

ADVANCES IN THE SYNTHESIS AND CHARACTERIZATION OF CONDUCTING POLYMER NANOCOMPOSITES FOR EMERGING APPLICATIONS

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Abstract- Conducting polymer nanocomposites (CPNCs) have emerged as multifunctional materials in which the redox activity, electronic/ionic transport and processability of conjugated polymers are coupled with the high surface area, mechanical reinforcement and multifunctionality of nanoscale fillers. Polyaniline (PANI), polypyrrole (PPy), polythiophene derivatives and poly(3,4-ethylenedioxythiophene) (PEDOT) are particularly important because their conductivity can be tuned through doping, morphology and chemical functionalization. Nanofillers including graphene and reduced graphene oxide, carbon nanotubes, MXenes, metal/metal-oxide nanoparticles, nanocellulose and other two-dimensional materials can establish conductive networks and modify interfacial charge transfer. This review summarizes recent progress in the synthesis and characterization of CPNCs, emphasizing in-situ oxidative polymerization, electrochemical polymerization, vapor-phase

approaches, solution processing, hydrothermal/solvothermal methods, electrospinning and emerging printing routes. The roles of Fourier-transform infrared spectroscopy, Raman spectroscopy, X-ray diffraction, X-ray photoelectron spectroscopy, electron microscopy, thermal analysis, electrochemical impedance spectroscopy and electrical measurements are critically compared. Particular attention is given to structure–property relationships and applications in supercapacitors, batteries, sensors, wearable electronics, electromagnetic-interference shielding, environmental remediation, catalysis and biomedical interfaces. Recent reviews emphasize that combining conducting polymers with nanofillers can overcome limitations of pristine polymers and improve conductivity, stability, morphology and application-specific performance [1–5]. Current challenges include reproducible dispersion, dopant migration, mechanical fatigue, environmental stability,

scalable manufacturing, lifecycle impacts and reliable benchmarking. Future research should integrate sustainable synthesis, hierarchical architectures, data-driven materials design, printed manufacturing and standardized device-level testing.

Keywords: conducting polymers; nanocomposites; polyaniline; polypyrrole; PEDOT; graphene; carbon nanotubes; MXenes; synthesis; characterization; sensors; supercapacitors; wearable electronics.

I. INTRODUCTION

Conducting polymers are π -conjugated macromolecules whose electronic structure can support charge transport after suitable doping. Unlike conventional polymers, they can combine polymeric flexibility and low density with electrical, electrochemical and optical functionality. Representative systems include polyacetylene, PANI, PPy, polythiophene, poly(p-phenylene), poly(p-phenylene vinylene) and PEDOT. Their properties are strongly influenced by backbone conjugation, oxidation state, dopant chemistry, chain ordering and morphology [1,6].

Pristine conducting polymers nevertheless face important limitations: limited mechanical robustness, processing difficulties,

environmental or electrochemical instability in some oxidation states, irreversible structural changes during repeated redox cycling and morphology-dependent conductivity. Nanocomposite design addresses these limitations by integrating the polymer with nanoscale carbon materials, metals, metal oxides, two-dimensional materials or functional inorganic phases. The large interfacial area allows charge transfer, nucleation and mechanical load sharing, while nanofiller networks can provide additional pathways for electron transport [2–4].

Recent literature has expanded the application space from conventional antistatic coatings and electrodes toward flexible/wearable sensors, non-invasive biosensing, environmental remediation, catalysis, biomedical interfaces and printed electronics. A 2024 review of industrial conducting polymers highlighted synthesis, characterization and applications across electronics, biomedical and optoelectronic fields, while recent reviews have specifically examined PANI, PPy and PEDOT nanocomposites for energy storage and sensing [2,4,7].

