres to centimetres. Structure depending on the number of graphene layers rolled into the cylinder, they can be single-walled (SWCNT) or multi-walled (MWCNT). It is stronger than steel but lighter than plastic, carry heat very well (better than copper), can conduct electricity like metal or behaves like a semiconductor. Synthesized in laboratories using processes such as chemical vapor deposition, Chemical Vapor Deposition CVD, also by Arc Discharge, or Laser Ablation.

## 3. Properties of PEDOT: PSS/CNT Nanocomposites

### 3.1. Structural Engineering of PEDOT: PSS/CNT Nanocomposites

One of the most effective approaches for improving PEDOT:PSS performance is the design of segregated structures, where CNT are selectively distributed within polymer domains. This arrangement provides continuous conductive networks, significantly lowering percolation thresholds and enhancing charge carrier mobility. Studies on polystyrene/PEDOT: PSS/CNT composites demonstrate that segregated morphologies yield superior electromagnetic interference (EMI) shielding effectiveness, while retaining flexibility and lightweight properties.[11]

### 3.2. Electrical and Optical Properties

PEDOT: PSS/CNT nanocomposites exhibit remarkably enhanced electrical conductivity compared to pristine PEDOT:PSS films. This improvement arises from synergistic interactions between the conductive polymer and the carbon nanotubes. The CNT act not only as highly conductive fillers but also as bridging pathways that reduce the interchain barriers in PEDOT, thereby facilitating efficient charge carrier transport. The high aspect ratio and delocalized π-electron structure of CNT promote the formation of percolative conductive networks, which effectively lower the overall resistance of the composite.[12]

In addition to electrical properties, these nanocomposites demonstrate excellent optical transparency and tunability. The incorporation of CNT can modify the optical bandgap of PEDOT: PSS, allowing control over light absorption and transmission. Thin films of PEDOT: PSS/CNT composites can achieve a desirable balance between high transparency in the visible region and high conductivity, making them ideal for transparent electrodes, touch panels, solar cells, and flexible displays.[13] Furthermore, these composites exhibit reduced reflection losses and enhanced light scattering, contributing to improved device efficiency in optoelectronic applications.

Another key advantage is their stability under optical excitation. The hybrid structure prevents photodegradation of PEDOT:PSS by shielding the polymer chains and enhancing exciton dissociation efficiency, which is crucial for organic photovoltaics and photodetectors. Thus, PEDOT: PSS/CNT


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nanocomposites combine the best of both materials—the flexibility and processability of PEDOT:PSS with the superior conductivity and stability of CNT.

### 3.3. Environmental Stability and Durability

One of the primary challenges in the application of conducting polymers is their vulnerability to environmental conditions, particularly fluctuations in temperature, oxygen exposure, and humidity. PEDOT: PSS, while an excellent conducting polymer, tends to degrade in electrical performance when subjected to harsh conditions, limiting its long-term applicability.[14]

Recent studies demonstrate that the integration of multi-walled carbon nanotubes (MWCNT) with PEDOT:PSS significantly improves the environmental stability and durability of the composite.[15] CNT act as robust reinforcing agents that provide mechanical strength,[16] prevent excessive swelling of PEDOT:PSS in humid conditions, and reduce oxidative degradation.[17] This results in composites that maintain relatively stable conductivity and mechanical integrity under prolonged exposure to heat and moisture.

Moreover, the hydrophobic surface of CNT counteracts the hygroscopic nature of PEDOT: PSS, thereby mitigating water absorption and ionic migration, which are major causes of conductivity loss in polymer films. Long-term tests reveal that CNT-PEDOT:PSS composites can retain their conductivity over extended operational cycles, making them highly suitable for flexible and wearable electronics, biomedical devices, and field-deployable sensors.

The enhanced mechanical durability of these composites also enables their use in bendable and stretchable devices, where repeated mechanical stress would otherwise lead to crack formation and loss of conductivity in pristine PEDOT: PSS. Thus, by combining the intrinsic flexibility of polymers with the robustness and stability of CNT, these nanocomposites overcome one of the most critical bottlenecks in practical device integration.

## 4. Synthesis, Formulation, and Processing

### 4.1. Dispersion & Formulation

Dispersants: PSS (native), bile salts, SDBS, DNA, Pluronic, chitosan; post-rinse required to minimize insulating residues. Secondary dopants/plasticizers: EG, DMSO, glycerol, sorbitol, ionic liquids, Zwitterions—improve chain ordering and film coalescence; tune rheology for printing. Acid treatments: $H_2SO_4$, MSA, HCl, $HNO_3$; mild acids (pTS, CSA) for gentler processing and stretchability. Acid rinses partially remove PSS, lower RS, increase WF, but must balance brittleness.

