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Chemically Doped Conductive Polymers for Wearable Health Monitoring

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ABSTRACT

Chemically doped conductive polymers are a class of “synthetic metals” that combine metal-level electrical conductivity with intrinsic mechanical flexibility, and they are emerging as core materials for wearable health-monitoring technologies. This review systematically summarizes recent advances in the field, focusing on chemical doping strategies—including small-molecule dopants, ionic liquids, and polymeric dopants—that effectively overcome the intrinsic conductivity limitations of conductive polymers while simultaneously improving mechanical compliance and environmental stability. Enabled by these material innovations, high-performance flexible sensors based on piezoresistive and chemiresistive mechanisms have been developed, allowing in situ, high-fidelity monitoring of physiological signals such as electrocardiography, electromyography, and joint motion, as well as environmental hazards including toxic gases and ultraviolet radiation. From a fabrication perspective, printed electronics and fiber-spinning technologies provide scalable and low-cost routes for producing flexible devices and electronic textiles. Furthermore, through flexible hybrid electronics, sensing elements have been successfully integrated with wireless communication and power supply modules to form complete wearable systems. Although challenges remain in long-term stability, reproducibility, and large-scale manufacturing, the integration of doping engineering with artificial intelligence and self-powered technologies is accelerating the evolution of chemically doped conductive polymers toward multimodal sensing, intelligent data analysis, and personalized health management, highlighting their substantial potential.

1 | Introduction

Wearable devices have developed rapidly in recent years, enabling a diverse range of health-monitoring and diagnostic applications [1–4]. These devices have been increasingly studied, integrating various sensing, data processing, and communication functionalities to provide real-time feedback on physiological parameters such as heart rate, body temperature, and biochemical markers [5–7]. Central to the development of next-generation wearable systems is the choice of materials, which must combine mechanical flexibility, biocompatibility, and reliable electronic performance. Organic polymer materials have emerged as particularly promising candidates in this context due to their intrinsic flexibility, lightweight nature, and ease of fabrication. These polymers are often processed into thin-film devices, which can comfortably conform to the dynamic contours of the human body, thereby minimizing discomfort and improving user compliance [8–10]. Among them, insulating polymers such as polyimide (PI) are commonly employed as substrate layers, providing mechanical

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support and electrical isolation for the active components [11, 12]. In contrast, conductive polymers (CPs), such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT), are increasingly utilized as functional materials for sensing and signal transduction, enabling the direct collection of physiological data [13–15].

Traditional organic conductive polymers offer several advantages, including solution processability, tunable chemical structure, and compatibility with flexible substrates. However, a major limitation of these materials compared to their inorganic semiconductor counterparts is their low electrical conductivity. This shortcoming can lead to reduced signal-to-noise ratios (SNRs) and compromised device sensitivity, which constrain their practical utility in wearable electronics. Chemical doping has emerged as an effective strategy to address this issue, with numerous studies demonstrating that the electrical conductivity of polymer films can be enhanced by 5–7 orders of magnitude through the introduction of suitable dopants [16, 17]. This dramatic improvement has been instrumental in advancing the application of conductive polymers in flexible devices.

However, recent research has revealed a critical trade-off associated with excessive doping. While higher doping levels can further boost electrical conductivity, they also significantly increase the Young's modulus of polymer films, resulting in a marked loss of flexibility [18–20]. This mechanical stiffening renders the films more susceptible to cracking and mechanical failure under repeated bending or deformation, which undermines their reliability in wearable applications that demand long-term durability and resilience [21–24]. Consequently, there is an urgent need in the field to develop new dopants and polymer systems that can achieve efficient conductivity enhancement without compromising mechanical compliance [25, 26]. Moreover, optimizing doping processes to balance conductivity and flexibility, while preventing over-doping, is essential for the realization of robust wearable devices. From an application-oriented perspective, it is also necessary for researchers to establish clear performance targets for electrical conductivity based on the specific requirements of different wearable applications. Such a tailored approach will facilitate the rational design of polymer-based materials and devices that can meet the demanding standards of modern wearable medical technology.

In this review, we systematically discuss the intrinsic properties of conductive polymers, the impact of chemical doping strategies on their electrical and mechanical performance, and their transformative role in wearable health-monitoring technologies. By analyzing recent advances in material design, doping engineering, and device integration, we highlight how chemically doped conductive polymers are enabling the development of flexible, high-performance sensors and multifunctional wearable systems. The opportunities and remaining challenges in achieving long-term stability, biocompatibility, and large-scale manufacturing are also addressed, providing a comprehensive foundation for future innovations in personalized health-monitoring and smart medical devices.

