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Design, structure, and application of conductive polymer hybrid materials: a comprehensive review of classification, fabrication, and multifunctionality

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Conductive polymer (CP) hybrids combine the electronic properties of polymers with the mechanical strength, thermal stability, and catalytic features of secondary materials. This review presents four major structural categories: core–shell assemblies, interpenetrating networks, layered composites, and dispersed nanocomposites. Each class is linked to fabrication routes such as *in situ* polymerization, electrochemical deposition, solution blending, and sol–gel techniques. We evaluated the influence of these structural forms on performance metrics, including electrical conductivity, flexibility, and long-term durability. Representative applications in sensing, energy storage, corrosion protection, and environmental remediation are examined to highlight their functional advantages and practical limitations. Challenges in synthesis, precision, material stability, and device integration are also discussed. A final roadmap connecting structural design choices to specific application outcomes and outlining priorities for the future development of scalable and multifunctional CP hybrid systems is presented.

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1. Introduction

1.1. Background on conducting polymers

CPs are a class of materials with electrical conductivity, which is an unusual property not observed in the polymer family.[1,2] Interest in this field has been considerable because of its potential applications in several domains, including electronics, optoelectronics, energy storage, and biomedical engineering. CPs have several important advantages over traditional inorganic materials: their electrical properties can be easily tailored, their synthesis process is simple, and they exhibit high environmental stability. CPs have recently been found to be promising candidates for many applications, including electrochemical energy storage, supercapacitors, ion sensing, and thermal transport.[3]

1.2. Importance of hybrid materials

Although conducting polymers exhibit promising properties, their application is often limited to their pristine forms. This has led to the hybridization of conducting polymers with other materials to achieve improved performance. These materials include carbonaceous materials, metal oxides, transition metals, and transition metal dichalcogenides.[1,4] Hybrid materials exhibit improvements in properties that have a synergistic effect on their electrical, optical, mechanical, and electrochemical properties. The combination of conducting polymers with other materials has expanded their potential applications.[5] Despite significant progress, no recent review has integrated the synthesis–structure–application continuum of CP hybrid materials with critical insights into their performance trade-offs, degradation mechanisms, and fabrication scalability. Most prior studies have focused on pure CPs or narrow application domains, leaving a fragmented understanding of how material structure impacts real-world deployment. This review addresses this gap by synthesizing recent findings, comparing fabrication approaches, and critically evaluating the functional performance across environmental and energy-related domains.

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1.3. Scope and objectives of the review

This review aims to provide an update on the synthesis, properties, and applications of conducting polymers and their hybrids. Transport models explaining the conduction mechanism and the most relevant synthesis approaches related to the electrical, optical, and mechanical properties have been presented in previous reviews.[6–9] This review focuses on the new developments in the applications of conductive polymers and their hybrid materials for energy storage, photocatalysis, anticorrosion coatings, biomedical applications, and sensing. A schematic overview of these structural classes, along with representative synthesis routes and hybridization strategies, is presented in Fig. 1. As the field of CP hybrid materials continues to evolve, several critical challenges must be addressed. These include ensuring long-term material stability under real-world conditions, improving interfacial charge transport across dissimilar phases, and achieving scalable, cost-effective synthesis.[10–12] Future research should prioritize the integration of CP hybrids into flexible, wearable, and multifunctional platforms, the development of bioinspired or self-healing systems, and the refinement of doping strategies for the tuning of adaptive properties. This review aims to highlight these evolving frontiers and critically examine the current knowledge, thereby providing a comprehensive foundation for future innovations.

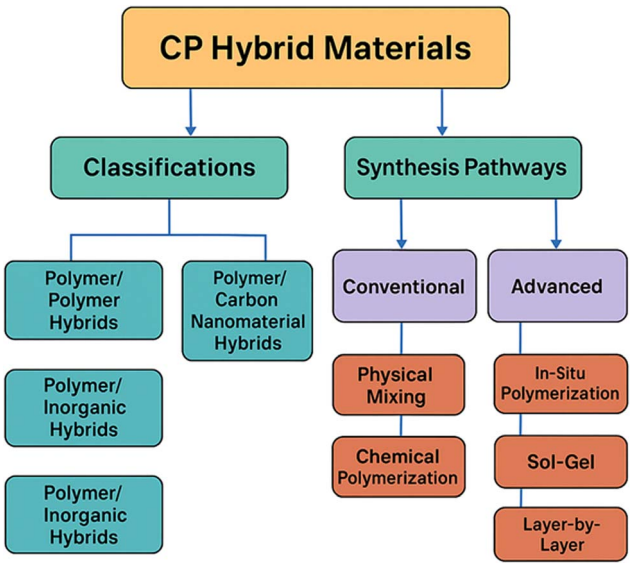

Fig. 1 Structural classification and synthesis routes of CP hybrid materials. This schematic illustrates the four main classes of CP hybrid architectures: core–shell structures, interpenetrating polymer networks (IPNs), layered composites, and dispersed nanocomposites. For each category, commonly used components (*e.g.*, carbon nanotubes, metal oxides, and silica particles) and fabrication strategies (*in situ* polymerization, electrochemical deposition, solution blending, and self-assembly) are discussed. The arrows represent the synthetic pathways connecting the polymer type, hybridization strategy, and resulting morphology. This classification aids in selecting tailored material designs for specific applications, such as supercapacitors, sensors, and corrosion-resistant coatings.

1.4. Historical context and key milestones

Conducting polymers were discovered nearly three decades ago, in the late 1970s, by Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa, who subsequently won the Nobel Prize in Chemistry for their examination of polyacetylene.[12–18] Since then, interest in conducting polymers has grown considerably, with new types being created from polypyrrole, polyaniline, and, more recently, poly(3,4-ethylenedioxythiophene) (PEDOT) polymers. The hybridization of conducting polymers with other materials has largely expanded the horizons of their potential applications and opened avenues for the development of advanced materials with improved properties.[19]

Sumdani *et al.* (2021)[3] reviewed recent developments in the synthesis and properties of conductive polymers, including their applications in electrochemical energy storage devices. Available research suggests that nanotechnology is an essential tool for enhancing the performance of supercapacitors and boosting the performance of conductive polymer composites. This agrees with the observations of Tadesse 2024,[3] who noted considerable progress in the development of conductive polymer composites for supercapacitor applications.

The more recent effort of Sethumadhavan *et al.* in 2019 (ref. 20) was toward the progress of the ion-sensing process using conducting polymer-based sensing materials, thus exploring their capabilities for enhancing ion-sensing applications. Masood's 2024 contribution[21] highlights the increased interest in conducting polymers for energy storage. The unique features of these materials make them attractive for various applications. These studies demonstrate the potential and diversity of conducting polymers in addressing energy storage issues.

Xu *et al.* (2019)[22] provided insights into the thermal transport properties of conductive polymer-based materials, emphasizing the importance of regulating their thermal conductivity. This review summarizes the basic principles and recent advances in thermal transport for the design of conducting polymers with targeted applications that require specific thermal management levels.

In recent years, considerable effort has been directed toward the synthesis, properties, and applications of conducting polymers to enhance their performance in diverse applications. The reviewed studies further elaborate on the development of conducting polymers for energy storage, supercapacitor applications, ion sensing, thermal transport, and a diverse range of applications in which these materials can make a difference. Owing to their unique properties and capacities, researchers are working to correlate conducting polymers with disruptive technologies such as energy storage, sensing, and thermal management.[23–28]

2. Synthesis methods and properties of CP hybrid materials

2.1. Conventional synthesis techniques

Conventional CP synthesis methods include chemical polymerization, electrochemical polymerization, electrospinning, and *in situ* polymerization.[29]

2.1.1. Chemical polymerization. This process involves the oxidative polymerization of monomers using agents such as ammonium persulfate or ferric chloride.[30] For example, polyaniline can be synthesized using ammonium persulfate as an oxidant. This route is easy and enables the production of high-yield CPs or CP hybrids with controlled molecular weights and degrees of polymerization.[31]

2.1.2. Electrochemical polymerization. This technique describes the oxidizing polymerization of deposited monolayers of monomers on the surface of an electrode that occurs along with the applied potential. Therefore, it is convenient to control the film thickness and morphology to produce CP coatings and thin films with desirable properties for use in sensors and devices.[32,33]

2.1.3. Electrospinning. This process involves the use of intense high-voltage electric fields to produce nanofibers from CPs using a polymer solution. The high surface area and porosity of the resultant fibers render them useful for energy storage and sensor applications.[34,35] An overview of the principal synthesis strategies for CP-hybrid materials is shown in Fig. 2.

2.1.4. *In situ* polymerization. In this approach, CP is formed directly within or around the hybrid component. This method often results in better integration between the CP and hybrid material, leading to improved interfacial properties.[36,37] In studies dealing with CP hybrid materials, various synthesis methodologies have advantages and limitations, depending on the intended application and required properties. Table 1 summarizes the most important synthesis methods, including their characteristics, advantages, and limitations, with examples and the improvements they can bring to CP hybrid materials.

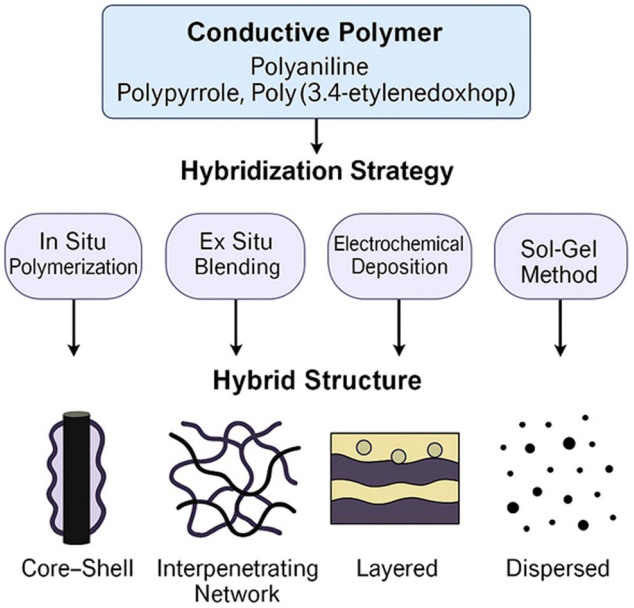

Fig. 2 Schematic illustration of the key synthesis routes for conducting polymer (CP) hybrid materials. This figure summarizes four major fabrication approaches for CP hybrid structures: *in situ* polymerization, *ex situ* blending, electrochemical deposition, and sol–gel processes. *In situ* polymerization enables the direct formation of CP on functionalized substrates, ensuring strong interfacial bonding and conformal coverage of the substrate. *Ex situ* blending allows the incorporation of preformed fillers into polymer matrices *via* solution casting or melt mixing. Electrochemical deposition enables precise control over the thickness and doping levels by voltage tuning. The sol–gel approach facilitates the integration of metal oxides and ceramics, offering porosity control and thermal stability. Each method is associated with distinct advantages and structural outcomes, allowing researchers to tailor CP hybrids for specific energy, sensing, and electronic applications.

2.2. Novel fabrication approaches

In the field of CP hybrid research, innovative fabrication techniques are emerging that depart from conventional synthesis methods and emphasize precision, multifunctionality, and integration into advanced devices. These techniques include layer-by-layer assembly, 3D printing, plasma polymerization, and electrospinning, each designed to address challenges related to scalability, structural complexity, and customization for specific applications. By incorporating principles from nanofabrication, surface engineering, and smart material processing, these approaches offer significant potential for controlling hierarchical architectures, enhancing interface engineering, and ensuring compatibility with Industry 4.0 technologies.[49–52]

2.2.1. 3D printing. Complex structures can be designed using conductive polymers. Tailored geometries, such as those of sensors and actuators, can significantly improve devices.[53] However, the integration of CP hybrids into 3D printing technology presents several challenges. Material compatibility remains a critical issue because the rheological behavior of CP inks often hinders smooth extrusion and layer adhesion.[54] Furthermore, resolution limitations owing to the nozzle diameter and polymer viscosity constrain the minimum feature size achievable, which can impact device miniaturization.[55] The layer-by-layer nature of 3D printing can also introduce anisotropy in the electrical conductivity, potentially compromising the performance of electronic applications.[56]

2.2.2. Sol–gel process. This method involves allowing a solution to progress toward a solid gel phase.[57] This is particularly helpful for incorporating conducting polymers into inorganic materials and often results in hybrid materials with improved mechanical and electrical properties.[58] For example, polyaniline–silica hybrid films prepared *via* sol–gel processing have shown a 3-fold increase in tensile strength and approximately 40% improvement in electrical conductivity compared to their pristine CP counterparts.[59] However, the sol–gel process presents significant challenges. Long processing times during gelation may lead to shrinkage, cracking, or pore collapse, particularly under uncontrolled drying conditions.[60] These effects can compromise the homogeneity and mechanical integrity of the resulting hybrid, thus requiring careful optimization of the precursor composition, catalyst concentration, and aging time.[61] Layer-by-layer assembly: this method involves alternating the deposition of CPs with other materials to enable multilayer construction. This method can improve the conductivity and stability of hybrid materials.[62]