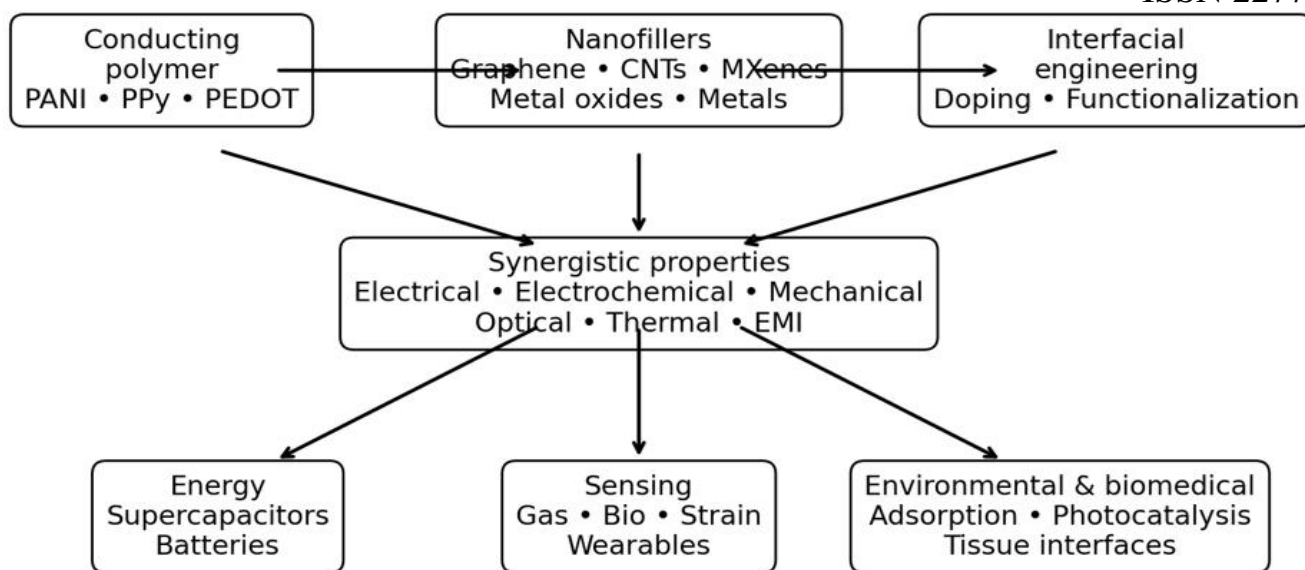


Figure 1. Conceptual framework linking conducting polymers, nanofillers, interfacial engineering and emerging applications.

II. CONDUCTING POLYMERS: CHEMISTRY AND CLASSIFICATION

Table 1. Representative conducting polymers and their principal design considerations.

Polymer	Key feature	Typical dopant/charge control	Strengths	Common limitations
Polyaniline (PANI)	Variable oxidation states; emeraldine is most used	Protonic acids and functional dopants	Low cost, easy synthesis, tunable conductivity, electroactivity	Brittleness; swelling/dedoping; cycling degradation
Polypyrrole (PPy)	Stable conjugated heterocycle	Anionic dopants during oxidation	Easy electrochemical synthesis, good redox activity, biocompatibility potential	Overoxidation; limited processability
PEDOT / PEDOT:PSS	Highly stable thiophene derivative	PSS or other counterions	High conductivity, optical transparency, flexibility	Acidic/ionic formulation issues; humidity dependence
Polythiophene derivatives	Backbone and side chains are highly tunable	Chemical/electrochemical doping	Optoelectronics, organic electronics	Synthesis and solubility depend strongly on side chains
Polyacetylene	Prototype highly conjugated polymer	Electron acceptor/donor dopants	Very high theoretical conductivity	Poor environmental/process stability

III. NANOFILLERS AND COMPOSITE ARCHITECTURES

Nanofillers are selected according to the target property rather than conductivity alone. Carbon nanomaterials provide conductive pathways and mechanical reinforcement; metal and metal-oxide nanoparticles can introduce

catalytic, magnetic, optical or redox functionality; MXenes contribute high conductivity and hydrophilic surface chemistry; and nanocellulose or other bio-derived materials can improve mechanical integrity and sustainability. The interfacial chemistry between filler and polymer is often as important as filler loading.

Table 2. Nanofiller classes used in conducting polymer nanocomposites.

Nanofiller class	Examples	Primary role	Typical benefit	Design concern
Carbon nanomaterials	Graphene, rGO, CNTs, carbon black	Conductive network; reinforcement	Higher conductivity, surface area and rate capability	Restacking/agglomeration; dispersion
2D materials	MXenes, MoS ₂ , h-BN	Layered interfaces and surface chemistry	Fast transport, multifunctionality	Oxidation/restacking; processing
Metal nanoparticles	Au, Ag, Pt, Cu	Electron transfer, catalysis, plasmonics	Sensitivity and catalytic activity	Cost, aggregation, environmental concerns
Metal oxides	MnO ₂ , TiO ₂ , ZnO, Fe ₃ O ₄	Redox, dielectric, photocatalytic or magnetic phase	Pseudocapacitance and multifunctionality	Phase control; interfacial resistance
Bio-derived nanomaterials	Cellulose nanofibers, chitosan derivatives	Mechanical/biological interface	Flexibility and potentially improved sustainability	Moisture sensitivity; batch variability