2 | Properties and Classification of Conductive Polymers for Wearable Applications

2.1 | Basic Characteristics and Classification of Conductive Polymers

Conductive polymers are a class of macromolecular materials characterized by an extended conjugated π-electron structure in their backbone (i.e., alternating single and double bonds) that can achieve metal- or semiconductor-level conductivity through "doping" treatments. Their discovery originated from an accidental laboratory incident in the 1970s: a graduate student of Japanese chemist Hideki Shirakawa mistakenly added an excessive amount of catalyst while synthesizing polyacetylene, unexpectedly producing a silver-colored film with metallic luster—*trans*-polyacetylene [27]. Subsequently, Shirakawa collaborated with American scientists Alan Heeger and Alan MacDiarmid to further investigate the material. They discovered that when this polyacetylene film was exposed to halogen vapors such as chlorine, bromine, or iodine, a spontaneous redox reaction (i.e., the doping process) occurred. After doping with iodine vapor, the electrical conductivity of the material increased by over seven orders of magnitude (10 million times), jumping from an initial semiconductor level (approximately 10^{-7} S/cm) to nearly metallic conductivity (up to 10^3 S/cm). This breakthrough completely overturned the traditional notion that "all polymers are insulators," inaugurating an entirely new field of research on conductive polymers. These materials, often referred to as "synthetic metals," combine the advantages of traditional polymers (such as flexibility, processability, low density, and low cost) with excellent electrical conductivity, making them ideal for manufacturing wearable health-monitoring devices.

2.1.1 | Classes of Conductive Polymers (e.g., Poly(3,4-ethylenedioxythiophene):Poly(styrenesulfonate), Polyaniline, and Polypyrrole)

Conductive polymers can be categorized into three types based on their chemical structure and application characteristics: classification by core chemical structure, classification by doping type, and classification by dopant or functionality. Among these, classification by core chemical structure is the most fundamental approach, which categorizes polymers based on the chemical composition of their backbone, primarily including polyacetylenes, polythiophenes, polyanilines, and polypyrroles. Classification by doping type is based on the type of charge carriers generated after doping, dividing them into p-type and n-type conductive polymers. Classification by dopant or functionality includes chemically doped, electrochemically doped, and self-doped types. Currently, the most extensively studied and widely applied conductive polymers include poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS), PANI, and PPy.

PEDOT:PSS is the most widely used water-based conductive polymer with the highest electrical conductivity. As a counterion, PSS not only imparts water solubility but also provides initial doping. After secondary doping with organic solvents, its conductivity can

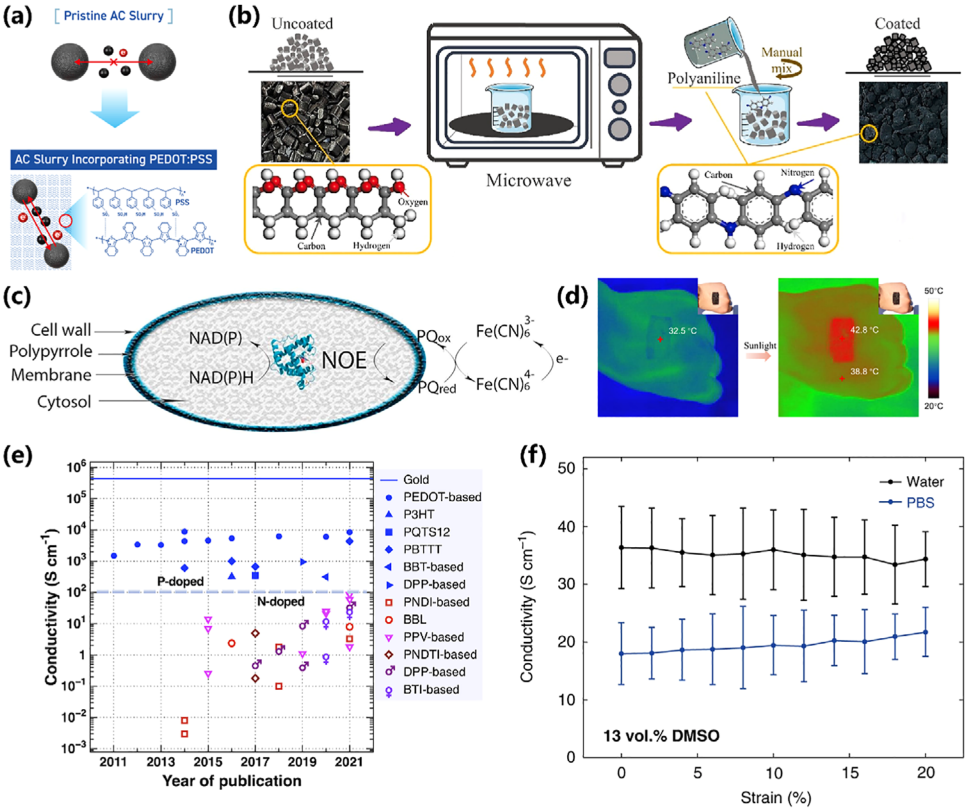

FIGURE 1 | (a) Incorporation of PEDOT:PSS into the pristine-activated carbon slurry to form a composite conductive material [28]. Copyright 2025, Elsevier Ltd. (b) Uncoated plastic particles are partially melted and coated with polyaniline powder [29]. Copyright 2025, Elsevier Ltd. (c) Schematic diagram of the electron-transfer mechanism at the cellular interface based on a PPy film, where the PPy film serves as a key conductive bridge connecting the biological system to the external circuit [30]. Copyright 2018, Elsevier B.V. All rights reserved. (d) Infrared thermal imaging of an integrated PPy-based smart clothing (IPSC) attached to the back of the hand before and after solar irradiation [31]. Copyright 2022, American Chemical Society. (e) Representative conductivity of solution-processed doped polymers [32]. Copyright 2023, The Authors. Published by Elsevier B.V. (f) Strain-dependent conductivity of pure PEDOT:PSS hydrogel measured in deionized water and phosphate buffered saline (PBS) [33]. Copyright 2019, The Author(s).