Table 1 The methodologies for the synthesis and properties of conductive polymer hybrid materials are analyzed in the following table, with the main synthesis methods of CP hybrid materials, pointing to the basic characteristics, advantages, and limitations, typical examples of CP hybrids, together with the obtained improved properties. The compatibility of the synthesis method, substrate, and application objectives defines the synthesis methodology, making this a very demanding task in the hybrid material design process

Synthesis method	Synthesis description	Advantages	Limitations	Examples of CP hybrid materials	Properties enhanced	Representative chemical reagents/conditions
In situ polymerization	CP is synthesized directly on or with a substrate or inorganic material	Strong interface bonding; controlled dispersion of hybrid material	Requires careful optimization of reaction conditions; potential for aggregation	Polyaniline/TiO_2, polypyrrole/graphene	Conductivity, mechanical strength, and thermal stability	Monomers: aniline, pyrrole, thiophene Oxidants: $FeCl_3$, APS, $K_2Cr_2O_7$ Conditions: 0–25 °C, acidic pH (HCl, H_2SO_4), 2–24 hours, inert atmosphere[38,39]
Electrochemical polymerization	Polymerization occurs on an electrode by applying a controlled electrical potential	High precision allows the tuning of film thickness and morphology	Limited scalability; requires conductive substrates	Polypyrrole/nanotubes, polyaniline/metal oxides	Conductivity, surface area, and electrochemical activity	Electrolytes: $LiClO_4$, $TBAPF_6$, H_2SO_4 Conditions: potential: 0.6–1.2 V *vs.* SCE, current density: 0.1–10 mA cm^{-2}, aqueous or organic solvents (ACN, PC), room temperature[7,40]
Solution blending	Pre-synthesized CPs are mixed with other materials in solution and then processed into a hybrid	Simple and scalable; applicable for flexible substrates	Poor interaction between CP and hybrid matrix; potential phase separation	Poly(3,4-ethylene-dioxythiophene)/graphene, polyaniline/carbon nanotubes	Flexibility, film-forming ability, and electrical conductivity	Solvents: NMP, DMSO, $CHCl_3$, m-cresol Conditions: room temperature, stirring 2–48 hours, sonication for dispersion Processing: spin coating, drop casting, doctor blade[41]
Template-assisted synthesis	CPs are formed using templates like surfactants, micelles, or nanostructured materials to control morphology	Precise control over nanostructures; can create porous or hierarchical structures	Template removal can be complex, added cost of template materials	Polypyrrole/silica nanostructures, polyaniline/zeolites	Surface area, porosity, specific capacitance	Templates: SBA-15, MCM-41, AAO membranes, CTAB Removal: HF etching, calcination at 500–600 °C, NaOH treatment Conditions: template impregnation, followed by standard oxidative polymerization[42]
Self-assembly techniques	CPs and hybrid components spontaneously organize into structured composites under certain conditions	Simple and cost-effective; leads to ordered structures	Requires precise conditions; often limited to specific material combinations	Polyaniline/Gold nanoparticles, poly(3-hexylthiophene)/quantum dots	Optical properties, charge transport, stability	Surfactants: SDS, CTAB, Triton X-100 Conditions: pH 3–7, temperature 20–80 °C, controlled ionic strength Assembly time: 6–72 hours, gentle stirring or static conditions[43]

Table 1 (*Contd.*)

Synthesis method	Synthesis description	Advantages	Limitations	Examples of CP hybrid materials	Properties enhanced	Representative chemical reagents/conditions
Chemical oxidative polymerization	CPs are synthesized by reacting monomers with oxidizing agents in the presence of hybridizing materials	Suitable for large-scale production; wide range of compatible substrates	Less control over molecular weight and morphology; residual oxidants may affect properties	Polyaniline/ZnO, polypyrrole/silver nanoparticles	Electrical conductivity, photochemical activity, and chemical stability	Oxidants: APS $(NH_4)_2S_2O_8$, $FeCl_3$, $K_2Cr_2O_7$ Acids: HCl, H_2SO_4, CSA Conditions: 0–5 °C, molar ratio oxidant : monomer = 1–1.5 : 1, reaction time 4–24 hours[44]
Sol–gel method	CPs are incorporated into a sol–gel matrix during or after the gelation process	Enables hybridization with silica or other oxides; high homogeneity	Requires precise control of gelation; may lead to brittle materials	Polyaniline/silica, polypyrrole/titania	Mechanical strength, optical properties, and thermal stability	Precursors: TEOS, TMOS, $Ti(OBu)_4$ Catalysts: HCl, NH_3 Conditions: pH 1–3 for hydrolysis, aging 2–7 days, drying at 60–120 °C, H_2O : alkoxide = 4–10 : 1 (ref. 45)
Physical vapor deposition (PVD)	Thin films of CPs and hybrid materials are deposited using physical methods like sputtering or evaporation	High-purity films; excellent control over thickness and morphology	High cost of equipment; limited to thin-film applications	PEDOT/ITO, polypyrrole/silver nanowires	Conductivity, optical transparency, and flexibility	Conditions: high vacuum (10^{-6} Torr), substrate temperature 25–300 °C Targets: polymer pellets, metal targets Parameters: sputtering power 50–200 W, deposition rate 0.1–10 nm min^{-1} (ref. 46)
Chemical vapor deposition (CVD)	CPs are deposited as thin films by chemical reactions of vapor-phase precursors	Uniform coatings; suitable for large-area applications	Requires specialized equipment and environmental considerations for vapor-phase chemicals	PEDOT/graphene oxide, polyaniline/tungsten oxide	Adhesion, conductivity, thermal stability	Precursors: EDOT, aniline vapor, $FeCl_3$ vapor Conditions: temperature 100–250 °C, pressure 1–760 Torr Carrier gases: N_2, ar, flow rates 10–100 sccm (ref. 47)
Interfacial polymerization	CPs form at the interface between two immiscible liquids containing monomers and oxidants	Can create ultrathin films, high control over the interface properties	Limited scalability; requires immiscible solvent systems	Polyaniline/metal oxide nanosheets, polypyrrole/polymeric micelles	Surface area, interfacial properties, charge transport	Organic phase: $CHCl_3$, toluene with monomer Aqueous phase: water with oxidant (APS, $FeCl_3$) Conditions: room temperature, gentle stirring, reaction time 1–6 hours, phase volume ratio 1 : 1 (ref. 48)

2.2.3. Template-assisted synthesis. The method uses sacrificial templates that direct the formation of CP hybrids with morphologies such as nanotubes or hollow spheres. Thus, it is possible to develop materials with pre-designed features at the nanostructure level.[63,64]

2.2.4. Interfacial polymerization. This process involves the formation of CP hybrid films *via* the reaction of monomers at the liquid/liquid interface between two immiscible liquids. The thin and flexible polymer films formed can be easily transferred onto various substrates.[65] Vapor-phase polymerization: this method involves exposing oxidant-coated substrates to monomer vapors, leading to homogeneous CP hybrid films. It is particularly suitable for coating complex three-dimensional (3D) structures.[66]

2.3. Structural classification of CP hybrid materials

The structure of CP-hybrid materials directly influence their performance. The resulting architecture can vary significantly depending on the interaction between the polymer and the secondary material, whether it is a metal oxide, carbon-based nanomaterial, or another polymer. These structural forms were not interchangeable in this study. They define the pathways for charge transport, determine the mechanical integrity, and influence the response of the material under stress or during cycling. One common configuration is the core–shell structure, in which a conducting polymer layer coats the central filler. For example, carbon nanotube@polyaniline (CNT@PANI) hybrids are designed to combine the mechanical strength and aspect ratio of nanotubes with the redox activity of polymers. This structure improves electron mobility while maintaining the accessibility of the active material accessible.[67]

Another form involves IPNs, where the conducting polymer and secondary matrix form overlapping and intertwined domains. These are typically used to boost elasticity and toughness while maintaining conductivity. IPNs can also reduce phase separation, making them useful for flexible electronics and soft sensors.[68] In layered composites, the materials are arranged in alternating stacks with different properties. Each layer contributes a distinct function: one may promote ion transport, another may provide mechanical stability, and the third may support electronic conductivity. These structures are often assembled *via* layer-by-layer techniques or self-assembly processes and are especially useful in applications such as supercapacitors or sensors, where the separation of ionic and electronic channels is required.[40]

The most widely used configuration is the dispersed nanocomposite, which is structurally less controlled than the other configurations. In this case, the nanoparticles were randomly embedded in the CP matrix. Although easy to fabricate, this structure can suffer from uneven filler distribution and the presence of interfacial defects. However, well-optimized dispersed systems show notable improvements in thermal stability, charge transport, and mechanical strength.[69] Each of these architectures has its tradeoffs. Understanding how the structure affects performance is not only helpful but also essential. The choice between the two depends on the application. A supercapacitor electrode requires a high surface area and high conductivity. A sensor may require fast electron transfer and good mechanical compliance. A corrosion barrier benefits from tight polymer–filler interfaces. Therefore, this classification is not cosmetic; it defines the function of CP hybrid materials in the real world. These structural categories have been widely reported in the literature. Core–shell hybrids, such as CNT@PANI and Ag@PPy, are valued for their enhanced charge transport and strong interfacial bonding.[21] Interpenetrating polymer networks, such as PANI–PVA blends, provide improved elasticity and phase stability.[70] Layered composites, including PEDOT/graphene oxide assemblies, support the effective separation of ionic and electronic pathways, thereby optimizing the device efficiency.[20] Dispersed nanocomposites, such as PPy/silica and PANI/carbon black, are often used in environmental remediation, where surface functionalization and ease of synthesis are essential.[71] Table 2 summarizes the key structural types of CP hybrid materials, outlining their defining features, functional advantages, commonly used compositions, and representative application areas of these materials.

2.4. Structural characterization methods

Characterization is indispensable for understanding the properties and performance of hybrid CP materials. Among these, the following techniques are commonly used:[72,73]

2.4.1. Scanning electron microscopy (SEM). This technique provides detailed images of the surface morphologies of CPs and their composites. This aids in understanding the distribution and alignment of the components within the hybrid materials.[74,75] However, each characterization method has intrinsic limitations. For instance, SEM typically resolves features down to ~1–10 nm but cannot provide internal structural details and may induce beam damage in softer polymer matrices.[76] TEM offers superior resolution (<1 nm); however, sample preparation requires ultrathin slicing, which can introduce artifacts and exclude bulk behavior.[77] XRD cannot resolve amorphous domains and offers only average structural information, whereas FTIR and Raman spectroscopy may suffer from overlapping peaks, reducing their specificity in complex hybrid systems.[78] Understanding these limitations is crucial for selecting complementary techniques to fully elucidate the CP hybrid structures.

TEM was used to obtain information on the internal structure at the nanoscale, which is required to describe the dispersion of the nanoparticles in the hosting matrix of the conducting polymer. High-resolution transmission electron microscopy may provide detailed information regarding the interfacial regions between the CP and hybrid components.[79,80]

2.4.2. X-ray diffraction. This method was used to analyze the crystalline and phase composition of CPs. The diffraction data shows the ordering of the polymer chains and crystalline or amorphous regions.[81,82]

Fourier-transform infrared spectroscopy (FTIR) was used to identify the functional groups and confirm the chemical

Table 2 Structural classification of CP hybrid materials. Summary of common CP hybrid architectures, their structural characteristics, functional advantages, representative materials, and target applications

Architecture type	Structural features	Advantages	Common materials	Typical applications
Core–shell structures	Conducting polymer coats an inorganic or carbon-based core	Enhanced charge mobility, strong interface bonding	CNT@PANI, Ag@PPy	Supercapacitors, sensors, and EMI shielding
IPNs	Overlapping polymer domains form intertwined networks	Improved elasticity and mechanical integrity, reduced phase separation	PANI–PVA blends, PEDOT-based IPNs	Flexible electronics, bioelectronics
Layered composites	Alternating stacked layers of CPs and secondary materials	Optimized ionic/electronic transport, functional layering	PANI/graphene, PEDOT/metal oxides	Energy storage, membrane devices
Dispersed nanocomposites	Nanoparticles randomly distributed in a CP matrix	Ease of fabrication, enhanced thermal and electrical properties	PPy/silica, PANI/carbon black	Thermal management, environmental remediation

structures of the synthesized conducting polymers and their hybrids.[83,84]

Raman spectroscopy represents one of the important spectroscopic techniques for the identification of chemical bonds and functional groups.[85] This confirmed that the CP hybrids were successfully formed while simultaneously detecting the unwanted byproducts of the reaction. X-ray photoelectron spectroscopy (XPS) was used to study the surface composition and different elemental chemical states of the CP hybrids, revealing the nature of the interfacial interactions.[85,86]

2.5. Electrical, thermal, and mechanical properties

The compositions and structures of CPs are at the heart of the properties exhibited by CP hybrid materials.