IV. SYNTHESIS AND PROCESSING STRATEGIES

Major synthesis routes for CPNCs

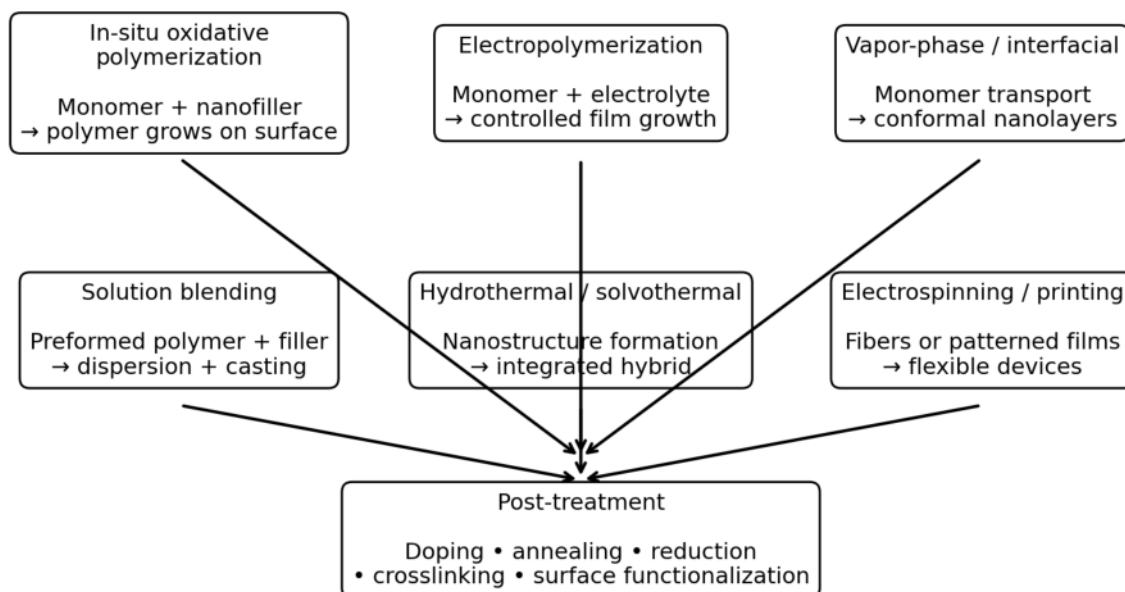


Figure 2. Schematic overview of major synthesis and processing routes for CPNCs.

4.1 In-situ oxidative polymerization

In-situ oxidative polymerization is one of the most widely used routes for PANI and PPy nanocomposites. A monomer and nanofiller are dispersed together, followed by addition of an oxidant under controlled temperature and acidity. Polymer chains nucleate and grow at or around the filler surface, often producing intimate interfacial contact. The approach is attractive because it can reduce phase separation and promote uniform coating of nanoparticles or sheets. Oxidant concentration, monomer-to-oxidant ratio, pH, temperature, reaction time, surfactant and filler surface

chemistry govern molecular weight, morphology and oxidation state [2,8].

4.2 Electrochemical polymerization

Electropolymerization enables direct deposition of conducting polymer films on conductive substrates. It is particularly useful for sensors, microelectrodes and supercapacitors because film thickness and loading can be adjusted through potential, current density, charge passed and deposition time. Nanofillers can be pre-deposited, dispersed in the electrolyte or incorporated through co-deposition. The method can yield strongly adhered, substrate-integrated architectures, although scale-up over

large areas requires control of current distribution and bath composition.

4.3 Vapor-phase and interfacial routes

Vapor-phase polymerization can produce thin, conformal conductive coatings and is relevant to flexible electronics and patterned devices. Interfacial polymerization confines the reaction to a liquid–liquid or liquid–solid interface, which can promote nanofibers, nanosheets and hierarchical structures. Recent work on liquid/liquid interfaces emphasizes that interfacial energy and nanostructure adsorption can be exploited to create ordered architectures [9].

4.4 Solution blending, hydrothermal and solvothermal processing

Solution mixing is simple and compatible with casting, coating and printing, but adequate dispersion of nanofillers is essential. Hydrothermal and solvothermal processes are useful for generating crystalline inorganic phases and integrated polymer/inorganic hybrids. In both approaches, solvent choice, viscosity, surface functionalization and drying history strongly affect filler distribution and porosity.

4.5 Electrospinning and additive manufacturing

Electrospinning converts polymer solutions into continuous micro- to nanoscale fibers.