### 4.2. Deposition Techniques

Laboratory: spin-coat, drop-cast, vacuum filtration + transfer; spray-coat for large areas and rough substrates. Manufacturing: slot-die, bar-coat, gravure, flexographic, inkjet, screen printing, aerosol-jet, extrusion/3D printing. Sub-100 °C drying compatible with plastics and textiles.


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### 4.3. Post-Processing & Morphology Control

Solvent annealing (EG/DMF vapors), acid rinses, thermal annealing (100–200 °C), mechanical stretching (uniaxial/biaxial) for alignment; layer-by-layer (LbL) to build alternating PEDOT-rich and CNT-rich strata; plasma/ozone for wettability (use cautiously).

## 5. Applications

### 5.1. Electromagnetic Interference (EMI) Shielding

Electromagnetic interference is a growing challenge in modern electronic devices due to the increasing density of wireless communication systems, portable gadgets, and IoT devices.[11,18] Traditional EMI shielding relies on metals like copper or aluminium, which are heavy, rigid, and prone to corrosion. The shielding occurs mainly through reflection, absorption, and multiple scattering of EM waves within the conductive CNT-PEDOT:PSS network.

PEDOT: PSS/CNT composites provide a lightweight, flexible, and corrosion-resistant alternative. CNT create a highly conductive network, while PEDOT:PSS ensures good processability and dispersion. Together, they achieve shielding effectiveness (SE) values comparable to metals (often >30 dB across a wide frequency range).[19] Additionally, their flexibility allows use in:

(i) Foldable smartphones and tablets
(ii) Flexible antennas and wearable electronics
(iii) Aerospace and automotive electronics where weight reduction is critical.

### 5.2. Flexible and Stretchable Electronics

The compatibility of PEDOT:PSS with solution-based processing enables fabrication of flexible films and coatings.[20] When combined with CNT, the films show improved conductivity under strain, making them viable for bendable displays, wearable devices, and stretchable circuits. One of the most exciting applications of PEDOT: PSS/CNT composites is in next-generation flexible electronics.[6] PEDOT:PSS is water-dispersible and solution-processable, which means thin films can be fabricated by techniques like spin coating, inkjet printing, or spray deposition. CNT reinforce the mechanical strength and provide excellent electrical conductivity even under strain.

When stretched or bent, CNT act as conductive bridges, maintaining percolation pathways and preventing conductivity loss. This makes the composite particularly suitable for devices requiring repeated mechanical deformation.

**Applications include**

(i) Wearable sensors (health monitoring, motion detection).
(ii) Stretchable circuits for soft robotics.
(iii) Bendable displays and flexible touchscreens.
(iv) Conductive textiles for smart clothing


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### 5.3. Thermoelectrics Devices

PEDOT:PSS is a leading polymer for thermoelectric energy harvesting. PEDOT, especially in its doped form like PEDOT:PSS, is highly valuable for thermoelectrics applications due to its exceptional properties, including high electrical conductivity, low thermal conductivity, flexibility, and ease of processing.[21] Incorporation of CNT improves the Seebeck coefficient and electrical conductivity, resulting in higher power factors and stable thermoelectrics performance.[22] PEDOT:PSS) and carbon nanotubes (CNTs) have numerous applications, particularly in flexible and low-power devices. These materials are used for both power generation and cooling and are increasingly important in areas like:

(i) Medical sensors,
(ii) Automotive Industries
(iii) Wearable thermoelectric generators (TEGs)
(iv) Wireless sensor networks (WSNs)
(v) Wearable Localized thermal comfort clothing.

### 5.4. Solar Energy Applications

The optical transparency and electronic tunability of PEDOT: PSS/CNT films make them attractive as hole transport layers (HTLs) in organic and perovskite solar cells, where they improve charge extraction and device efficiency.[23] PEDOT:PSS) is the most commonly used HTL in Pe-LED devices and is known to cause luminescence quenching at the HTL/EML interface. This quenching of photoluminescence is attributed to either exciton dissociation due to traps present at the HTL/EML interface, or mismatch in energy levels causing charge build up, or both defects at the interface and energy level mismatch., Several strategies have been explored to address the challenges posed by the PEDOT:PSS interface and to overcome the issues related to PEDOT:PSS HTL.