be significantly enhanced to over 1000 S/cm. To address the "electron transport bottleneck" in flow-electrode capacitive deionization (FCDI) technology, Cho et al. [28] incorporated PEDOT:PSS as an electron mediator into the flow-electrode slurry (Figure 1a). Upon dispersion in the aqueous slurry, the long-chain polymer structure of PEDOT:PSS enables the formation of continuous and flexible conductive pathways between insulating activated carbon particles, thereby enhancing the overall electronic conductivity of the electrode and reducing charge-transfer resistance. The introduction of this conductive polymer resulted in comprehensive performance improvements in the FCDI device, including higher salt removal rates, lower energy consumption, and faster reaction kinetics.

Polyaniline exhibits rich chemical properties, and its conductive state (emeraldine salt) can be achieved through acid doping, with the doping level adjustable via pH. Despite its low cost, challenges such as poor processability in certain solvents and mechanical brittleness remain obstacles to practical applications. In recent years, significant improvements in the mechanical properties of polyaniline have been achieved through nanostructural design and composite material strategies. Zeng et al. [29] utilized polyaniline to coat or modify the surface of recycled plastic particles, transforming the originally insulating plastic particles into conductive fillers (Figure 1b). When these conductive plastic particles are incorporated into an insulating cement mortar matrix, they can contact or approach each other, forming a percolating conductive network. This composite material thus exhibits a piezoresistive effect, allowing real-time monitoring of stress, strain, or microdamage states through changes in electrical resistance. This ultimately leads to the development of a "sustainable smart building material" for structural health monitoring.

Polypyrrole is typically synthesized via electrochemical polymerization or chemical oxidation polymerization. It readily forms films on various substrates and exhibits excellent biocompatibility and environmental stability. Ramanavicius et al. [30] exposed microorganisms to pyrrole monomers, leveraging the biological activity of the microbes to achieve in situ polymerization of polypyrrole on the cell surface, effectively "clothing" the microorganisms in a conductive polymer layer (Figure 1c). This PPy coating significantly enhances electron-transfer efficiency by constructing continuous conductive networks, increasing effective contact area, and strengthening adhesion between microorganisms and electrodes. As a result, the system achieves markedly improved output power density and higher Coulombic efficiency.

2.1.2 | Intrinsic Electrical, Mechanical, and Structural Properties

Heeger [34] pointed out that not all polymers possess conductive capabilities; a necessary condition for a polymer to be conductive is the presence of a "conjugated structure," specifically an alternating arrangement of single and double bonds (π-conjugated system) along the backbone. This structure allows π-electrons to become delocalized rather than confined between two atoms. Through doping, quasiparticle defects can be introduced, forming true charge carriers—manifested primarily as "polarons" and "bipolarons" in most conductive polymers. Under the influence of an electric field, these quasiparticles can move along the polymer chains and hop between chains, enabling macroscopic electrical conduction.

Conductive polymers inherently exhibit excellent flexibility, which stems from the rotational freedom of their polymer chains, allowing thin films to bend without fracturing. Building on this, further material design (e.g., selecting polymers with low glass transition temperatures) and structural engineering (e.g., constructing wavy geometric configurations) can significantly enhance their stretchability. Their Young's modulus typically falls within the range of 0.1–5 GPa, substantially lower than that of metals and traditional semiconductor materials, thus endowing them with intrinsic flexibility [35].

Furthermore, the microstructure of conductive polymers plays a decisive role in their properties. For instance, the phase-separated morphology of PEDOT:PSS, the nanofiber structure of PANI, and the nanoparticle assembly of PPy all directly influence the formation of conductive pathways and the mechanical behavior of the materials.

2.2 | Mechanical Compliance for On-Skin and Textile Electronics

The core advantage of conductive polymers lies in their exceptional flexibility and mechanical compliance, which stands in stark contrast to traditional rigid electronic materials. This characteristic enables polymer-based electronic devices to be seamlessly integrated with soft and dynamically deformable interfaces such as the human body and textiles.

2.2.1 | Comparison With Inorganic Conductors

Unlike intrinsically flexible conductive polymers, inorganic semiconductors (such as SnO_2 and ZrO_2) are inherently brittle materials. Their atomic structures consist of strong ionic or covalent bonds forming a three-dimensional rigid crystal lattice, resembling the structure of glass. This configuration lacks ductile deformation mechanisms, rendering them intrinsically nonstretchable with fracture elongation rates approaching zero. Such materials typically exhibit high Young's modulus values reaching hundreds of GPa, demonstrating extreme rigidity. This high modulus often leads to "mechanical mismatch" issues, where significant stress concentration occurs at the interface between rigid materials and soft tissues (e.g., skin) during deformation, resulting in poor contact, signal acquisition distortion, or even structural failure of devices.