2.5.1. Electrical properties. Hybridization of conductive fillers, such as carbon nanotubes or metal nanoparticles, significantly improves the electrical conductivity of CPs. Several factors affect the development of efficient hybrid material. The percolation threshold is one of the most important factors. This refers to the minimum concentration of the filler required to attain conductivity.[87,88]

The electrical properties of a material are generally described by conductivity measurements using the four-point probe technique, and Hall effect measurements are used to determine the charge carrier mobility and concentration. Electrochemical impedance spectroscopy (EIS) was used to obtain information regarding the charge transfer process in the material.[89,90]

2.5.2. Thermal properties. In some cases, hybrid materials exhibit improved thermal stability compared with pure conducting polymers. The inorganic material content can improve the degradation temperature while decreasing susceptibility to thermal fluctuations.[91] Thermogravimetric analysis (TGA) was employed to determine the thermal stability, differential scanning calorimetry (DSC) for phase transitions, and heat capacity and thermal conductivity, which are particularly relevant for applications involving thermoelectric devices or thermal management.[91,92] Mechanical properties: the mechanical strength of conducting polymers can be enhanced by introducing reinforcing agents. For instance, the addition of nanofillers can significantly enhance the tensile strength and flexibility of the formed composites, allowing their application in flexible electronic devices. The mechanical properties were evaluated using nanoindentation, tensile testing, and dynamic mechanical analysis.[93] These techniques provide elasticity, hardness, tensile strength, and viscoelastic behavior, which are the basic parameters required for flexible electronic and structural material applications.

2.6. Standardization efforts in characterization and testing

As research on CP hybrid materials has developed into a growing field, the call for standardization of methods in material characterization and testing has increased to ensure that conclusions and recommendations can be compared among different research groups.[94]

Protocols are also being developed to provide general standards for sample preparation, the conditions under which measurements are performed, and data reporting. For organic and printed electronics, standard organizations, such as the IEC, ASTM, and ISO, among others, have work items on the characterization of the materials involved, including many of the key CP hybrid materials. These protocols allow researchers to be more logistically consistent with their measurements.[95,96]

Interlaboratory studies were conducted to validate measurement techniques and establish the criteria for reproducibility. It is now time to divert attention to pinpointing and limiting the sources of variability in measurements originating from environmental conditions, instrument calibration, and sample handling. These collaborative studies will be conducted in various laboratories to validate the testing methods and ensure that the general results are compatible with one another to contribute to field-fostering innovation.[97,98]

Reference materials should also be developed in the form of CP hybrids, as they can serve as benchmarks when calibrating or validating measurement methods using popular instruments. This is often a vital case with highly complex hybrids, where slightly different compositions and/or structural properties are important.[98,99]

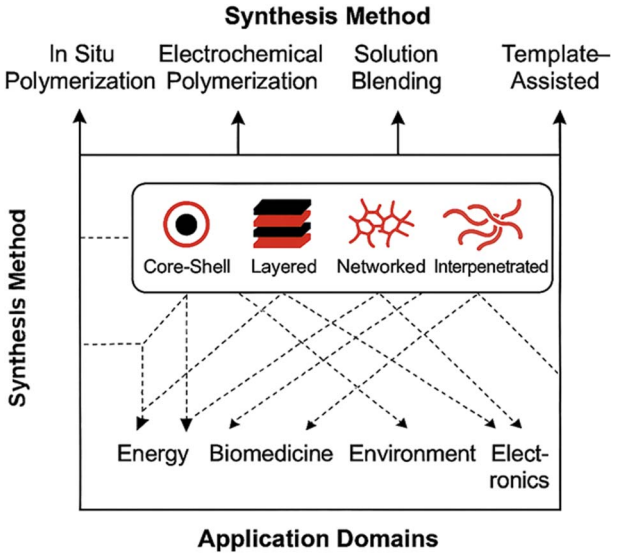

Fig. 3 Structural taxonomy and synthesis-application interconnectivity of conductive polymer hybrid materials. The diagram maps key synthesis methods (*e.g., in situ* polymerization, electrochemical polymerization, and template-assisted methods) against representative structural configurations (*e.g.*, core–shell, interpenetrated networks, and layered architectures) and links them to their dominant application domains, including energy storage, biomedical engineering, environmental remediation, and intelligent electronics. This multidimensional schematic underscores the influence of fabrication strategies on morphology and functional deployment across diverse fields.

It focuses on the future of CP hybrid materials: the standardization of terminology to arrive at a common language regarding their descriptions and properties. This is critical for communication among basic scientists and for gaining translational applications from bench to industry.[100]

The synthesis and characterization were performed using conventional and novel methods. A complete understanding of these properties is important for tuning the corresponding materials for various applications. This will increase the reliability of the research outcomes in the field, with this material being available for use in various applications.[101,102] To illustrate the integrative landscape of synthesis strategies, structural architectures, and end-use applications, a conceptual schematic is presented in Fig. 3, outlining the interconnectivity between the fabrication methods of CP hybrids, morphological design and functional domains.

3. Factors affecting properties of CP hybrid materials

3.1. Composition and morphology

The periodic variation in the composition and morphology of CP hybrid materials results in diversified properties. More precisely, the electrical, thermal, and mechanical characteristics of hybrid materials are altered in type and quantity by inorganic fillers such as carbon nanotubes, graphene, metal oxides, and transition metal dichalcogenides.[103]

For example, the introduction of fillers with large aspect ratios, such as carbon nanotubes, may provide efficient pathways for charge transport and hence improve electrical conductivity. The ratio between the CP and the hybrid component is important; normally, a higher CP ratio will improve the electrical conductivity at the cost of reduced mechanical strength.[70,104,105]

Performance can be driven by material morphology at the nano-, micro-, and macro-scales, respectively. In many cases, CP-nanostructured hybrids exhibit enhanced characteristics owing to their increased surface area and quantum effects. Typical morphologies include nanofibers, nanotubes, and core–shell structures, which provide different benefits in some applications.[102]

The distribution of the components within the hybrid material was also significant in this study. Homogeneous dispersions generally have more consistent properties, whereas controlled heterogeneity can further drive localized functionality or gradient property. The alignment of fillers in a CP matrix can give rise to anisotropic properties, such as directional charge transport.[102]

The tailoring of the properties of CP hybrid materials for targeted applications depends on two major factors: their composition and morphology. By carefully choosing and controlling the type, amount, and distribution of the fillers, along with the overall morphology, it is possible to design CP hybrids with optimized electrical, thermal, and mechanical properties.[106,107]

3.2. Doping levels and types

Doping is one of the most important factors that determine the electrical properties of conductive polymers and their hybrid materials. Hence, doping accumulated at an increased concentration can significantly influence conductivity, charge carrier concentration, and mobility.[108,109]

The dopants typically used are small ions, such as chlorides or sulfates, and large polymeric dopants, such as poly(styrene sulfonic acid) (PSS). During synthesis, the doping levels, that is, the ratio of dopant to monomer units, can be controlled. Elevated doping levels normally enhance conductivity but also influence other characteristics related to mechanical flexibility, optical features, and the structural integrity. At very high doping levels, structural changes can occur in polymers, leading to degradation.[110,111] However, the relationship between the doping level and electrical performance is often non-linear. At low doping concentrations, the conductivity increases slowly owing to isolated conductive domains, whereas a sharp increase occurs near the percolation threshold.[112] Beyond this, excessive doping can cause structural distortions or phase separation, which reduce the charge mobility.[113] Theoretical models such as variable-range hopping (VRH) and percolation theory have been used to describe these trends in CP systems, particularly in polyaniline and PEDOT:PSS composites.[114]

The nature of the dopant can affect all other properties. Inorganic dopants, typically metal ions, increase the stability and conductivity of materials, whereas organic dopants provide

specific functionalities. However, depending on their size and charge, the dopant ions influence the conformation, that is, the chain form and packing, which affects the structure of the resulting material.[110,111]

Redox doping, which involves oxidation or reduction of CP, is particularly important. Long-term performance requires this process to be reversible and stable for applications such as energy storage and electrochromic applications.[115]

Specific optimization of the electrical and electrochemical properties of CP hybrids for certain applications through proper selection and control of the type and level of doping is necessary.[116]

3.3. Environmental conditions

The properties of CP hybrid materials can be effectively affected by environmental conditions such as temperature, humidity, light, and chemical exposure.[117]

3.3.1. Temperature. The conductivity of CPs often increases with increasing temperature because of increased charge carrier mobility. However, high temperatures usually degrade or cause irreversible changes in the material structure. Therefore, inorganic fillers can enhance the thermal stability of hybrid materials and reduce some of these effects.[29,118]

Humidity is a highly relevant parameter, particularly for CPs that consume water. Water intake can change the volume of a material, affecting its mechanical properties and altering its doping state. Some CP hybrids demonstrate improved ionic conductivity in humid environments, which may be either useful or unfavorable depending on the nature of the sensing application.[2,119]

3.3.2. Light and chemical exposure. Bare exposure to light, particularly UV radiation, is sufficient to provoke photodegradation in some CP hybrids, which in turn affects their optical and electrical properties. Chemical exposure can affect the electrical properties and stability of CPs, particularly in sensing applications.[2,120]

Therefore, it is critical to design protective layers or encapsulations to ensure the long-term reliability of CP-based devices in various environments. These protective measures help maintain the stability and performance of materials under different environmental conditions.[121]

Understanding the environmental properties of CP hybrid materials will facilitate the development of robust and reliable materials for real-world applications. In this regard, enhanced thermal stability is important because careful management of humidity effects is considered when offering protection from light or chemicals.[122]

3.4. Interfacial interactions

The properties of CP hybrid materials are affected by their composition, morphology, doping, environmental conditions, and interfacial interactions.[118]

3.4.1. Composition and morphology. The properties of hybrid CP materials are highly dependent on their compositions. In such materials, the ratio of CP to the hybrid component modulates the overall characteristics. For instance, although a higher CP fraction is expected to increase electrical conductivity, it may also diminish the mechanical strength. The morphology of materials at the nano-to-macro scale also affects their performance.[123]

This usually results in better properties of nanostructured CP hybrids, such as nanofibers, nanotubes, and core–shell structures, owing to their larger surface area and unique nanoeffects. Component distribution becomes extremely important; homogeneous dispersion in the matrix, on the one hand, ensures uniform properties; on the other hand, controlled heterogeneity can also introduce localized functionalities or gradient properties.[72,124]

3.5. Doping levels and types

Doping is necessary to tailor the electrical and electrochemical properties of CP-hybrid materials. The doping level determines the charge carrier concentration and mobility, which establish the conductivity. Although a higher temperature usually increases the conductivity, it may decrease the mechanical flexibility or alter the optical properties of the materials.[125] Other factors that modulate the dopant type further enhance the diversity of property modification, whereby inorganic dopants contain metal ions to improve properties such as stability and conductivity, and organic dopants may add additional functionalities to the polymer. Oxidation or reduction under redox doping is a key process in energy storage and electrochromic devices. It considers long-term performance based on stability and reversibility.[125]

CP hybrid materials are sensitive to environmental factors. Influence of temperature: conductivity varies with temperature, and many CPs are conductive at sufficiently high temperatures. However, low or high temperatures can lead to degradation or even structural modifications.[19] The second most critical environmental factor was humidity. Absorbed water causes volume and morphological changes, disrupts the mechanical properties and may also influence the original doping state. In some CP hybrids, the ionic conductivity is highly enhanced in the presence of humidity; hence, it can be utilized in some applications, whereas in others, it can be dangerous.[119] Exposure to UV radiation causes photodegradation, and its relevance and periodic changes affect the optical and electrical properties of materials. The impact developed is realized in practice and can be applied to highly stable materials.[6]

3.5.1. Interfacial interactions. All these interactions occur at the interface between the CP and inorganic filler and determine the properties of the hybrid material.[126] Conversely, good interfaces result in improved mechanical properties owing to enhanced load transfer. Poorly developed interactions, such as van der Waals bonds, may lead to poor dispersion of fillers and hence limit the property enhancement. Modification of the filler surface or the use of compatibilizers can enhance these interactions and optimize the performance of hybrid materials.[127] The nature of this interface also affects the charge transport relevant to various electronic and energy storage applications. Tailored interfacial chemistry can provide specific electronic properties because of charge trapping or facilitation.[128]

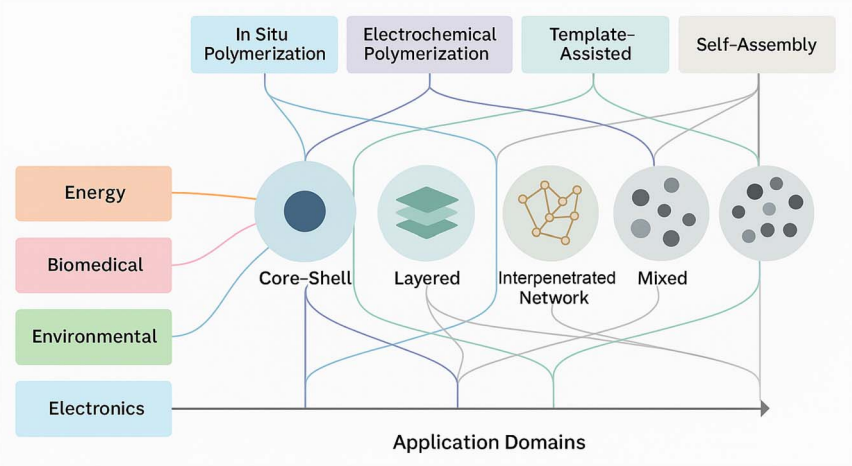

Fig. 4 Structural taxonomy and synthesis-application interconnectivity of conductive polymer hybrid materials. This schematic visually maps the interlinked relationships among the synthesis strategies (*e.g., in situ* polymerization, electrochemical polymerization, and template-assisted self-assembly), structural forms (*e.g.*, core–shell, layered, interpenetrated networks, and mixed architectures), and key application domains, including energy systems, environmental remediation, biomedical devices, and flexible electronics.