Conducting polymers can be electrospun directly in selected formulations or blended with carrier polymers. Inkjet, screen and other printing methods offer a route toward patterned flexible electrodes and sensors, but rheological control, nozzle compatibility, drying, adhesion and electrical uniformity remain important scale-up parameters. Recent wearable-biosensor reviews identify electrospinning, inkjet printing and 3D printing as promising routes for flexible CPNC devices [10].

V. FACTORS GOVERNING NANOCOMPOSITE PERFORMANCE

The performance of a CPNC is controlled by coupled variables rather than by nanofiller loading alone. A conductive network forms when the concentration and spatial distribution of conductive filler allow a continuous pathway. Excess filler may cause aggregation, reduce polymer continuity and increase brittleness. Similarly, very thick conducting-polymer coatings can obstruct ion diffusion in electrochemical electrodes. Therefore, optimization should consider percolation, interfacial area, pore size, dopant mobility, mechanical strain and electrolyte accessibility simultaneously.

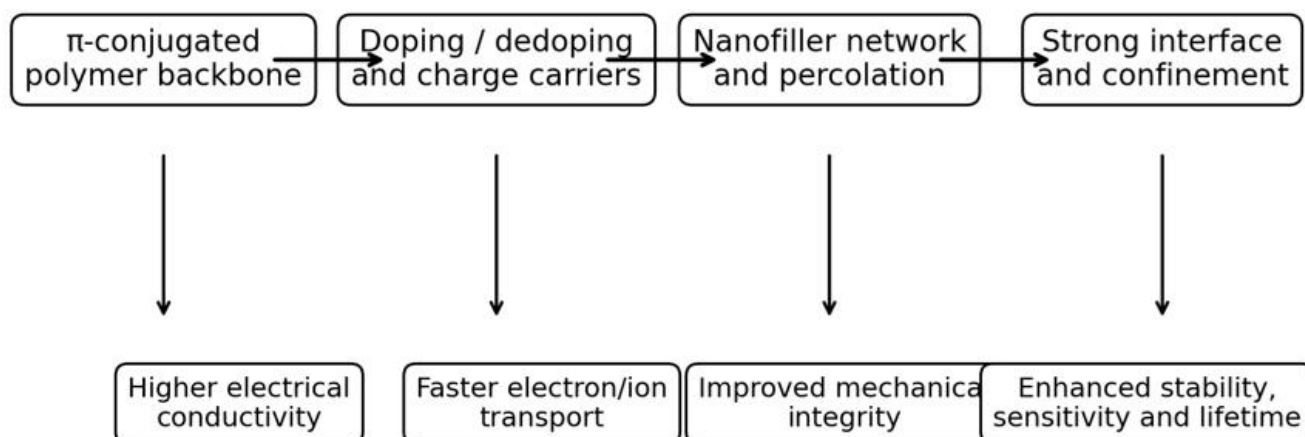


Figure 3. Simplified structure–property pathway linking conjugation, doping, nanofiller networks and interfaces to device performance.