In contrast, conductive polymers possess intrinsic flexibility and stretchability derived from their inherent chemical structures. They can effectively dissipate stress through deformation while maintaining functional stability under repeated bending conditions. With Young's modulus typically ranging between 0.1 and 10 GPa and fracture strain capable of reaching several tens of percent, these materials demonstrate superior mechanical compatibility with biological tissues, thereby effectively mitigating mechanical mismatch problems [36].

Overall, when compared to traditional inorganic conductors, conductive polymers exhibit distinct advantages in flexibility, fatigue resistance, and mechanical compatibility with soft matter. However, their absolute electrical conductivity and operational environmental stability generally remain inferior to top-tier metallic conductors.

2.2.2 | Advantages for On-Skin and Textile Integration

Unlike traditional rigid electronic materials, conductive polymers inherently possess the flexibility of polymer chains and can be readily processed into thin films, fibers, or elastomeric composites. This enables devices to conform closely to human contours like a "second skin," maintaining secure adhesion even when bent or stretched at joints without causing significant constraint or detachment, thereby achieving unobtrusive wearability. In a study by Xue et al. [31], an integrated smart textile based on polypyrrole was developed (Figure 1d). By coating or weaving PPy onto the inner side of fabrics (in direct contact with the skin), synergistic functions of photothermal conversion and passive thermal sensing were realized on a single textile platform. The photothermal effect converts solar energy into heat, providing active warmth to the wearer. Simultaneously, the thermoelectric effect leverages temperature gradients across the fabric to generate voltage signals, enabling real-time, self-powered monitoring of both body surface and ambient temperatures. This integrated design offers a novel and practical solution for developing next-generation wearable systems that combine energy management with intelligent sensing.

2.3 | Intrinsic Conductivity Bottlenecks Prior to Doping

Indeed, although CPs can achieve high electrical conductivity through doping, their intrinsic conductivity ceiling and charge-carrier mobility remain significantly lower than those of most metals and high-quality inorganic semiconductors. This fundamental limitation restricts the performance of conductive polymers in high-frequency or high-current application scenarios.

2.3.1 | Mechanisms Leading to Low Intrinsic Conductivity

The electrical conductivity of conductive polymers is their most critical performance metric, spanning over ten orders of magnitude and covering a broad range from insulators to conductors [37]. The factors influencing conductivity are complex and interconnected, primarily including the following aspects:

Molecular structure is the intrinsic factor determining the theoretical upper limit of conductivity. First, polymer chains obtained through synthesis are not infinitely long and often exhibit chemical defects (e.g., dislocations, cross-linking), chain entanglements, and breaks. These structural defects interrupt the delocalization of π-electrons, acting as scattering points or energy barriers for charge transport along the backbone [38, 39]. Second, the highest occupied molecular orbital and lowest unoccupied molecular orbital bandgap (E_g) of many conductive polymers remains relatively wide (typically greater than 1.5 eV), fundamentally limiting the intrinsic carrier concentration and predisposing them to exhibit semiconductor-like behavior rather than metallic conductivity [40].

The most fundamental reason for the lower conductivity of conductive polymers compared to metals lies in the constraints of their microstructure. Most conductive polymer films are semicrystalline or amorphous, preventing free charge transport in highly disordered regions. Charges must migrate between localized states via phonon-assisted hopping mechanisms, a process significantly slower than the free electron diffusion in metals, resulting in extremely low carrier mobility. Additionally, poor interchain contact, excessive chain spacing, or random chain orientation can significantly increase interchain transport resistance, making it the rate-limiting step in the conduction process. For instance, in the representative PEDOT:PSS system, the conductive phases (PEDOT nanocrystalline regions) are surrounded by insulating PSS phases. Charges must "tunnel" or "hop" through these insulating barriers, limiting conductivity unless post-treatment methods are employed to improve phase separation [41].

Although processing techniques such as stretch alignment can partially enhance chain ordering and crystallinity, achieving perfect alignment of all molecular chains in large-scale production remains challenging. Disordered regions persist and continue to act as transport bottlenecks [42].

In summary, the relatively low conductivity of conductive polymers is not attributable to a single factor but is collectively determined by the inherent nature of the materials and their microstructures. These factors contribute to higher electrical resistance, limiting the performance of such materials in applications requiring weak current detection or high-frequency response in electronic devices. Therefore, developing advanced doping strategies to overcome these bottlenecks has become a key research direction in the field and will be a focal point of discussion in the subsequent sections of this article.

3 | Chemical Doping Strategies for Enhanced Conductivity

3.1 | Fundamentals of Chemical Doping

Chemical doping serves as the cornerstone for enhancing the electrical conductivity of conductive polymers. This process fundamentally alters the electronic band structure of polymers through the introduction of dopants, significantly increasing charge-carrier concentration. Essentially, chemical doping relies on redox reactions or protonation mechanisms to modulate the oxidation state of polymers, thereby optimizing their electrical performance.

3.1.1 | Types of Dopants (e.g., Small Molecules, Ions, and Polymers)

Based on their chemical properties and mechanisms of action, dopants can be primarily categorized into three types: small-molecule dopants, ionic dopants, and polymeric dopants.