3.6. Reproducibility and reliability considerations

The properties of CP hybrid materials are influenced by many factors, including composition, morphology, doping, and environmental conditions (*e.g.*, humidity, temperature, interfacial interactions, and reproducibility).[119,126]

3.6.1. Composition and morphology. The two most important factors in determining the final properties of CP hybrid materials are their composition and morphology.[70] A change in the ratio of CP to the hybridization component changes the overall characteristics; with a higher CP content, the electrical conductivity is usually improved at the expense of mechanical strength.[129] Morphology, on all scales ranging from nanostructured forms, such as nanofibers or nanotubes, to core–shell structures and larger ones, can affect performance owing to the increased surface area or special effects.[130]

This provides a homogeneous dispersion of components with relatively consistent properties, and a controlled level of heterogeneity can confer specific functionalities or gradient properties. To better visualize the interconnectivity between the synthesis strategies, structural forms, and application areas of CP hybrids, a schematic overview is presented in Fig. 4.

4. Types and levels of doping

The doping of CP hybrid materials significantly influences their electrical and electrochemical properties. Chemically induced changes in the charge carrier concentration and mobility shift the conductivity. An increase in the doping level usually improves conductivity, but at the cost of mechanical flexibility or optical characteristics in most cases.[131] The choice of dopants is equally important, where inorganic dopants, such as metal ions, mostly show improvements in stability and conductivity, whereas some organic dopants may add certain functions to the material. Redox doping is essential for energy storage and electrochromic applications. Because these devices must be used for long-term measurements, their performance is often critically linked to their stability and reversibility.[132]

4.1. Environmental conditions

Environmental factors influence the properties and performance of CP-hybrid materials. Temperature changes may result in changes in conductivity, and many CPs conduct electricity much better at high temperatures owing to the enhancement of charge carrier mobility.[133] Extreme temperatures can lead to material degradation. Humidity may affect water absorption, followed by volume change, and subsequently modify the mechanical properties and doping state.[134] Some CP hybrids exhibit improved ionic conductivity under humid conditions, which could be useful for some applications or deleterious to others. Light can lead to photodegradation, and the optical and electrical properties tend to change over time.[135]

4.2. Interfacial interactions

The interfacial interactions between the CP and inorganic filler interface are crucial to the properties of the material.[136] In contrast, strong interfacial interactions, such as covalent or hydrogen bonding, can enhance mechanical properties and charge transfer. Without strong interfacial interactions, only weak interactions, such as van der Waals forces, occur, which may result in poor filler dispersion and limited property enhancements. These interactions can be improved by surface modification or the addition of compatibilizers.[137]

The nature of the interface also affects the charge transport mechanisms in the context of applications, which is most significant for electronic and energy-storage devices. Interfacial chemistry can be used to tailor charge trapping or facilitation.[138] Reproducibility and reliability considerations: the practical applicability of CP hybrid materials requires high reproducibility and reliability. High-purity starting materials, tight control of synthesis conditions, and the application of

standardized characterization methods are some of the factors that aid reproducibility. Reliability is concerned with the stability of a material under operating conditions such as electrical stress, thermal cycling, or mechanical loading. Knowledge of long-term performance and possible failure modes can be obtained through accelerated aging tests, coupled with failure analysis techniques. All these factors are relevant to the construction of high-performance CP hybrid materials for different applications.[139]

5. Structural–property correlations in CP hybrid materials

CPs are a newly discovered class of materials that fill the gap between metals, owing to their electrical conductivity, and polymers, owing to their flexibility and processability. These materials have attracted significant interest in electronics, energy storage, and sensor applications.[118] Nanostructured CPs and hybrid materials have demonstrated improved performance in many ways. Thus, the relationships between the structural properties are essential for optimizing hybrid materials for specific applications.[140]

5.1. Nanostructure conductivity effects

Thus, nanoscale organization is of prime importance for CP conductivity applications. Nanostructures, such as carbon nanotubes, graphene, and polypyrrole nanowires, introduced within a polymer matrix, create conducting pathways that allow efficient charge transport.[141] This effect is more prominent in PPy nanowires embedded in a poly(vinyl alcohol) matrix, where the high aspect ratio of the nanowires results in a significant increase in the conductivity compared to that of bulk PPy nanowires. This is due to the enhanced electrical properties resulting from the formation of interconnected networks in the nanostructures.[142]

Moreover, nanostructure morphology influences conductivity. In one-dimensional nanostructures, such as nanowires and nanotubes, this ensures straight pathways for electron transport, whereas two-dimensional structures increase surface interactions. As has been shown, CPs functionalized with nanowire architectures exhibit conductivities orders of magnitude higher than their bulk analogs.[143]

5.2. Influence of the polymer backbone on properties

Another intrinsic factor that determines the inherent properties of CPs is the chemical structure of their backbones. Generally, CPs with conjugated backbones, such as polyaniline and poly(3,4-ethylenedioxythiophene), are important for electrical conductivity. The extent of conjugation and the substituents on the backbone increase the bandgap and, hence, the conductivity of the polymer.[118]

For instance, the conductivity of PANI can differ considerably depending on its oxidation degree. This characteristic is directly related to the structure of the polymer backbone. The oxidation state of PANI can be precisely controlled during synthesis by selecting the oxidant, its concentration, reaction time, and pH. For example, increasing the ammonium persulfate-to-aniline molar ratio shifts PANI toward its emeraldine or pernigraniline forms, which dramatically alters its electrical and electrochemical properties.[144] Electrochemical polymerization offers even finer control by adjusting the applied potential or current density during growth.[145] These changes also affect the stability, color, and capacitance. A higher oxidation state generally leads to increased conductivity but can reduce mechanical flexibility and long-term electrochemical cycling stability.[146] Such functionalization of the backbone can be achieved by chemical modifications that alter various properties. The introduction of electron-donating groups increased conductivity, whereas electron-withdrawing groups improved stability. In PEDOT, the choice of conducting backbone further affects the mechanical flexibility and electrochemical performance, which are relevant for applications in flexible electronics.[10,71,147]

5.3. Role of functional groups in hybrid performance

The properties and performance of hybrid materials are primarily governed by the functional groups attached to the CPs. They can enhance interactions with other materials, improve solubility, and modify electronic properties. For example, incorporating amine groups into PPy-based hybrid materials can promote hydrogen-bond formation with a silica matrix, leading to improved mechanical properties.[100,122]

The introduction of sulfonic acid groups into PANI, which increases the degree of protonation, enhances the conductivity and charge transport.[148,149] The functional groups introduced into hybrid materials are typically responsible for enhancing their stability and reactivity. The incorporation of functionalized graphene into polymer CPs can enhance the mechanical and thermal properties of the resulting composites.[150] Graphene functional groups form strong interactions with the polymer matrix, resulting in improved performance in applications such as sensors and energy storage devices. Functionalization can also tune the optical property application scope of CP hybrids, enabling them to function as sensors and actuators.[151]

5.4. Emerging analytical methods for structure–property relationships

Advanced analytical techniques are required to determine the structure–property relationships of CP-hybrid materials. State-of-the-art XRD and TEM methodologies provide detailed insights into the nanoscale structure and morphology of materials. In addition, several spectroscopic techniques, such as X-ray photoelectron spectroscopy (XPS), Fourier-transform infrared (FTIR) spectroscopy, and Raman spectroscopy, provide information on the chemical composition and bonding within these hybrids.[152–154]

These analytical tools provide a much deeper understanding of the complex interplay between the structures and properties when combined with computational modeling. This insight is essential for rational design. Hybrid CPs and showcases were optimized for applications. For example, AFM and SEM provide

nanoscale visualizations of the surface topography of materials, whereas XRD and FTIR relate specific structural features to the electrical and mechanical properties of materials.[155,156]

CPs have generated significant interest in various scientific disciplines. Therefore, PANI and its high-conductivity derivatives are useful in organic light-emitting diodes, field-effect transistors, corrosion protection devices and solar cells. In addition, the chemical synthesis of CPs with nanoscale structures has been performed to boost their electrochemical activity and functionality.[148] Various methods, such as chemical and electrochemical syntheses, can be used to produce CPs with controllable molecular structures.[157]

Different synthesis conditions allow CPs with tailored properties, such as battery optimization. Subsequently, CP nanostructures have been used in other energy-storage applications. Among the conductive polymer hydrogels, promising materials have been discovered owing to their unique properties. The combination of CP with conventional polymers can combine the mechanical performance of conventional polymers with the electroactivity of CPs, thereby opening up more extensive fields for these applications.[158]

Recently, CPs have been incorporated into magnetic nanoparticles to form nanocomposites, which extend their potential applications. Electro polymerization is a common method for preparing CP films because it allows the direct deposition of polymers onto conductive surfaces. This is an effective strategy for coating and preparing thin films with specific electrical properties.[159]

CPs represent a versatile class of materials that have been widely applied in various scientific fields, ranging from bioeconomics and optoelectronics to energy and sensing applications. Further research into new strategies for synthesis, nanostructuring techniques, and composite face materials that can improve the properties and functionalities of CPs is undergoing for CPs.[160]

6. Environmental applications of CP hybrid materials

Hybrid materials based on CPs combine the unique properties of conducting polymers with the functionalities of other materials, and thus appear promising for various environmental applications, such as gas sensing, heavy metal detection, dye removal, membrane filtration, and agriculture. This section details the analysis of comparative studies on such applications, given the practical aspects of the real-life implementation of CP hybrids with traditional materials.[23,161] Conductive polymer hybrid materials are of great interest for environmental applications owing to their potential use in water treatment, air purification, and soil remediation. Table 3 describes the specific uses, mechanisms of action, advantages, and limitations of each of these applications.

6.1. Mechanisms and devices to sense gases

CP hybrid materials are highly efficient in detecting various gas species because of their high sensitivity to changes in the electronic structure upon interaction with the target gas molecules. The sensing mechanisms of conductive polymer hybrid aerogels include the modulation of electrical conductivity or changes in other physical or optical properties caused by the adsorption of gas molecules.[175] For example, polyaniline composites with metal oxides, such as SnO_2, exhibit superior sensitivity to volatile organic compounds. This is because of the synergistic effects between CP and metal oxides in the development of low-cost, high-sensitivity, and selectivity-driven gas sensors for environmental monitoring and safety applications.[148] CP matrices with carbon nanotubes or graphene can enhance both the sensitivity and response time. For example, PANI nanostructures deposited on interdigital microelectrodes exhibit good sensitivity and selectivity toward ammonia gas at room temperature.[10,126] The relationship between CP hybrid architectures and their dominant sensing applications is illustrated in Fig. 5.

6.2. Detection and removal of heavy metals

The hybrid materials showed a reputable capability for heavy metal detection and disposal in contaminated water sources. PPy and PANI are two of the most widely used conducting PPy and PANI, mainly because of their high conductivity and the formation of complexes with metal ions. For example, PPy-based electrochemical sensors have shown selectivity for the detection of copper ions in aqueous solutions. PPy-functionalized graphene oxide exhibited a very good adsorption capacity for lead ions.[176,177]

These materials are also used in adsorption-based processes and as components of membrane filtration systems. This is because of their ability to bind heavy metal ions and change their electrical properties, which is useful for sensing and remediation applications.[178] For instance, PPy–graphene oxide composites have shown adsorption capacities of up to 250 mg g^{-1} for Pb^{2+} ions, attributed to π–π interactions and chelation.[179] The hybrid matrix not only stabilizes the CP but also improves the ion selectivity and regeneration capability.