VI. CHARACTERIZATION OF CONDUCTING POLYMER NANOCOMPOSITES

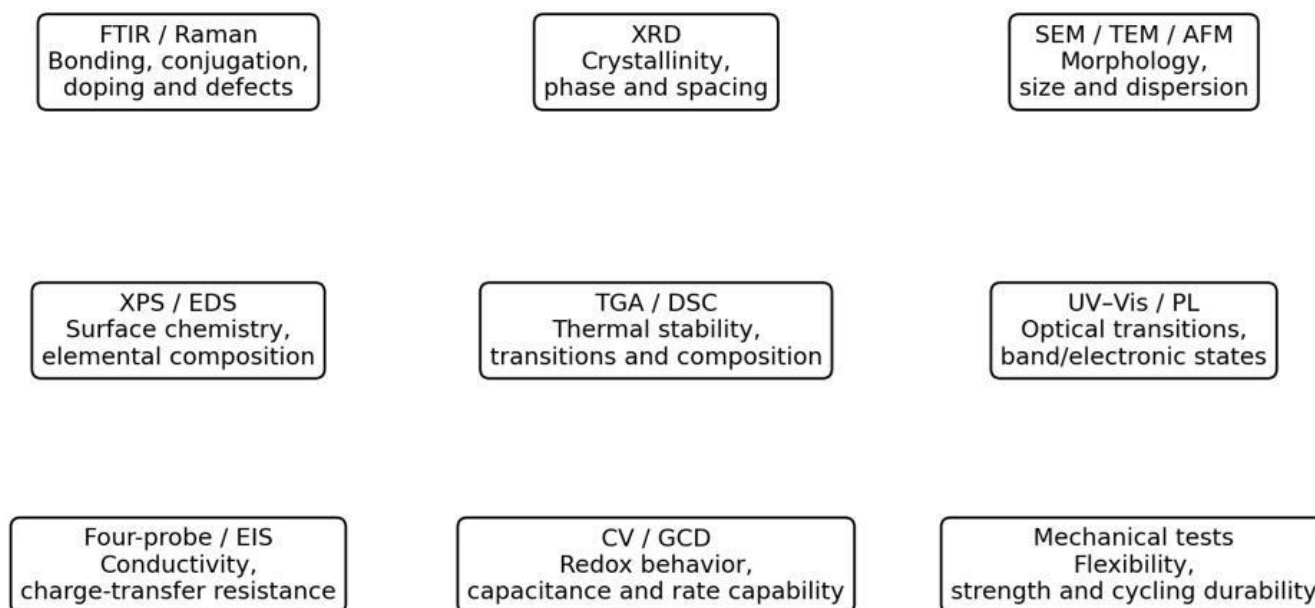


Figure 4. Complementary characterization workflow for CPNCs.

Table 3. Major characterization techniques and their roles in CPNC research. Recent nanocomposite reviews commonly combine microscopy, spectroscopy, thermal analysis and electrochemical methods to connect structure with performance [3,11].

Technique	Primary information	Typical interpretation	Why it matters
FTIR	Functional groups and bonding	Band shifts, new bands, dopant interactions	Confirms chemical interactions
Raman	Conjugated backbone, defects, carbon filler	Vibrational modes, D/G ratio, polymer bands	Sensitive to conjugation and carbon structure
XRD	Crystallinity and phase	Peak position, width, d-spacing	Tracks ordering and filler restacking
SEM/TEM	Morphology and dispersion	Particle size, coating, pores, interfaces	Links microstructure to transport
AFM	Surface topology	Roughness, nanoscale morphology	Useful for thin films
XPS	Surface elemental/chemical state	Oxidation state and dopant chemistry	Quantifies surface composition
TGA/DSC	Thermal stability and transitions	Mass loss, T _g , melting/crystallization	Composition and processing window
UV–Vis/PL	Electronic/optical structure	Absorption maxima, spectral shifts	Tracks doping and electronic states
Four-probe	Electrical conductivity	Bulk/sheet resistance	Direct transport metric
EIS	Charge and ion transport	R _{ct} , impedance, diffusion features	Separates resistive and capacitive processes
CV/GCD	Electrochemical storage	Redox peaks, capacitance, rate response	Device-level energy-storage performance

VII. ELECTRICAL, ELECTROCHEMICAL, MECHANICAL AND THERMAL PROPERTIES

7.1 Electrical conductivity and percolation

Electrical transport arises from conjugated polymer chains, dopant-induced charge carriers and conductive nanofiller networks. The effective conductivity often increases sharply near a percolation threshold. Filler aspect ratio, orientation, dispersion and interfacial resistance determine the threshold and the magnitude of

the conductivity gain. For practical devices, conductivity should be reported together with thickness, measurement geometry, humidity, temperature and dopant state.

7.2 Electrochemical properties

CPNC electrodes combine electric-double-layer capacitance from porous carbonaceous phases with pseudocapitance from reversible polymer redox reactions. PANI, PPy and PEDOT can therefore deliver high charge storage, but repeated swelling/shrinkage during cycling may cause cracking and loss of electrical contact. Nanofillers act as conductive

scaffolds and mechanical buffers. Recent reviews emphasize the importance of hierarchical architectures and interface engineering for improving charge-transfer kinetics and stability [4,7].

7.3 Mechanical and thermal properties

Nanofillers can increase modulus and tensile strength by transferring load across polymer–

filler interfaces, while flexible substrates and fibrous architectures can preserve deformability. Thermal stability is commonly improved when inorganic or carbon fillers restrict chain motion and act as barriers to heat/mass transport. However, high filler content may reduce ductility. Thus, a balanced composition is required for wearable and flexible systems.