Small-molecule dopants, as low-molecular-weight compounds, can significantly enhance the performance of conjugated polymers such as PPy and PEDOT through redox reactions. These dopants modify the charge state of the polymer by either extracting electrons (p-type doping) or injecting electrons (n-type doping), thereby introducing charge carriers (holes or electrons) into the energy bands and substantially increasing electrical conductivity. Common small-molecule dopants include strong acids like sulfuric acid and methanesulfonic acid (used for PANI and PPy); secondary dopants such as ethylene glycol and dimethyl sulfoxide (used for PEDOT:PSS); and oxidizing agents like iodine and ferric chloride. For instance, the research team led by Qiu [43] innovatively introduced perfluorooctanoic acid (PFA) as a secondary component. By synergizing with lignosulfonate (LGS), they successfully elevated the conductivity of PEDOT:LGS thin films to 0.1255 S cm^{-1}, achieving a "$1 + 1 > 2$" enhancement effect (Figure 2a).

Ionic dopants embed into the polymer matrix in the form of ions during the doping process. Their unique advantage lies in the introduction of mobile ions, which is crucial for enhancing the electrochemical performance of materials. This type of doping generates charges on the polymer backbone via redox reactions while incorporating counterions to maintain electrical neutrality. Common ionic dopants include ionic liquids and various anionic/cationic salts. Notably, the Bao [45] research group developed a fluorosurfactant-based ionic dopant that not only increased the conductivity of PEDOT:PSS by 2–3 orders of magnitude but also retained over 80% visible light transmittance and exhibited excellent stability under tensile strain (Figure 2c).

Polymeric dopants refer to dopants that are polymers themselves and can be used to modulate the electrical, optical, and mechanical properties of conjugated polymers. The most representative example is the PEDOT:PSS composite material, formed by PSS with PEDOT. This type of doping regulates