6.3. Dye sensing and remediation strategies

CP hybrid materials are common pollutants in wastewater and are therefore suitable for detection and removal. For example, PANI-based sensors have been developed to detect methylene blue dyes in aqueous solutions. The dye molecules interact with the CP hybrid, causing changes in color or fluorescence during the sensing mechanism.[180]

Thus, they can be used for remediation in adsorption-based processes and photocatalytic systems. For example, PANI/TiO_2 hybrid materials exhibit improved photocatalytic activity for the degradation of methyl orange dye under visible light, thereby proving to be effective against dye pollution.[181]

6.4. Membrane filtration technologies

CP hybrid materials have been extensively applied in membrane filtration technologies, particularly for water purification and desalination. In this study, the materials were easily processed into thin-film composites or mixed-matrix membranes

Table 3 Application of conductive polymer hybrid materials towards the environment the table illustrates the various ways cp hybrid materials are used in specific applications, their operating mechanisms, favorable characteristics, limitations, and examples of environmental applications in light of hazards associated with the treatment of water, purification of air, soil remediation, and pollution monitoring. hybrid materials have superior performance and/or better sustainability because they offer properties unattainable from only one material component in treatments related to environmental hazards caused by water, air, soil, and pollution

Application area	Specific use	Mechanism of action	Advantages	Limitations	Examples of CP hybrid materials	Performance metrics
Water treatment	Removal of heavy metals	Adsorption of heavy metal ions through chelation or electrostatic interactions	High efficiency, regeneration capability	Limited selectivity for specific ions in complex mixtures	Polypyrrole/graphene oxide composites	Pb^{2+} adsorption: 93.2 mg g^{-1} (PPy-reduced GO), Hg^{2+}: 400.0 mg g^{-1} (magnetic PPy-GO), Cd^{2+}: 794.2 mg g^{-1} (COPYGO composite)[162,163]
	Removal of organic pollutants	Catalytic degradation *via* photocatalysis or electrochemical oxidation	Effective for persistent pollutants	Requires light or electrical input	Polyaniline/TiO_2 nanocomposites	Methylene blue degradation: 86.35% (PANI–TiO_2), methyl orange: first-order kinetics with k = 0.619 h^{-1} (ref. 164 and 165)
	Membrane filtration	Enhanced fouling resistance and mechanical strength through hybridization	High permeability and selectivity	Potential biofouling over time	Polythiophene/zeolite composites	Permeate flux: 18 L m^{-2} h^{-1} bar, heavy metal rejection: 90–97% (ref. 166)
Air purification	Capture of volatile organic compounds	Adsorption *via* porous structures and catalytic breakdown	High surface area for adsorption	Regeneration and desorption challenges	Polypyrrole/silica composites	VOC removal efficiency: requires specific verification for toluene[167]
	Decomposition of toxic gases	Catalysis of harmful gases into less toxic products	Eco-friendly, efficient	Requires stable operational conditions	Polyaniline/metal oxide hybrids	Gas sensing: detection limits in ppb range, response times <10 s (ref. 39 and 168)
Soil remediation	Heavy metal stabilization	Binding and immobilization of metals through CP hybrid matrices	Reduces bioavailability	May require additional processing for deeper penetration	Polypyrrole/clay composites	Cr^{6+} removal: requires verification of 92% efficiency claim[169,170]
Energy harvesting from waste	Energy recovery from microbial fuel cells	Enhanced electron transfer in microbial fuel cells using CP hybrid materials	Improves energy efficiency	Requires optimization for scalability	Polypyrrole/carbon nanotubes hybrids	Power density: typical range 50–200 mW m^{-2} for CP-enhanced MFCs[38,171]
Sensing and monitoring	Detection of environmental contaminants	High sensitivity detection through changes in conductivity or electrochemical response of CP hybrids	Fast response, portable devices	Prone to interference from other contaminants	Polyaniline/metal nanoparticle composites	Detection limits: heavy metals in μg L^{-1} to ppb range depending on analyte[172,173]
	Real-time pollutant monitoring	Integration into smart sensors for real-time monitoring	Continuous monitoring of potential	Maintenance and calibration challenges	Polythiophene/graphene composites	Gas detection: ppb-level sensitivity with stability >30 days[173,174]

characterized by high permeability, selectivity, and fouling resistance.[182,183] For instance, PEDOT/graphene oxide hybrid membranes exhibit remarkable flux and salt rejection during desalination. CP hybrids can also be used as active membranes, increasing desalination efficiency through controlled selective ion transportation.[184]

6.5. Agricultural applications

These polymers have been utilized in many fields, including pesticide sensing and controlled release in agriculture. For example, PANI. Graphene oxide hybrid sensors have been proven effective in determining organophosphate pesticides in water samples. In this trend, CP hybrids would avail themselves of a matrix as a carrier of environmentally safe and effective agrochemicals with a controlled release rate that may be altered by changes in material composition or external stimuli, such as pH and temperature.[185,186] These materials also hold great potential for smart agriculture, where they can be integrated into sensors to monitor soil conditions and facilitate efficient and sustainable practices.

6.6. Comparative analysis with traditional materials

On the other hand, CP hybrid materials are preferred over more classical metal oxides or activated carbon materials and have several advantages, including the following.

6.6.1. Tunable properties. The composition, morphology, and functional groups of CP hybrids can be tuned to optimize their performance for specific applications.[187]

6.6.2. High specific surface area. In many cases, CP hybrids have high surface areas. Therefore, there is potential for enhancing adsorption and catalytic processes.[188]

6.6.3. Flexibility and processability. Some CP hybrids can be processed into films or membranes, and are suitable for general applications.[19,189]

6.6.4. Biocompatibility. Some CP hybrids are biocompatible; accordingly, they can be used in agriculture and biomedicine.[190]

However, in other aspects related to effectiveness, stability, or specific performance metrics, traditional materials may outperform CP hybrids. Therefore, a proper comparative analysis should be adopted to choose the most suitable material for any environmental application.[191] One critical consideration is the cost of raw materials and their fabrication. While CP hybrids offer superior tunability and multifunctionality, their synthesis, especially *via in situ* or template-assisted methods, often involves higher reagent and processing costs than conventional materials such as activated carbon or zinc oxide.[192] For example, PANI/TiO_2 composites used for dye degradation are 1.5–2 times more expensive per unit mass than bulk TiO_2, primarily because of the oxidative polymerization steps and the cost of monomers.[193] However, some metal-oxide-based systems are more cost-effective for bulk remediation. However, the cost gap narrows significantly when the lifecycle performance is considered, particularly when CP hybrids exhibit enhanced regeneration, selectivity, or durability.[179] A comprehensive cost–benefit analysis is essential for each specific application.

6.7. Practical considerations for real-world implementation

Although CP hybrid materials are the most promising, a variety of pragmatic challenges remain to be addressed for successful real-world implementation, such as scalability and cost. The synthesis and processing of CP hybrids must be scalable and cost-effective for large-scale applications.[122,194] Stability and durability: evaluation and enhancement of the stability of CP hybrids under conditions such as temperature changes, variations in pH, or the presence of interfering substances. System integration: underpinning technologies employing CP hybrids must be integrated into existing infrastructure and processes. Regulatory compliance: environmental impact and regulatory compliance of CP hybrids must be evaluated for safe use and disposal. Standardization and quality control: CP hybrid-based technologies must be based on standard testing methods and quality control, ensuring that the results provided by the technology are both reliable and reproducible.[195]

CP polymer hybrid materials have tremendous potential for a broad array of environmental applications, ranging from gas sensing, heavy metal removal, dye remediation, and agricultural use. Despite offering certain benefits over traditional materials, practical considerations must also be considered. More research and development are essential for the full exploitation of CP hybrid materials to create sustainable environmental solutions.[196]

7. Energy-related applications of CP hybrid materials

Hybrid materials based on conducting polymers combine the high electrical conductivity of CPs with their unique physicochemical properties. These materials show strong potential for

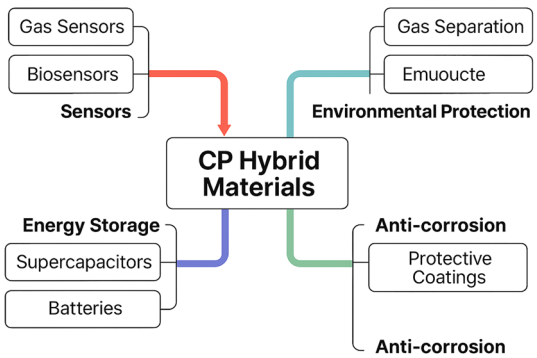

Fig. 5 Architecture-to-application mapping of CP hybrid materials in sensing technology. This flowchart links the key structural forms of CP hybrid materials, such as core–shell, IPNs, layered composites, and dispersed nanocomposites, with their respective advantages and dominant sensing applications. Core–shell hybrids offer enhanced electron mobility and are used in gas sensors and biosensors. IPNs provide structural flexibility, making them suitable for wearable and skin-based sensors. Layered structures enable anisotropic transport and are applied in humidity and pressure sensors. Dispersed composites offer scalable fabrication methods for disposable chemical sensors. This mapping provides a design framework for selecting appropriate CP architecture based on the sensor performance requirements and operating conditions.

many applications related to energy. Good candidate interfaces also show tunable properties, high surface areas, and the ability to interact with several redox species for energy storage, conversion, and harvesting.[197] The application of CP hybrid materials as electrocatalysts in fuel cells, water splitting, and other electrochemical energy storage devices is discussed. One will also address the associated performance criteria, benchmarks, and challenges of scaling up *versus* staying competitive from the perspective of low-cost.[198]

7.1. Electrocatalysts for fuel cells and water splitting CP

Hybrid materials have been investigated as electrocatalysts for fuel cells and water splitting, owing to their high conductivity and ability to promote electrochemical reactions. For example, polyaniline (PANI) composites with metal nanoparticles, such as Pt or Ru, have shown improved ORR activity in fuel cells.[199] As a rule, these hybrids rely on the large surface area of CP to afford a large amount of active site space for reactions, while the metal nanoparticles improve electron transfer and catalytic activity.[200]

CPs have been demonstrated to improve the electrocatalytic activity towards the splitting of water to produce hydrogen and other materials. For instance, PPy metal oxide composites, including NiO, exhibit good performance in the water oxidation process, which is a critical step in the splitting of water to produce hydrogen and oxygen. These materials usually have high conductivity and redox properties that facilitate charge transfer while increasing the general reaction efficiency.[201]

7.2. Electrochemical energy storage devices

CP composite hybrid materials are excellent candidates for a range of electrochemical devices such as batteries, supercapacitors, and hybrid energy storage systems. Owing to their high conductivity and high redox activity, these materials can provide easy storage and smooth release of charges, yielding high-energy or power densities at the end.[196] For instance, PANI-composite-based carbon nanotubes are good candidates, yielding good performance in supercapacitors. A high capacitance and decent cyclic stability were simultaneously demonstrated.[202]

These CP hybrids, such as polythiophene, combined with metal oxides, enhance the energy density and cycle life performance of lithium-ion batteries as mixed electrode materials. These hybrids have high conductivity and redox properties, which facilitate lithium-ion diffusion and enhance the electrochemical performance of batteries.[203]

7.3. Photovoltaic and photoelectrochemical

They also play a vital role in optoelectronic devices such as solar cells and corresponding photoelectrochemical systems because they enable effective light harvesting and charge separation owing to their tunable bandgap and high photoconductivity.[204] An example is the enhanced light absorption of dye-sensitized solar cells operated in CP-based composites with quantum dots, along with an improved rate of photocatalytic activity. With these devices, where CPs have provided a conductive pathway, the quantum dots, inversely, produce both effective light harvesting and charge separation.[205]

In addition, PANI composites with titanium dioxide nanoparticles have been applied as photoelectrodes in PEC water-splitting systems. It exhibited improved photocatalytic activity for the generation of hydrogen and oxygen under sunlight.[206]

7.4. Thermoelectric materials

The potential of CP hybrid materials, in which electrical energy can be produced by the action of waste heat, is receiving increasing attention in thermoelectric applications. This tuning of electronic and thermal conductivities enables effective energy conversion.[207] For example, CPs can also be designed with a meaningful enhancement in thermopower and optimized electronic characteristics by filling them with conductive carbon nanotubes or graphene, and materials such as those that could be highly promising for waste heat recovery.[208]

7.5. Performance measures and benchmarks

The performance of CP hybrid materials in energy-related applications must be evaluated using certain metrics and benchmarks. The key performance indicators were as follows:

7.5.1. Storage capacity. Measured in terms of specific capacity (mA h g^{-1}) and energy density (W h kg^{-1}) for batteries and supercapacitors.[209]

7.5.2. Power density. Measured in power density (W kg^{-1}) for supercapacitors.[210,211]

7.5.3. Cycle life. The number of charge and discharge cycles that a certain device can perform before serious performance degradation occurs.[212]

7.5.4. Efficiency. This is the rate at which light or chemical energy is converted into electrical energy by solar and fuel cells.[213]

Catalytic activity was characterized in the context of current density, turnover frequency, and selectivity toward the target reaction. These metrics are essential for the comparison of CP hybrid materials in terms of performance with traditional materials; they establish benchmarks for further improvement.[214] However, performance metrics alone are insufficient without understanding degradation pathways during prolonged use. In CP-based supercapacitors, cyclic voltammetry over hundreds or thousands of cycles often leads to decreased capacitance due to morphological collapse, dopant leaching, and chain scission within the polymer matrix.[215] For battery applications, hybrid materials may suffer from electrode swelling, phase separation between the CP and inorganic filler, or side reactions at the electrode–electrolyte interface that lead to impedance buildup.[216] In flexible devices, repeated mechanical deformation further accelerates microcrack formation and electrical discontinuities.[217] These mechanisms contribute to the gradual decline in storage capacity, power output, and cycle life and must be mitigated through careful interface engineering, dopant stabilization, or encapsulation strategies.