### 5.5. Bioelectronics

To understand the physiology and pathology of electrogenic cells and the corresponding tissue in their full complexity, the quantitative investigation of the transmission of ions as well as the release of chemical signals is important. Organic (semi-) conducting materials and in particular organic electrochemical transistor are gaining in importance for the investigation of electrophysiological and recently biochemical signals due to their synthetic nature and thus chemical diversity and modifiability, their biocompatible and compliant properties, as well as their mixed electronic and ionic conductivity featuring ion-to-electron conversion.[24] The tremendous technological progress in microelectronic fabrication have fostered the development of bioelectronic devices based on solid-state materials. There has been tremendous progress over last decade on the development of bioelectronic devices utilizing polymer PEDOT:PSS to interface electronics and biological matter including microelectrode arrays, neural cuff electrodes, organic electrochemical transistors, PEDOT:PSS-based biosensors, and organic electronic ion pumps.

PEDOT:PSS-based bioelectronic materials exhibit high conductivity, mechanical flexibility, and biocompatibility, making them particularly suitable for integration into neural devices for brain science


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research.[25] These materials facilitate high-resolution neural activity monitoring and provide precise electrical stimulation across diverse modalities. This review comprehensively examines recent advances in the development of PEDOT:PSS-based bioelectrodes for brain monitoring and modulation, with a focus on strategies to enhance their conductivity, biocompatibility, and long-term stability. These PEDOT:PSS/CNT based polymer nanocomposites exhibited (i) long-term water resistance (ii) high adhesion strength on the PES membrane, (iii) enhanced electrical properties [due to the MWCNTs and PEDOT:PSS promoting effective electrical stimulation (ES) operation in devices containing bioelectronic interfaces (BEI)], and (iv) good anticoagulant ability and negligible hemolysis of red blood cells. Ions and neurotransmitters are two key elements governing neuronal activities that can be monitored by organic electronics. PEDOT:PSS can be utilized to mediate the communication between biological systems and bioelectronics leading to many applications such as:

(i) Brain monitoring and modulation.
(ii) Recording and Modulation of Electrophysiological and Biochemical Cell Signals.
(iii) Physiology and pathology of electrogenic cells and the corresponding tissue in their full complexity.
(iv) Novel Organic Bioelectronic Interfaces for Efficient Removal of Protein-Bound Uremic Toxins
(v) Effective electrical stimulation (ES).
(vi) Good Anticoagulant ability and negligible Hemolysis of red blood cells

## 6. Future Directions and Challenges

Despite remarkable progress, challenges remain in achieving consistent large-scale fabrication and long-term stability of PEDOT: PSS/CNT nanocomposites. Future directions should focus on Developing green synthesis routes for scalable processing. Exploring novel hybrid fillers (graphene, MXenes, metal nanowires) alongside CNT. Enhancing interfacial interactions through surface functionalization.

Designing multifunctional composites that integrate EMI shielding, thermoelectrics, and optical properties for next-generation wearable and sustainable electronics. Below are few points mentioned to make PEDOT:PSS and CNT polymer nanocomposite a better and suitable matrix-filler combination for threshold processing parameters:

(i) Junction engineering: reduce tube–tube contact resistance via covalent-safe π–π linkers, metal nanoparticle welding, or acid-induced reorganization without embrittlement.
(ii) Humidity-robust performance: ion-blocking yet breathable encapsulants; hydrophobic PSS analogues or PSS-free formulations.
(iii) Selective enrichment: metallic SWCNT sorting for electrodes; semiconducting fractions for sensors/TE with optimized S.
(iv) Patterning: high-resolution, photo patternable PEDOT systems; laser sintering of printed traces.
(v) Biocompatibility: endotoxin removal from CNT; stable neutral pH formulations for skin/implant contact.


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(vi) Sustainable chemistry: greener acids/dopants, recyclable substrates, and closed-loop water processing.

## 7. Conclusion

PEDOT: PSS/CNT nanocomposites deliver a rare combination of printability, conductivity, flexibility, and multifunctionality that is unmatched by either component alone. Through careful ink formulation, acid/post-treatments, and structural control, these materials can rival sputtered metal oxides in transparent electrodes, enable soft/stretchable wiring and sensors, and unlock emerging applications in thermoelectrics, energy storage, EMI shielding, and bio-interfaces. Continued progress will depend on taming moisture sensitivity, engineering low-resistance junctions without sacrificing toughness, and scaling eco-conscious manufacturing. With these advances, PEDOT: PSS/CNT hybrids are poised to underpin the next wave of conformal, wearable, and sustainable electronics.

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