VIII. EMERGING APPLICATIONS

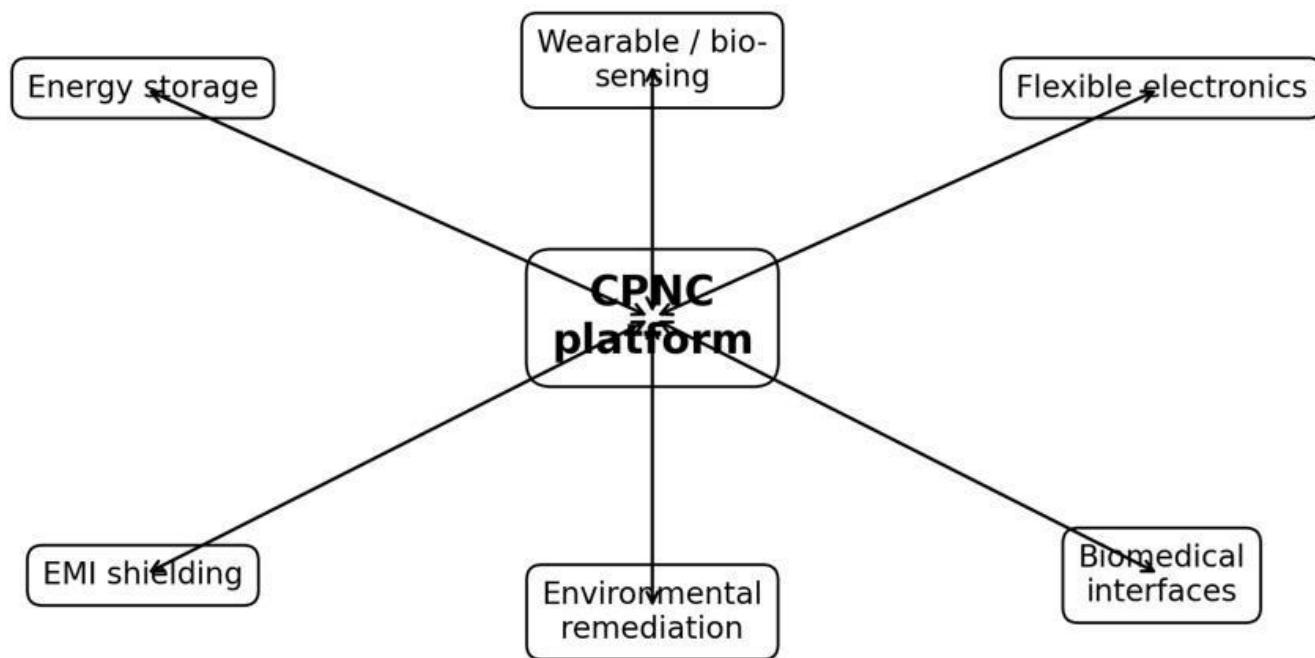


Figure 5. Representative emerging application domains of CPNCs.

Table 4. Application-focused comparison of representative conducting polymer nanocomposites.

Application	Representative CPNC	Functional mechanism	Key metrics	Major challenge
Supercapacitors	PANI/graphene; PPy/CNT; PEDOT/carbon	Pseudocapacitance + double-layer storage	Capacitance, rate capability, retention	Cycling stability and mass loading
Gas sensors	PANI/metal oxide;	Doping/redox and	Sensitivity,	Humidity and

	PPy/CNT	adsorption-induced resistance change	selectivity, response/recovery	baseline drift
Biosensors	PEDOT:PSS/graphene; PPy composites	Electrocatalysis and interfacial charge transfer	LOD, selectivity, response time	Biofouling and long-term stability
Wearable electronics	PEDOT, PANI or PPy with CNT/MXene	Stretchable conductive pathways	Gauge factor, hysteresis, durability	Cracking and skin/environment interface
EMI shielding	CP/CNT/graphene hybrids	Absorption/reflection of electromagnetic waves	SE, frequency range, thickness	Mechanical integrity and broadband performance
Photocatalysis/environment	PANI/TiO ₂ , PANI/ZnO, carbon/CP hybrids	Charge separation + adsorption	Removal efficiency, kinetics, reusability	Real-water complexity and catalyst recovery
Biomedical interfaces	PEDOT-based composites	Electrical stimulation, sensing, cell interaction	Biocompatibility, impedance, stability	Sterilization and long-term biointerface stability
Flexible electronics	PEDOT-based printed composites	Conductive, transparent/flexible films	Sheet resistance, transparency, bend cycles	Printing uniformity and adhesion

8.1 Energy storage

Supercapacitors are among the most developed application areas. CPNCs can combine the fast surface-controlled charge storage of carbon nanomaterials with the high pseudocapacitance of conducting polymers. PANI, PPy and PEDOT are repeatedly highlighted in recent reviews, with morphology and nanofiller identity strongly affecting ion diffusion and redox accessibility [4,12]. Future studies should emphasize areal/volumetric metrics, realistic mass loading, full-cell testing, long-term

cycling and standardized reporting rather than only three-electrode laboratory values.