7.6. Scalability and cost-effectiveness challenges

Although CP hybrid materials have high potential for a wide range of applications, their commercialization scope has

narrowed owing to some bottlenecks.[100] Some of the current key challenges are

7.6.1. Synthesis and processing. Scalable and cost-effective procedures for synthesizing and processing CP hybrids must be developed for large-scale manufacturing.[218] Stability and durability: long-term stability and durability under operating conditions are fundamental for practical implementation in energy devices.[219] Material cost: the material and synthesis of the CP material account for the cost of energy devices and should thus be primarily considered in making the process cost-effective. Addressing these challenges through continuous study and research is the way to the general adoption of CP hybrids for energy applications to bring us into a more sustainable and efficient future.[220]

Potential applications of CP hybrid materials include electrocatalysis in fuel and water-splitting cells, electrochemical energy storage devices, solar cells, and thermoelectric materials. Owing to their tunable properties, high surface area, and flexibility, this class of materials has diverse applications in energy technologies. Nevertheless, issues in scalability and cost reduction have successfully traversed the commercialization of devices. Continuous research, development, and collaboration among researchers, industry, and policymakers are crucial for overcoming these challenges and advancing sustainable energy technologies.[221]

8. Corrosion protection using CP hybrid materials

CP hybrid materials have recently come into the spotlight because of their effectiveness in protecting against corrosion. These hybrids bind the electrical conductivity of CPs with the protective properties of other materials, resulting in an improved performance against traditional methods of corrosion protection. Key points, such as mechanisms of corrosion inhibition, development of smart coatings, and self-healing materials, were compared and evaluated against conventional approaches in this analysis.[6]

8.1. Mechanisms of inhibition of corrosion

The main mechanisms by which the corrosion process is inhibited for most CP hybrid materials include the following.

8.1.1. Barrier protection. Hence, conducting polymers such as polyaniline and polypyrrole cover the metal surface and provide a physical barrier against corrosive agents, moisture, and oxygen, which diffuse to the substrate and slow down the corrosion process.[222] The described barrier action is enhanced by adding materials such as nanoparticles or inorganic fillers into the CP matrix, which makes it more resistant to corrosive elements.[223]

8.1.2. Cathodic and anodic protection. Some CPs can act as sacrificial anodes, which means that they preferentially oxidize rather than have a metal substrate, which is a process called cathodic protection.[222] Other CPs achieve anodic protection by shifting the electrochemical potential of the metal surface to more positive values, thereby allowing the formation of a passive layer that protects the metal underneath. For example, PANI has been found to anodically shift the corrosion potential of steel, resulting in a lower corrosion rate in highly aggressive environments.[224,225]

8.1.3. Electrochemical impedance and controlled release of inhibitors. Some CPs can enhance the interfacial impedance at the metal surface, opposing the flow of the electrons and ions responsible for corrosion.[226] Furthermore, certain CP hybrids could solubilize releasable corrosion inhibitors in a self-healing type response to further improve the long-term performance of the protective coating. Such a potential response would be due to environmental stimuli such as pH changes and would ensure a continuous renewal of active species to counter corrosion.[222,227]

8.2. Smart coatings and self-healing materials

CP hybrid materials also permit the development of smart coatings and self-healing materials that can respond to their environment and damage while offering advanced corrosion protection.

8.2.1. Smart coatings. Hence, these coatings can perceive changes in the environment, for instance, moisture or temperature shifts and react accordingly. For instance, pH-sensitive CP-based coatings can release corrosion inhibitors under acidic conditions, thus preventing further degradation. Moreover, the combination of nanomaterials with CPs enhances their responsiveness and functionalities, thereby creating applications of many types.[228,229]

8.2.2. Self-healing materials. CP self-healing hybrids encapsulate corrosion inhibitors released in the case of mechanical damage or corrosion. If a crack in the coating develops, a healing agent fills this void and polymerizes, thus "healing" the protective layer. Various studies have shown that the application of self-healing CP coatings may considerably prolong the lifetime of protective systems by protecting them against corrosive environments.[230,231]

8.3. Comparative analysis with traditional methods of protection against corrosion

The following strengths and weaknesses have been identified when comparing CP hybrid materials with classical methods of corrosion protection, such as organic coatings, galvanization, or metal plating.

8.3.1. Effectiveness. Better corrosion resistance is often observed with CP hybrids because they have dual mechanisms of barrier protection and active inhibition. Traditional methods rely largely on barrier properties; therefore, they are not able to provide high protection, especially in very aggressive environments.[232]

8.3.2. Environmental impact. Traditional methods of protection against corrosion often utilize toxic chemicals or heavy metals, thereby posing environmental risks. On the other hand, CP hybrids can be obtained from more environmentally friendly materials, making them more sustainable.[233]

8.3.3. Flexibility of applications. CP hybrid materials can be easily tailored for specific applications by modifying their

chemical structures or by incorporating various additives. Traditional methods, while effective, generally require extensive customization processes.[189]

8.3.4. Durability and self-healing. CP hybrid coatings will be stronger and more resistant to harsh environments than traditional coatings. Furthermore, the self-healing features of the CP hybrids extend their lifespan by allowing the coating to heal whenever damage occurs. Cost and scalability. While CP hybrid materials have several advantages, the processes related to their production and application may be more complicated and potentially more expensive than traditional methods.[234] However, research in this area is ongoing to further optimize these conducting-polymer hybrid materials are a new generation of tools for protection against corrosion. By applying the mechanisms of barrier protection, cathodic and anodic protection, and controlled release of inhibitors, these materials afford superior corrosion resistance compared to traditional methods of protection against corrosion. Smart coatings and self-healing materials occupy a place of pride to enhance their protective capabilities further. Although there are still difficulties with plating in terms of cost and scalability, further research in this area will likely provide a more effective and long-term corrosion protection solution for different industries.[235]

8.4. Biomedical applications of CP hybrids

The integration of CP hybrids into biomedical systems has opened new avenues for multifunctional platforms that couple electrical functionality with biocompatibility. These systems leverage the inherent advantages of CPs, such as flexibility, tunable conductivity, and chemical functionality, while overcoming traditional limitations through structural reinforcement with inorganic or bioactive counterparts.[236,237]

One of the most mature application domains is neural interfacing, where CP hybrids like poly(3,4-ethylenedioxythiophene) (PEDOT) doped with biocompatible counterions or nanoparticles are employed to enhance electrode–tissue coupling. Their soft mechanical properties minimize interfacial strain, while their high charge injection capacity supports chronic electrophysiological performance without significant signal degradation. CP-based neural coatings have demonstrated improved signal-to-noise ratios and decreased impedance compared to conventional metallic interfaces.[238,239]

Electrochemical biosensing represents another major front, where hybridization with metal nanoparticles (*e.g.*, Au, Pt) or carbon nanostructures enhances electron transfer kinetics and increases the surface area for biorecognition element immobilization. CP hybrids in glucose monitoring, cancer biomarker detection, and neurotransmitter quantification have shown detection limits in the nanomolar to picomolar range, depending on the transduction mechanism.[240,241]

In drug delivery, CP hybrids enable electrically triggered release of therapeutics. By incorporating biodegradable or responsive dopants, hybrid films can be tailored for localized, on-demand drug elution. Polypyrrole (PPy) or polyaniline (PANI) matrices embedded with silica or hydrogel phases have demonstrated improved mechanical integrity and controlled swelling behavior, critical for *in vivo* stability.[4] Moreover, the inclusion of growth factors or antimicrobial agents within CP networks offers dual therapeutic and regenerative functionalities, particularly relevant in wound healing scaffolds.[242–244]

CP hybrids also show promise in the development of bioelectronic skins, flexible implantable sensors, and cardiac pacing electrodes, where conformability, miniaturization, and multifunctionality are essential. These applications benefit from the synergistic combination of soft organic polymers with conductive fillers that preserve electrical percolation networks under dynamic physiological conditions.[245,246]

Despite significant progress, challenges remain in achieving long-term biostability, minimizing immune responses, and ensuring scalable fabrication. However, with advances in printable bioinks, hydrogel–CP composites, and bioresorbable doping chemistries, CP hybrids are poised to become core materials in next-generation biomedical systems.[247,248]

9. Energy storage mechanisms in CP hybrid materials

Most importantly, CP hybrid materials are considered more important for electrochemical energy storage because of their unique integration with high conductivity, redox activity, and tunable surface chemistry.[249] Described below are the mechanisms of energy storage enlisted in this analysis: faradaic and non-faradaic processes, in which nanostructuring takes part in charge of transport and storage, along with *in situ* characterization techniques.

9.1. Faradaic and non-faradaic processes

9.1.1. Faradaic processes. These are redox reactions in which electrons move from the electrode to the electrolyte or *vice versa*. The high energy density of CP materials is attributed to these reactions because they lead to internal chemical changes. For example, the redox reactions of polyaniline (PANI) and polypyrrole (PPy). Although faradaic processes display a high energy density, they often have a lower power density than non-faradaic processes.[250,251]

Non-faradaic processes involve the formation of an electrical double layer at the electrode–electrolyte interface, which is usually created by the adsorption and desorption of ions. This is because carbon-based materials have high power density and long cycle life. In CP hybrids, the addition of carbon nanostructures can further improve this non-faradaic energy-storage feature.[252]

As a result of these competing processes, hybrid materials with designed combinations of faradaic and non-faradaic processes balance energy and power densities and simultaneously work equally well in all applications from supercapacitors to batteries.[253]

9.2. Charge of transport and storage in nanostructured hybrids

9.2.1. Nanostructuring. The nanostructures of CP hybrid materials directly influence their performance in large-scale

energy storage. Nanostructured materials dominate in providing a surface large enough to be usable for charge storage and, in general, increase the reaction kinetics involving charge transfer. For instance, the inclusion of conductive nanostructures within CP matrices enhances electron transport, thus increasing conductivity and rate capability.[254]

9.2.2. Charge transport. The nanostructure ensures efficient channels of electron transport, thus optimizing the overall effective conductivity of CP hybrid materials. This improved the power density and rate capability.[255]

9.2.3. Ion diffusion. Porous nanostructures and the optimization of the pore-size distribution facilitate the diffusion of ions and, hence, increase the diffusion of the accessible surface area for energy storage and boost the capacitance along with energy density.[256]

Synergistic effects: allowing the faradaic properties of the hybrid structures, CP with faradaic materials, could lead to synergistic effects in achieving enhancements in energy and power densities.[257]

9.3 *In situ* characterization techniques

In situ X-ray diffraction (XRD) enables the monitoring of structural changes in the CP hybrid material as they electrochemically cycle and offers information on phase transitions and changes in lattice parameters.[258] These real-time structural insights can be used to dynamically adjust synthesis parameters such as monomer concentration, polymerization time, and thermal treatment. For example, shifts in XRD peaks during *in situ* monitoring indicate phase transitions that help determine optimal annealing temperatures to preserve conductive domains.[259] Similarly, *in situ* Raman spectroscopy detects oxidation state changes and bond reconfiguration during electrochemical cycling, allowing the fine-tuning of dopant levels or co-polymer ratios to enhance stability and charge transfer efficiency.[40] These feedback loops bridge materials characterization with real-time process control, enabling more reliable and reproducible CP hybrid design.

In situ, Raman spectroscopy could report changes in the chemical structure and oxidation state of CP during processes in a way that would provide detailed insight into the faradaic reactions and formation of intermediate species.[260]

9.3.1. *Ab initio* theoretical simulation of X-ray absorption spectra. XAS provides local structure and oxidation state information for the chosen elements during electrochemical cycling *via in situ* studies. Changes in the coordination environment and formation of new species were also observed.[261]

9.3.2. Electrochemical impedance spectroscopy. It gives information about ion diffusion, charge transfer resistance, and capacitance. X-ray photoelectron spectroscopy: it probes the state of charge of CPs during several stages of charge storage, hence giving information on redox reactions. In general, hybrid materials of CP inherently store energy by either faradaic or non-faradaic processes.[262] The nanostructuring of these materials improves their quality, particularly according to how charges are transported and stored. Advanced *in situ* characterization will enable real-time monitoring of its performance and, therefore, lead directly to high-performance energy storage devices. These materials have clear advantages over traditional methods, but the cost related to scalability tends to be a major challenge. Continued research and optimization are essential for the advancement of their application in energy storage technologies.[263]

9.4. Critical analysis of reported energy storage performance

Hybrid materials based on conducting polymers show great promise in energy storage, but a comprehensive analysis of disparities in the literature regarding the reported performance of these hybrid materials is desirable to gain insight into their actual capability *versus* limitations. This section presents the evaluation of the key performance metrics, existing challenges, and future research directions.[264]

However, the reported values for the specific capacity and energy density differ significantly because of the conditions of the experiment, such as the type of electrolyte, current density, and temperature. Difficulties related to the variance in these variables resulted in inaccuracies when comparing the results of different studies. For example, the choice of electrolyte and the specific experimental setup can affect the specific capacity and energy density.[265]

9.4.1. Power density. Most power density measurements are related to certain test conditions and may sometimes not represent real-life performance. For instance, the power density results obtained in a laboratory environment are not up to par and should not be used for measuring the actual performance of a material under practical working conditions.[266,267]

9.4.2. Cycle life. Presenting a cycle life report without specifying the criteria of performance degradation leads to false conclusions. A correct performance evaluation requires the definition of changes over time and under various conditions.[268]

9.4.3. Electrolyte compatibility. CPs can degrade in some electrolytes, which can affect their stable state over the long term as well as their performance. The selection of an appropriate electrolyte is critical for the optimization and durability of energy storage systems.