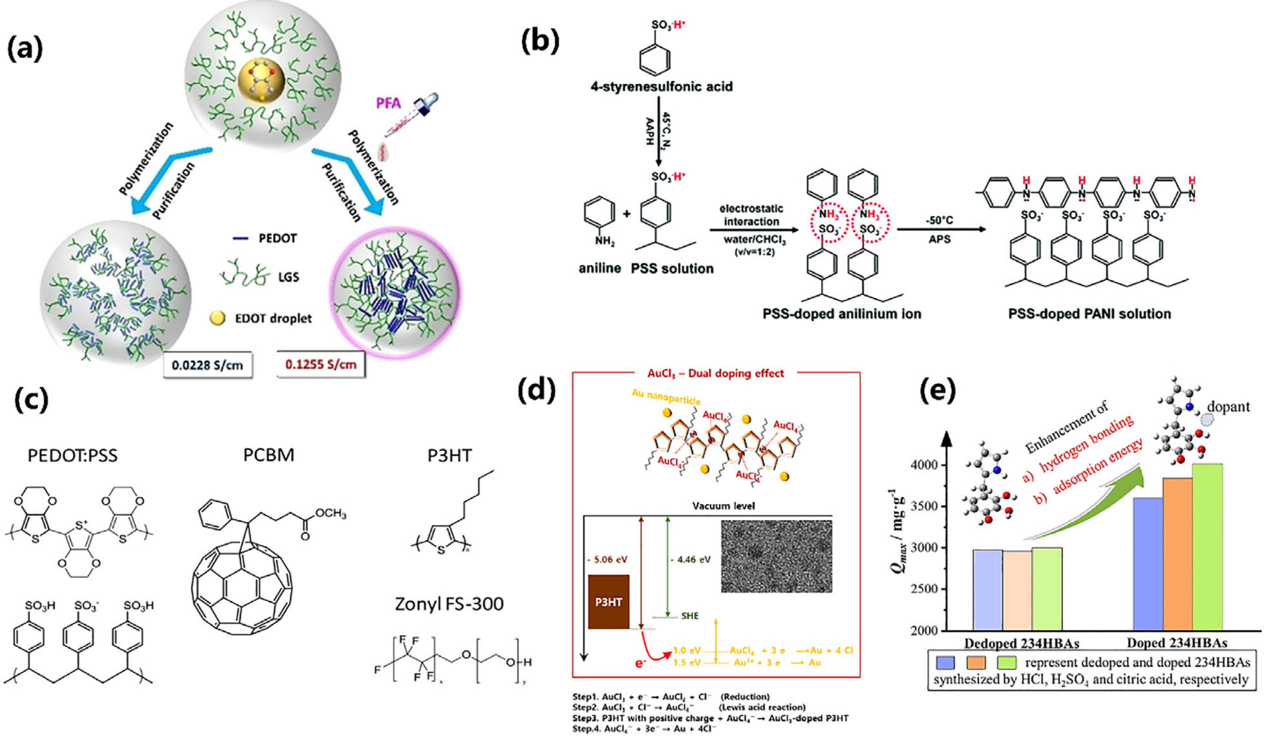

FIGURE 2 | (a) Effect of PFA dopant addition on the dispersion polymerization process of EDOT in LS solution [43]. Copyright 2019, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) Synthesis process of PSS-doped PANI/graphene nanocomposite [44]. Copyright 2014, Royal Society of Chemistry. (c) Chemical structures of PEDOT:PSS, [6,6]-phenyl C61 butyric acid methyl ester (PCBM), poly(3–hexylthiophene) (P3HT), and the fluorinated surfactant ionic dopant Zonyl FS-300 [45]. Copyright 2012, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (d) Charge-transfer doping mechanism using $AuCl_3$ dopant in P3HT [46]. Copyright 2020, Elsevier Ltd. All rights reserved. (e) Comparison of adsorption energies for dedoped and doped 234HIBA materials synthesized using HCl, H_2SO_4, and citric acid, respectively [47]. Copyright 2023, Elsevier B.V. All rights reserved.

performance through charge-transfer mechanisms. Research by the Jang [44] team demonstrated that using high-molecular-weight PSS enables the uniform composite of hard-to-process PANI with graphene in an aqueous phase, resulting in a nanocomposite that combines high conductivity with exceptional gas-sensing performance. This provides a novel solution for H_2S gas detection (Figure 2b).

3.1.2 | Doping Mechanisms (e.g., Charge Transfer and Acid/Base Interactions)

The core of chemical doping lies in modulating the electronic band structure of a polymer by withdrawing or injecting electrons from its backbone, thereby introducing new localized energy states within the bandgap and generating mobile charge carriers (such as polarons and bipolarons). To maintain electrical neutrality, the doping process is typically accompanied by the incorporation of counterions. This mechanism fundamentally differs from doping in inorganic semiconductors, which is achieved via atomic substitution, and is essentially based on redox reactions or acid–base protonation processes.

In redox doping (i.e., charge-transfer doping), the dopant acts as an electron acceptor or donor, enabling p-type or n-type doping, respectively. For example, Au^{3+} in $HAuCl_4$ can oxidize the P3HT backbone, withdrawing electrons to generate hole-type carriers (polarons), while Au^{3+} is reduced to gold atoms (Au^0). These gold atoms subsequently aggregate to form gold nanoparticles. Due to the higher work function of gold compared to P3HT, interfacial charge transfer occurs upon contact, with electrons migrating from P3HT to the gold nanoparticles, resulting in secondary p-type doping of P3HT (Figure 2d) [46].

Another common mechanism is acid–base doping, which is applicable to systems such as PANI. For instance, when treated with a protonic acid, the protons (H^+) released from the acid combine with the imine nitrogen atoms of the polymer, protonating them and imparting a positive charge. Concurrently, the acid's anions are incorporated as counterions between the chains, achieving doping and enhancing conductivity. In the synthesis of polypyrromethane (PPm), macromolecular phytic acid (PA) or small-molecule hydrochloric acid (HCl) can be used as dopants. The protons dissociated from the acid combine with the lone pair electrons of the pyrrole nitrogen atoms, protonating the backbone and forming polarons or bipolarons (Figure 2e). The corresponding acid anions (e.g., phytate or chloride ions) are embedded as counterions within the polymer framework to stabilize the doped structure and maintain charge balance [47].

3.2 | Impact of Doping on Electrical and Mechanical Properties

Chemical doping is essentially a process involving redox reactions that inject charges into the polymer backbone and introduce corresponding counterions to maintain electrical neutrality. This process not only significantly increases the charge-carrier concentration of the material but also induces changes in the molecular conformation and microstructure of the polymer. These factors collectively determine the final electrical and mechanical properties. While doping enhances electrical conductivity, it also exerts complex effects on mechanical behavior, making it a double-edged sword.

3.2.1 | Enhancements in Conductivity, Stability, and Flexibility

Effective chemical doping can elevate the electrical conductivity of conjugated polymers (CPs) from insulating or semiconducting levels to near-metallic ranges (10^2–10^4 S/cm). For instance, when specific ionic liquids are used to dope PEDOT:PSS, their "dual effect" mechanism enables a leap in thin-film conductivity by over three orders of magnitude, outperforming or at least matching the effects of traditional additives like dimethyl sulfoxide (DMSO) (Figure 3a) [48].

Beyond the significant enhancement in conductivity, doping also improves the environmental and electrochemical stability of the materials. The research team led by Cho [49] treated doped polymers with low-dielectric-constant solvents and employed an "anion exchange" strategy, replacing initial small anions with larger, more stable ones (Figure 3b). This exchange effectively suppresses the "dedoping" phenomenon under harsh conditions such as humidity and high temperatures, enabling the device to maintain stable conductivity during long-term operation and significantly extending its service life.

Additionally, certain dopants can exert a "plasticizing" effect, weakening brittle phases in the polymer and enhancing chain mobility, thereby improving the material's flexibility and stretchability. For example, in traditional PPy actuators, basic motion responses can be achieved, but the output force is often limited and brittle fracture tends to occur. Sen and Palmore [50] introduced a macromolecular dopant with redox activity. Under electrical stimulation, this dopant cooperates with PPy in a synergistic reaction, facilitating greater ion insertion and extraction, which enhances the actuator's volume change and stress output. Meanwhile, the long-chain structure of the macromolecule itself acts as an internal plasticizer, significantly improving PPy's flexibility and mechanical durability (Figure 3c).