8.2 Sensors and biosensors

Conducting polymers provide a chemically responsive, electroactive interface. Nanofillers increase surface area, provide catalytic sites and improve electron transfer. PANI and PPy nanocomposites have been widely investigated for gas and biosensing, while PEDOT-based systems are increasingly used in biomedical and wearable formats [8,10,13]. Emerging sweat sensors integrate CPNCs with microfluidics and wireless electronics; key

unresolved issues include dopant leaching, signal drift, humidity effects and mechanical cracking.

8.3 Environmental remediation and photocatalysis

CPNCs can adsorb contaminants through electrostatic interactions, π - π interactions and functional groups while inorganic semiconductors can contribute photocatalytic degradation. Conducting polymers may facilitate charge separation and broaden light absorption. However, performance in model dye solutions does not necessarily translate to complex wastewater. Future work should evaluate competing ions, natural organic matter, catalyst recovery, transformation products and ecotoxicity.

8.4 Biomedical interfaces

PEDOT and related conducting polymers are attractive for neural interfaces, biosensors, tissue engineering and electrically assisted drug delivery because electrical signals can be coupled to biological environments. Recent reviews describe PEDOT-based systems for biosensing, tissue engineering, drug delivery and cell-related applications [14]. Translation requires careful evaluation of sterilization, inflammatory response, mechanical mismatch, degradation products and long-term electrical stability.

8.5 Electromagnetic-interference shielding and flexible electronics

Hybrid conductive networks can dissipate incident electromagnetic energy through reflection, absorption and multiple internal scattering. The polymer matrix provides flexibility while graphene, CNTs, MXenes or metallic fillers create conductive pathways. In flexible electronics, PEDOT:PSS and related materials enable transparent or deformable conductors, while nanocomposites can improve mechanical durability and environmental stability.

IX. RECENT ADVANCES AND RESEARCH TRENDS

Recent research is moving from simple binary mixtures toward hierarchical and multifunctional architectures. Ternary systems such as polymer/graphene/CNT or polymer/MXene/metal oxide can provide complementary pathways for electrons, ions and mechanical stress. Interfacial polymerization and highly ordered architectures are being explored to reduce transport bottlenecks [9,15]. Sustainability is also becoming central: researchers are examining water-based processing, bio-derived components, low-temperature synthesis, recyclable substrates and lifecycle impacts.

Another important trend is device-oriented evaluation. Rather than optimizing isolated material properties, current work increasingly considers printed pattern fidelity, adhesion, bending/stretching, humidity, real analytes,

realistic electrode mass loading and wireless integration. This shift is essential for translating laboratory-scale CPNCs into robust technologies.

X. CHALLENGES AND LIMITATIONS

Table 5. Major translational challenges and possible mitigation strategies.

Challenge	Origin	Consequence	Potential strategy
Nanofiller agglomeration	High surface energy / poor compatibility	Nonuniform conductivity and weak interfaces	Surface functionalization, surfactants, controlled in-situ growth
Dopant instability	Ion migration, humidity and solvent exposure	Conductivity drift and aging	Stable dopants, crosslinking, encapsulation
Mechanical fatigue	Repeated swelling and bending	Cracking and loss of contact	Elastic scaffolds, hierarchical networks
Scale-up variability	Heat/mass transfer and dispersion differences	Batch-to-batch variation	Inline monitoring, statistical process control
Benchmarking	Different test conditions and loadings	Difficult comparison across studies	Standardized protocols and device-level metrics
Environmental footprint	Solvents, oxidants, metals and nanomaterial waste	Sustainability and regulatory barriers	Greener solvents, recovery, lifecycle assessment
Biocompatibility	Residual monomers/dopants or nanoparticles	Inflammation or toxicity concerns	Purification, stable formulations, long-term studies

XI. FUTURE PROSPECTS

- Design CPNCs using quantitative structure–property–performance relationships rather than empirical filler screening.
- Develop hierarchical 3D architectures that independently optimize electronic transport, ion diffusion and mechanical compliance.

- Expand aqueous, low-temperature and bio-derived synthesis routes and quantify environmental impacts through lifecycle assessment.
- Adopt printed and roll-to-roll compatible processing for scalable flexible electronics and sensors.

- Use stable dopant chemistries, covalent interfaces and self-healing matrices to suppress conductivity drift and fatigue.
- Standardize reporting of conductivity, electrochemical metrics, analyte conditions, mass loading, device geometry and cycling protocols.
- Integrate CPNCs with microfluidics, edge electronics and wireless systems for real-time wearable sensing.
- Explore machine learning and automated experimentation to optimize polymer composition, filler ratio, morphology and processing conditions.