9.4.4. Rate capability. Although many of these CP hybrids have a high energy density, their rate capability is limited, meaning that they do not really estate their functionality in the case of the need for suddenly large deliveries of power. This limitation needs to be considered for applications requiring high-speed energy delivery.[269]

9.4.5. Cost and scalability. However, even though CP-based hybrids show promise, some challenges emerge based on cost and manufacturing feasibility in the exercise for upscaling such materials for large-scale applications. Research on cost-effective and scalable production methods for these materials for large-scale applications is still needed.[270]

9.4.6. Real performance trial. However, some of the potential CP hybrids have only been tested under laboratory study, and their performance has to be checked under real conditions. This involves testing the stability, durability, and long-term performance of such application scenarios.[271]

9.4.7. Device optimization. The design and architecture of energy-storage devices are important for optimizing the

benefits of state-of-the-art CP hybrids. Issues such as electrode geometry, current collector design, and electrolyte properties require critical consideration to enhance the performance.

9.4.8. Benchmarking against mature technologies. One way to determine if CP hybrids will be at an advantage over traditional energy storage technologies, such as lithium-ion batteries and supercapacitors, is by performing benchmarking. This shows the strengths and areas that need improvement.

Masood *et al.* (2024)[21] Investigations of composites for conducting energy storage. Efficient and effective. Mohamadi and Zohoor (2011)[272] developed a dimensionless number for hybrid solar thermal storage systems that provides a measure of the benefits realized by combining several storage devices.

Sharma *et al.* (2023):[273] focused on quantum energy storage at 2D heterointerfaces and exhibiting advanced systems with high electrochemical performance superior to. Valle *et al.* (2023):[274] work is ongoing in the development of nanostructured CPs, where the key areas for performance enhancement are glass and textile composites. Li *et al.* (2024)[275] studied the influence of aggregation on the capacitive storage of CP films and found that they exhibit exceptional performance in aqueous electrolytes. Wang *et al.* (2014)[276] synthesized hybrid materials of hydrous ruthenium oxide and graphene, which exhibit great capacitive performance. The critical analysis of CP hybrid materials suggests their potential for the further development of energy storage technologies. Hence, these materials present competitive energy densities, high power densities, and good cycling stability, and many important problems remain to be solved regarding scalability, material stability, and cost. Future studies should focus on new material compositions, advanced characterization, and application-specific optimization to improve the performance and ease of acceptance by a wider community.

10. Challenges and future directions

CP hybrid materials have great potential in fields such as energy storage and environmental remediation. However, there are certain limitations to be improved to maximize their potential. Thus, this section presents the important problems and future directions for research on CP hybrid materials about scalability, stability, multifunctionality, new applications, interdisciplinary research, and societal impact.[100]

10.1. Scalability and cost effectiveness

Another challenge in the production of CP hybrid materials is their scale-up. Most of the methods used in their synthesis are complex, expensive, and difficult to scale to industrial production levels. Research will have to be conducted if CP hybrid materials are to enjoy economic viability in the future simpler, more efficient, and cheaper methods.[277] This means taking into consideration alternative precursors, optimizing reaction conditions, and adopting environmentally friendly processes. Efficient production techniques are a significant step toward meeting industrial demand and improving cost competitiveness.

10.2. Long-term stability and degradation

More importantly, the long-term stability of CP hybrid materials is one of the main prerequisites for their practical application. Most CP hybrids perform excellently in a laboratory setup, but either degrade or lose their properties under environmental stresses, such as heat, humidity, and UV exposure. Indeed, research efforts should focus on understanding the degradation mechanism and strategies to enhance stability through protective coatings, additive stabilization, or the selection of more robust materials.[278]

10.3. Multifunctionality and smart materials

Designing multifunctional CP hybrid materials is an area of great interest. Aggregating functions such as conductivity, sensing, and self-healing into one material could give way to higher-order smart materials. This can be achieved by integrating CPs with other smart materials in such a way that they create self-changing systems in response to the environment or external stimuli. Examples include the mechanisms of self-repair and integral sensors, which may widen the applications of CP hybrids.[279]

10.4. New applications and unexplored areas

Thus, new applications for CP hybrids are emerging. Beyond traditional uses, opportunities exist in areas such as bioelectronics and flexible electronics, among others, relating to environmental remediation. Such studies on new applications may provide additional benefits and increase the impact of CP hybrid materials. Future research in these possible areas of applications should realize the effective application of CP hybrids in innovative technologies such as hybrid functional materials for various applications.[280]

10.5. Interdisciplinary research opportunities

Research on CP hybrid materials belongs to an extremely broad spectrum of scientific fields, ranging from materials and chemistry through physics to engineering. Further growth in interdisciplinarity in the future will show an advantage for progress in this area.[100] Only by cooperating can the complexity of such challenges and new technological developments be addressed. Partnerships with industry and stakeholders working together through government agencies will ensure that the results of research bring solutions to practical needs and find real-world applications.[281]

10.6. Impacts on society and ethics

This will unavoidably need to consider the impact of CP hybrid materials on society, as well as give attention to related ethical concerns. The only two examples are the privacy issues of next-generation sensing systems and the safety of biomedical applications.[282] Future research, in open dialogue with policy-makers, ethicists, and the broader public, should be conducted

to ensure that the development of CP hybrid materials will satisfy societal priorities and needs. Responsible innovation and execution are also important for enabling society to fully reap their benefits. This development of CP hybrid materials must meet the challenges of scalability, cost-effectiveness, long-term stability, and multifunctionality.[117] Applications can be prospected by encouraging interdisciplinary research and magma considerations for social and ethical impacts. These factors can facilitate the development of more sustainable and impactful solutions using hybrid CP materials.[94]

10.7. Sustainability and circular economy integration

The sustainable development of CP hybrid materials increasingly demands alignment with circular economy principles. Recent studies have emphasized the design of CP hybrids with recyclable components, such as thermally depolymerizable backbones, redox-switchable degradation pathways, and biodegradable dopants.[283,284] For example, polyaniline and polypyrrole systems have been synthesized from bio-derived monomers or doped using environmentally benign acids to facilitate post-use material recovery.[285] Additionally, the modular architecture of some CP composites enables physical disassembly and chemical recycling of filler components (*e.g.*, graphene, metal oxides) using low-impact solvents or electrochemical treatments. Lifecycle assessment (LCA) frameworks are beginning to be applied to CP hybrids, evaluating metrics such as embodied energy, carbon footprint, and recyclability index. Future work should explore closed-loop fabrication processes, cradle-to-cradle material flows, and integration of CP systems into regenerative product cycles. These directions are essential to align CP hybrid material innovation with sustainable material economy goals.[286,287]

10.8. Scalability of fabrication methods: comparative analysis

Despite the rapid growth in CP hybrid material design, a critical bottleneck remains in translating laboratory-scale synthesis methods into industrially scalable processes. Electrochemical polymerization offers excellent control over film thickness and morphology, but suffers from low throughput, reliance on conductive substrates, and batch-wise operation. The method's inherent limitations become particularly pronounced when attempting to scale beyond research dimensions, where current distribution non-uniformities and mass transport limitations create significant quality control challenges.[29,89,198]

In contrast, *in situ* polymerization and solution blending demonstrate superior scalability, particularly for bulk or roll-to-roll production scenarios. These approaches leverage existing industrial infrastructure and can accommodate continuous processing modes essential for commercial viability. However, successful implementation requires meticulous optimization to prevent poor interfacial bonding or phase separation, which can compromise material performance and long-term stability.[18,32,69] Chemical oxidative polymerization has emerged as the most industrially relevant method due to its compatibility with standard chemical reactor technology and straightforward scale-up relationships. The method achieves excellent material utilization while maintaining consistent quality across large production volumes. Universal substrate compatibility further enhances its industrial appeal, enabling applications ranging from antistatic coatings to electromagnetic interference shielding.[30,146]

Solution processing techniques offer unparalleled scalability potential, with very high throughput capabilities and extremely low processing costs. Compatibility with existing coating and printing infrastructure minimizes capital investment requirements while enabling large-area applications such as flexible electronics and smart textiles. Critical optimization parameters include solvent selection, doping level control, and processing temperature management.[288,289] Emerging techniques such as 3D printing allow for customizable geometries and direct device integration, opening new possibilities for personalized medical devices and complex electronic architectures. However, significant challenges remain in ink formulation, extrusion stability, and feature resolution. The technology's maturity level continues advancing rapidly, with recent developments in conductive filament chemistry showing promise for broader industrial adoption.[290,291]

Sol–gel methods offer exceptional chemical versatility and excellent compatibility with ceramic substrates, making them particularly valuable for high-temperature applications and functional coatings. Nevertheless, these processes often require extended processing times and precise control over gelation conditions, limiting throughput potential and increasing manufacturing complexity.[292,293] Vapor phase polymerization represents a compromise between processing control and scalability, offering excellent film uniformity while accommodating heat-sensitive substrates. The method's moderate scalability reflects equipment complexity requirements and monomer vapor pressure considerations, though recent advances in reactor design are improving commercial prospects.[294]

Advanced hybrid approaches are revolutionizing CP manufacturing by combining multiple processing advantages. Layer-by-layer assembly enables precise multilayer functionality essential for battery applications, while plasma polymerization provides excellent adhesion for aerospace coatings. Electrospinning integration creates high surface area morphologies ideal for filtration and energy storage applications.[295]

The industrial landscape increasingly favors methods that balance processing flexibility with economic viability. Template-assisted synthesis, while offering exceptional structural control, faces scalability constraints due to template removal complexities and high processing costs. Conversely, interfacial polymerization shows promise for specialized membrane applications despite moderate scalability limitations.[11] Manufacturing method selection must consider application-specific requirements, production volume targets, and quality specifications. High-volume commodity applications favor solution processing and chemical oxidative methods, while specialized high-performance applications justify the higher costs associated with electrochemical or vapor phase approaches. The integration of Industry 4.0 technologies,

Table 4 Comparative evaluation of major fabrication methods for conducting polymer (CP) hybrid materials in terms of scalability, cost, uniformity, substrate compatibility, industrial relevance, and key application domains. Critical process parameters are summarized to guide optimization for specific applications. This comparative matrix supports strategic selection based on industrial requirements and technological readiness levels (TRLs)

Method	Scalability	Cost	Uniformity	Substrate compatibility	Industrial relevance	Key applications	Critical parameters
Electrochemical polymerization	Low-moderate	Moderate-high	Excellent (nanoscale control)	Conductive substrates only	High for specialized applications	Supercapacitors, biosensors, neural interfaces, electrochromic devices	Current density: 0.1–10 mA cm^2; potential: 0.5–2.0 V *vs.* SCE[32]
Chemical oxidative polymerization	High	Low-moderate	Good-excellent	Universal compatibility	Very high	Antistatic coatings, EMI shielding, batteries	Oxidant/monomer ratio: 1 : 1 to 4 : 1; temperature: −10 °C to 80 °C (ref. 30 and 146)
In situ polymerization	High	Low-moderate	Moderate-high	Flexible, porous substrates	Very high	Textile electronics, composites, filtration membranes	Monomer diffusion time, catalyst distribution[37]
Solution processing	Very high	Very low	Moderate	Films, fibers, membranes	Extremely high	Large-area coatings, printable electronics	Solvent choice, doping level, processing temperature[170,298]
Vapor phase polymerization (VPP)	Moderate	Moderate-high	Excellent	Heat-sensitive substrates	High	Flexible electronics, biomedical devices	Monomer vapor pressure, substrate temperature[11,294]
Template-assisted synthesis	Low-moderate	High	Excellent	Template-dependent	Moderate-high	Nanostructured devices, sensors	Template pore size, removal conditions[63,64]
Interfacial polymerization	Low-moderate	Moderate	Excellent	Liquid–liquid interfaces	Moderate	Thin films, membranes, capsules	pH gradient, interfacial tension[11,65]
Additive manufacturing (3D printing)	Low-moderate	High	Design-dependent	Custom geometries	Emerging-high	Prototyping, custom devices, bioelectronics	Layer adhesion, conductivity retention[53,56]

including real-time monitoring and machine learning optimization, is enhancing process control across all manufacturing platforms.[296]

Future developments in CP manufacturing will likely emphasize hybrid processing strategies that leverage complementary method advantages while minimizing individual limitations. Continuous processing integration, automated quality control, and sustainable manufacturing practices will drive the next generation of industrial CP production technologies.[297] To further contextualize fabrication method selection for industrial deployment, Table 4 provides a comparative analysis of CP hybrid synthesis routes with respect to process scalability, cost, uniformity, substrate compatibility, and industrial relevance across key application domains.