3.2.2 | Trade-Offs and Optimization Strategies

Chemical doping does not always lead to comprehensive performance improvements; the process often involves a series of trade-offs. Firstly, excessive doping may result in a decline in mechanical properties, increasing material brittleness and reducing flexibility. For example, Okuzaki's team [52], while studying composites of conductive polymer PEDOT/polyaniline with hydrogels, found that as the doping level increased, the material's modulus, strength, and toughness reached an optimum of around 64% doping. However, when doping was increased to 100%, the material became noticeably stiffer and more brittle, with tensile properties deteriorating sharply (Figure 3e). Secondly, in humid or aqueous environments, conductive polymers are prone to "dedoping," leading to a gradual decline in electrical conductivity. Weisenberger et al. [51] reported an n-type polymer fiber with high conductivity, excellent thermoelectric properties, and spinnability. Although it demonstrated good stability in air, its conductivity still decreased significantly over time under 80% humidity (Figure 3d). Additionally, some dopants themselves may introduce biocompatibility risks. For instance, PANI in its doped state often exhibits cytotoxicity due to the use of strong acid small molecules (such as hydrochloric acid or camphorsulfonic acid) as dopants. These dopants may leach out in vivo, creating a locally acidic environment and causing chemical toxicity. In contrast, dedoped PANI shows significantly reduced toxicity, but its conductivity is also lost [53].

To address these challenges, researchers have proposed various optimization strategies. One approach is to identify an optimal doping concentration window. For example, Cabuk and Gündüz [54] adjusted the concentration of boric acid doping and found that a moderate doping level achieved the best balance among bandgap, conductivity, and mobility, which is crucial for high-performance optoelectronic devices. Determining an optimal doping concentration range enables PANI to deliver its best performance in specific optoelectronic applications, such as serving as a hole-transport layer or an active layer. Another strategy involves developing milder and more efficient doping systems. For instance, Daraeinejad and Shabani [55] used bioactive polyelectrolytes as dopants, successfully transforming potentially toxic PANI into conductive scaffolds with good biocompatibility that even promote cell growth, opening new pathways for tissue-engineering materials. A third approach is constructing multicomponent composite materials to achieve synergistic performance enhancement. For example, incorporating carbon materials as conductive frameworks into polyaniline hydrogels not only improves electron-transport efficiency, rate capability, and cycling stability but also effectively suppresses volume expansion during charge–discharge processes, enhancing the material's mechanical toughness and fatigue resistance [56, 57].

Chemical doping benefits wearable conductive polymers, but the improvements are not strictly monotonic with doping level. Doping raises carrier density and can reorganize microstructure, enabling large conductivity gains and lower series/sheet resistance for low-noise, low-power readout. Proper dopant/counterion choices also enhance operational stability (e.g., reduced humidity-induced dedoping) and broaden processing windows via additives, post-treatments, or anion exchange. In some cases, ionic liquid or plasticizing dopants improve both conductivity and mechanical compliance, supporting durability under bending or stretching. However, over-doping may stiffen and embrittle films, increase cyclic hysteresis and fatigue, and cause long-term drift through dopant migration/leaching or environmental dedoping; dopant chemistry can also impact biocompatibility and transparency. Thus, doping should be optimized at the device level within an application-specific "doping window" that balances conductivity, compliance, interfacial stability, and reliability.