XII. CONCLUSION

Conducting polymer nanocomposites provide a versatile platform for coupling electronic/ionic transport with flexibility, chemical functionality and nanoscale interfacial

engineering. PANI, PPy and PEDOT remain central because their conductivity and redox behavior can be tuned through doping and morphology, while carbon nanomaterials, MXenes, metals and metal oxides introduce complementary electrical, mechanical, catalytic and optical functions. The synthesis route determines dispersion, interfacial bonding and morphology, and these features ultimately control transport, stability and device performance. The field is now progressing toward hierarchical, multifunctional and printable systems for energy storage, sensing, environmental technologies, biomedical interfaces and flexible electronics. The next stage of development should prioritize reproducibility, sustainable processing, realistic device-level testing and long-term stability so that promising laboratory materials can move toward scalable applications.

XIII. SUGGESTED RESEARCH WORKFLOW FOR A NEW CPNC SYSTEM

Stage	Recommended activities	Decision criteria
1. Define target	Select application, operating environment and required performance	Device-level specifications
2. Select polymer/filler	Match conductivity, redox activity, flexibility and surface chemistry	Compatibility and sustainability
3. Design interface	Functionalize filler or choose in-situ growth	Dispersion and interfacial adhesion
4. Synthesize	Compare at least two scalable routes	Yield, reproducibility, morphology
5. Characterize	Use spectroscopy + microscopy + thermal + electrical/electrochemical methods	Structure–property correlation

6. Optimize	Vary loading, dopant, thickness and processing	Performance vs. stability
7. Validate	Test realistic conditions and full devices	Retention, selectivity, durability
8. Translate	Assess scale-up, safety, lifecycle and cost	Technology readiness

References

[1] Namsheer K., Rout C. S. Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications. RSC Advances. 2021;11:5659–5697. DOI: 10.1039/D0RA07800J.

[2] Conducting polymers in industry: A comprehensive review on the characterization, synthesis and application. Alexandria Engineering Journal. 2024;88:253–267. DOI: 10.1016/j.aej.2024.01.029.

[3] A comprehensive overview of common conducting polymer-based nanocomposites; Recent advances in design and applications. European Polymer Journal. 2021;160:110773. DOI: 10.1016/j.eurpolymj.2021.110773.

[4] Conducting polymer based nanocomposites for supercapacitor applications: A review of recent advances, challenges and future prospects. Journal of Energy Storage. 2024;100(B):113551. DOI: 10.1016/j.est.2024.113551.

[5] Progress in synthesis and applications of Polyaniline-Coated Nanocomposites: A comprehensive review. European Polymer

Journal. 2024;221:113574. DOI: 10.1016/j.eurpolymj.2024.113574.

[6] Namsheer K., Rout C. S. Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications. RSC Advances. 2021;11:5659–5697.

[7] Polymer-based nanocomposites for supercapacitor applications: a review on principles, production and products. RSC Advances. 2025. DOI: 10.1039/D4RA08601E.

[8] Synthesis and sensing applications of polyaniline nanocomposites: a review. RSC Advances. 2016. DOI: 10.1039/C6RA03049A.

[9] In Situ Engineering of Conducting Polymer Nanocomposites at Liquid/Liquid Interfaces: A Perspective on Fundamentals to Technological Significance. ACS Materials Au. DOI: 10.1021/acsmaterialsau.3c00068.

[10] Recent advances in conducting polymer nanocomposites for non-invasive sweat-based biosensors: A review. 2026. (Recent review of CPNC engineering, fabrication and wearable biosensing.)

[11] An overview of the progress in the synthesis of nanocomposites for industrial applications: Techniques preparation, definitions, and characterization. *Synthetic Metals*. 2024; DOI: 10.1016/j.synthmet.2024.117665.

[12] Exploring recent advances and synthesis strategies in conductive polymers and their composites in supercapacitor systems: a comprehensive review. *RSC Advances*. 2025; DOI: 10.1039/D5RA06603D.

[13] Conducting polymers in biosensing: A review. *Chemical Physics Impact*. 2024;8:100642.

[14] Conducting polymer PEDOTs for biomedical application. *Synthetic Metals*. 2024;307:117700. DOI: 10.1016/j.synthmet.2024.117700.

[15] Highly Ordered Conducting Polymers: Fabrication Strategies and Applications. *Accounts of Materials Research*. 2025;6(10):1190–1203. DOI: 10.1021/accountsmr.5c00136.

[16] Advancements in GO-Polymer Nanocomposites: A Paradigm Shift in Energy Harvesting and Sensor Engineering. *ACS Applied Polymer Materials*. 2026. DOI: 10.1021/acsapm.6c01111.