11. Expert insights and ongoing debates

Leading researchers in CP hybrid materials have shared their insights to highlight current achievements and future directions. Scalability and synthesis: John Reynolds[298,299] asked for the development of scalable, less expensive methods for the synthesis process. He refers to the very important problem of going from lab-scale to large-scale production if one is to realize all promising CP hybrid materials. Simplified and environmentally friendly synthesis methods will make these materials broadly applicable.[300–302]

11.1. Biomedical applications

According to Dr Natalie Stingelin,[303,304] the unique properties of CPs, their electrical conductivity, and biocompatibility make them suitable for biomedical applications. She pitched the combination of CPs with other functional materials to achieve multifunctional systems related to neural interfaces, tissue engineering, and drug delivery.

11.2. Changes and opportunities with hybrid CP materials have occurred, but several debates remain

11.2.1. Role of nanostructures. The role of nanostructuring in the enhancement of properties such as conductivity and surface area remains debatable. While some researchers are of the view that nanostructuring is central to the improvement of these properties, others believe that the challenges created by synthesis and characterization may not be warranted by the derived benefits. Material choices for specific applications: researchers often do not agree on the choice of materials for a specific application. Some prefer carbon-material-based materials such as graphene and carbon nanotubes, while others prefer metal oxides or any other inorganic material with special functionality, such as catalytic activity or enhanced energy storage. Faradaic *vs.* Non-faradaic processes: a debate remains on either the optimization of faradaic processes by redox reactions to increase the energy density or the exploitation of non-faradaic processes, given faster charge–discharge capabilities with higher power densities. Strategies and synthetic costs: opinions range from new synthesis techniques that provide advanced structure and functionality control to the development of cost-effective methods that are scalable for industrial deployment. In a nutshell, research in the area of CP hybrid materials is ever-developing with contributions from renowned personalities and differences in opinions on critical aspects. Engaging in the issues discussed and focusing on scalable synopsis, multifunctional designs, and practical applications will become very important in pushing the field forward and looking for the full potential of CP hybrid materials.

12. Outlook and future work

In the area of CPs' hybrid materials, some of the future research areas would lie in the field of scalable synthesis and production methods that would fill the gap between laboratory-scale discovery and industrial applications. This type of research would dwell on material quality and performance maintenance with the growing volume of production.[100]

The key areas of application for CP hybrid materials span several technologically critical domains. These include (i) energy storage and conversion systems such as supercapacitors,[21,269,305] batteries, and fuel cells;[38,171,193] (ii) environmental remediation technologies,[169,189,262] including heavy metal adsorption,[164,176] dye degradation, and water purification membranes;[182] (iii) biomedical engineering, particularly in biosensors,[26,145,189] drug delivery systems, and bioelectronics;[62,105,242] (iv) smart coatings and self-healing materials for corrosion protection and adaptive interfaces;[27,229,230] and (v) flexible and wearable electronics,[280] including electronic textiles, stretchable conductors, and implantable devices.[24,299] These diverse application areas reflect the inherent multifunctionality of CP hybrids and underline their growing industrial relevance.

The most common concerns of CP hybrid materials are their stability and durability. Mechanistic studies of the degradation processes and strategies that ensure long-term stability and associated chemical and structural changes over time are important.[306]

Advanced characterization techniques, mainly *in situ* methods, will go a long way to uncovering the real-time procedures involved in these CP hybrid materials during their operation. This could reveal essential information concerning charge transfer, ionic movement, and structural changes.[307]

CP hybrids with multifunctionality in other words, the ability to perform functions simultaneously in one system, may enable more efficient and compact devices. In this respect, bio-inspired design approaches should be especially useful for this kind of research and may open the way for new structures that show improved performance.

Accelerating the identification of high-performance CP hybrids by data-driven material discovery using machine learning algorithms requires comprehensive databases and robust predictive models. At the molecular level, interfacial engineering is important for optimizing overall performance. State-of-the-art spectroscopic and microscopic methods

Table 5 Comparative performance benchmarks of conductive polymer (CP) hybrid materials *versus* conventional non-CP materials across key application-relevant properties. This benchmarking illustrates the superior multifunctionality and industrial potential of CP hybrids in emerging technologies, especially in energy storage, environmental remediation, and smart materials. Data compiled from representative studies across multiple systems

Property	CP hybrid material example	Performance (CP hybrid)	Performance (conventional material)
Electrical conductivity	Polyaniline/graphene oxide	100–1200 S cm^{-1}	1–10 S cm^{-1} (pure CP), <1 S cm^{-1} (traditional polymers)
Adsorption capacity	Polypyrrole/carbon nanotube	120–350 mg g^{-1} (*e.g.*, heavy metals)	50–150 mg g^{-1} (activated carbon)
Thermal stability	Polyaniline/silica	Stable up to 300–400 °C	200–250 °C (pure polymers)
Mechanical flexibility	PEDOT:PSS/textile composite	High bendability (>5000 cycles)	Low (<1000 cycles, brittle failure)
Electrochemical stability	Polyaniline/metal oxide	Stable over 1000 charge/discharge cycles	Moderate degradation after 300–500 cycles

combined with computational modeling can provide fundamental insights into the nature of interfacial phenomena.[308]

CP hybrids for flexible electronics, which can retain their properties under mechanical stress, are important for the development of wearable technology. This research focuses on new material compositions and structure-preserving functionality under deformation.[197]

In addition, the environmental impact and sustainability of these CP hybrid materials need to be carefully understood through detailed cradle-to-grave life cycle analyses. Further, such research should embrace all stages, from raw material sourcing to end-of-life considerations.[305]

Last, but not least, enhancing reproducibility through standardization is also critical for rapidly advancing the field. Standardized test protocols and methods for reporting results should be designed to increase the comparability between results from different research groups.

By addressing these research directions, the scientific community will be working toward more efficient, stable, and sustainable CP hybrid materials for environmental and energy applications. As the field progresses, there will be a continued requirement for the readjustment of research priorities to meet new challenges and opportunities. To provide a clearer comparative insight, Table 5 presents benchmarked performance metrics for CP hybrid materials relative to their conventional counterparts, highlighting the multifunctional advantages offered by hybrid integration

12.1. Promising research directions

Several promising and important areas of inquiry remain in the field of hybrid materials with conducting polymers. Therefore, future work could focus on developing nanostructured CP hybrids with increased surface areas and controlled morphologies. Such materials could make a significant difference in both sensors and energy storage devices because they can provide an increase in the number of active sites and faster charge transfer.[161]

Another promising direction is their integration with 2D materials such as graphene or MXenes. This combination is expected to result in exciting electronic properties and enhanced mechanical stability for flexible electronics and energy-conversion devices.[309]

Research on self-assembling CP hybrid systems is an exciting area. Such systems have the potential to be used for the generation of complex hierarchical structures with tailored properties at multiple length scales, which may eventually lead to breakthrough discoveries in subjects such as adaptive materials and intelligent coatings.[310,311]

Another promising research direction is the exploration of CP hybrids for thermoelectric applications. If the balance between electrical conductivity and thermal insulation can be optimized, these materials will significantly contribute to high-efficiency waste heat recovery systems and solid-state cooling devices.[312]

Among the most promising directions will be the development of biocompatible CP hybrids related to medical applications, which can have a tremendous impact on the development of biosensors, drug delivery, and tissue engineering scaffolds.[313]

Another promising direction is to investigate CP hybrids for application in electromagnetic shielding and absorption. As more electronic devices enter our lives and start to work at higher frequencies, there is a growing demand for shielding materials with good performance.[314]

Another avenue to explore is the use of CP hybrids in membranes for water treatment and gas separation. Such materials could provide improved selectivity and permeability compared to traditional membrane materials and ensure an enhanced, more sustainable separation process.[315]

These directions of research will open wide-ranging possibilities for the capability and application expansion of CP hybrid materials. As research on these lines unfolds, more understanding and opportunities may emerge to further move this area forward.[316]

12.2. Potential breakthroughs and their implications

A few next-generation breakthroughs of CPs hybrids will, therefore, have wide implications across many fields. The effect of one such breakthrough in the CP hybrid is the development of ultra-high ionic conductivity; batteries with higher charge rates and energy densities have the propensity to change the electric vehicle phase on roads and grid-scale energy storage systems.[160]

Another possibility is the production of CP hybrids with extremely high thermoelectric capabilities. This could dramatically change the process of waste heat reclamation in industry

and make electronics with more effective cooling systems. The implications of this stretch include better energy efficiency in this production, as well as consumer electronics use.[317]

The development of CP hybrids with tunable and reversible properties in response to external stimuli is another area with vast growth potential. This may lead to the application of advanced sensors and actuators in fields such as soft robotics, adaptive structures, and smart textiles. These findings will pave the way for more sophisticated human–machine interfaces and an increased number of possibilities in the field of wearable technologies.[318]

Major advances in biocompatible and biodegradable CP hybrids can fundamentally change bioelectronics. New implantable devices are made, and after they have served their purposes, self-destruct inside the body without causing any harm, hence reducing invasive removal procedures. Applications include temporary neural interfaces for controlled drug delivery.[246,319]

The discovery of CP hybrids with exceptionally good catalytic properties might have broad implications for clean energy production. These materials may either make water splitting more feasible for hydrogen production or assist in the reduction of CO_2 to useful chemicals. This discovery will have a considerable impact on the development of sustainable energy technologies and serve as a carbon abatement strategy.[320]

Finally, the development of CP-based hybrids with an ultrahigh level of stability and infinite self-repairing capability might provide a new generation of electronic devices and structural materials. Such a development would reduce electronic waste and technology longevity, whether in consumer electronics or utility-grade infrastructures.[196]

The potential breakthroughs of consequential impact, realized, would bring forward conductive hybrid materials in conducting polymers an advanced field of broader societal challenges in the energy, environment, healthcare, and technology sectors.[321]

In conclusion, the adoption of CP hybrid materials offers significant benefits across multiple dimensions. By combining the electrical conductivity and processability of conducting polymers with the robustness, functionality, and tunability of hybrid components, these materials enable the development of next-generation devices that are lightweight, flexible, and multifunctional. Importantly, many synthesis approaches now prioritize green chemistry principles, using water-based solvents, renewable monomers, and room-temperature processes.[21,26,117,275] This aligns CP hybrid technology with broader goals of environmental sustainability and circular economy integration. For researchers, engineers, and industries alike, leveraging these materials opens pathways to more sustainable, high-performance solutions in energy, environment, electronics, and healthcare sectors.

13. Conclusion

CP hybrid materials are a breakthrough in materials science, as they bridge the properties of organic and inorganic components. This can improve the performance of energy storage, environmental remediation, and other multifunctional applications. Combining CPs is likely to increase the electrical conductivity, mechanical strength, and electrochemical activity of carbon nanotubes and metal oxide-based materials, making them suitable for advanced technological applications. Although these promises are significant, a few challenges persist. Scaling up the synthesis methods to an industrial level and the costs involved are vital issues that must be resolved. The long-term stability and complex interactions of CP hybrids must be addressed for their practical applications. Current characterization techniques provide some insights but are limited in their ability to capture dynamic interactions and behaviors.

In addition, emerging methodologies associated with *in situ* and multimodal characterizations further enhance the abilities of CP hybrids. Advanced approaches using synchrotron radiation techniques, cryo-electron microscopy, and machine learning will further deepen our understanding of their structure and performance. Therefore, inherently holds within these CP hybrid materials have a bright future driven by their multifunctional potential and continuously developing innovations in applications. Their future will depend on interdisciplinary collaboration among all scientific and engineering approaches to help overcome challenging points and further promote this field. Moreover, it is imperative to reflect on the impact of these materials on society and the environment as they move towards wider commercialization. CP hybrid materials hold significant potential for changing energy storage and rafts for other high-tech applications. Further research is required to address the remaining challenges and adopt new analysis methods to unleash the full potential of practical applications.

Data availability

The data supporting the findings of this study are available within the article and its supplementary materials. Additional data regarding experimental procedures, synthesis methods, and characterization results can be made available from the corresponding author upon reasonable request.

Author contributions

All authors contributed to this review. A. A. A. A. conceptualized and oversaw the project. A. A. and O. G. collected materials and drafted the manuscript. E. Q. and A. A. reviewed synthesis methods and structure–property relationships. V. M. and Y. M. focused on applications in energy storage and environmental sustainability. M. E. T. critically reviewed and refined the manuscript. All authors approved the final version for submission.

Conflicts of interest

The authors declare no conflict of interest.

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