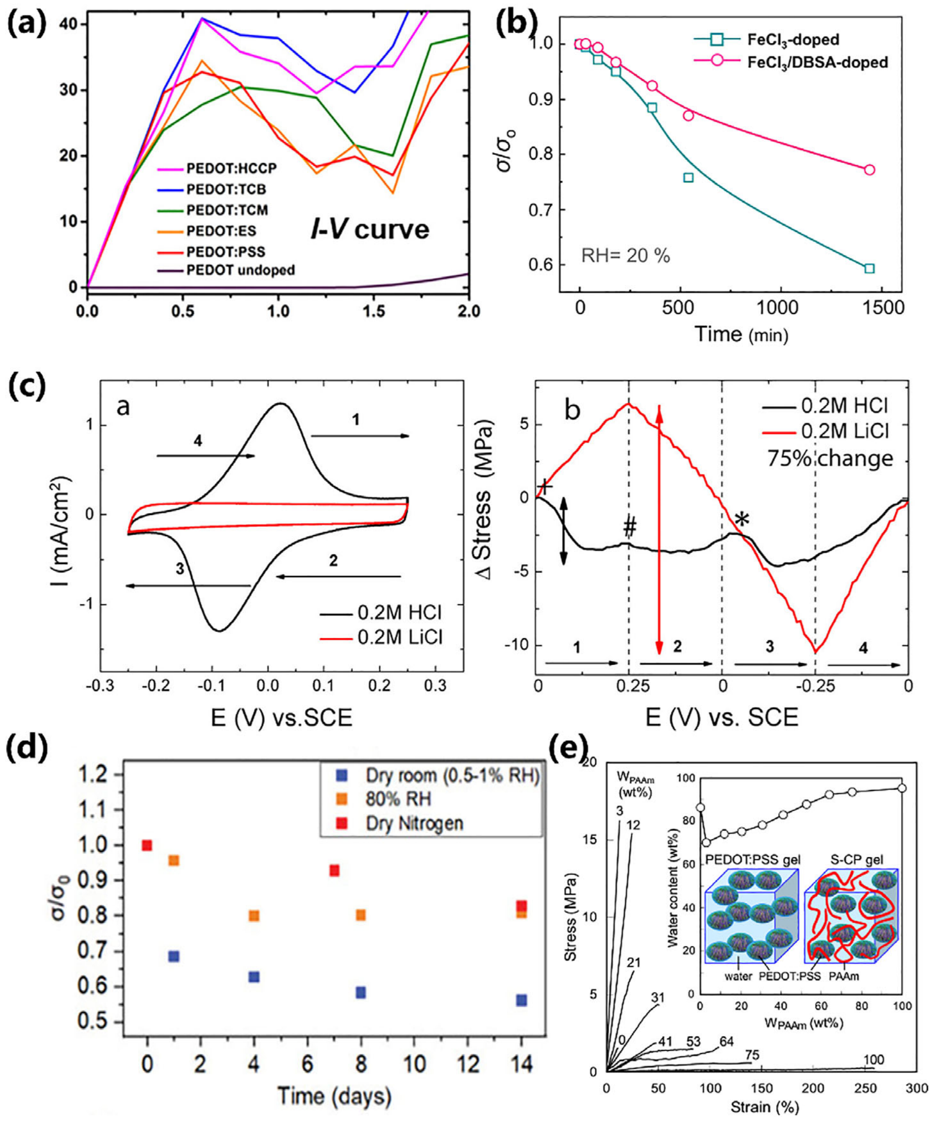

FIGURE 3 | (a) PEDOT:X exhibits more pronounced metallic behavior in its electrical properties compared to undoped PEDOT [48]. Copyright 2018, American Chemical Society. (b) σ of $FeCl_3$-doped and $FeCl_3$/dodecylbenzenesulfonic acid (DBSA)-doped poly(2,5-bis(3-hexadecylthiophene-2-yl)thieno[3,2-b]thiophene (PBTTT) films as a function of relative humidity at 20% room temperature [49]. Copyright 2025, Royal Society of Chemistry. (c) Cyclic voltammetry curves of PPy[IC]-coated electrodes and the corresponding stress–potential curves of the material under the same conditions [50]. Copyright 2016, American Chemical Society. (d) Impact of ambient humidity on the stability of material performance, showing significant performance degradation in high-humidity environments [51]. Copyright 2023, Wiley-VCH GmbH. (e) Stress–strain curves of PEDOT:PSS–polyacrylamide (PAAm) composite conductive hydrogels with varying PAAm content [52]. Copyright 2019, Institute of Physics Publishing Ltd.

3.3 | Recent Advances in Doping Techniques

In recent years, significant progress has been made in the doping technology of conductive polymers. Research has not only optimized traditional doping pathways but also brought forth a variety of innovative strategies aimed at achieving breakthroughs in key aspects such as doping efficiency, stability, uniformity, and controllability.

3.3.1 | In Situ Versus Ex Situ Doping

In situ doping refers to the simultaneous introduction of dopants during polymer synthesis or polymerization, directly yielding doped polymers with high electrical conductivity. For instance, Mishra et al. [58] developed a one-step in situ synthesis technique that ingeniously integrates Fe/Mg bimetallic doping with the polymerization of polyaniline. While polyamic acid undergoes imidization to form a dense three-dimensional network, Fe^{3+} ions initiate the polymerization of aniline and achieve Fe/Mg co-doping, enabling polyaniline nanostructures to be directly embedded into the forming polyimide matrix.

Ex situ doping, in contrast, involves postprocessing of presynthesized neutral polymers. Classic examples include iodine vapor doping of polyacetylene and electrochemical doping. A major advantage of such methods lies in the precise control over doping levels (e.g., by adjusting dopant concentration or duration). As demonstrated by Jiang's team [59], through sophisticated electrochemical doping engineering, the amount of charge injected into the polymer backbone can be reversibly and precisely regulated simply by tuning the applied voltage. This enables gradient control of electrical conductivity, which increases significantly with rising doping levels.

3.3.2 | Novel Dopants and Hybrid Approaches

In recent years, research on conductive polymer doping has increasingly focused on developing green, efficient, and multifunctional dopants and composite strategies. In the area of biocompatible dopants, natural small molecules such as fructose, sorbitol, and vitamin C have garnered widespread attention due to their low toxicity and excellent biocompatibility. For instance, the team led by Ouyang [60] introduced D-sorbitol into the PEDOT:PSS system, where it served dual roles as both an auxiliary dopant and a plasticizer. This approach not only enhanced the conductivity of the film but also significantly improved its ductility, offering a viable material pathway for applications such as implantable bioelectrodes, tissue-engineering scaffolds, and flexible sensing skins. In terms of composite doping methods, researchers are striving to deeply integrate the doping process with material preparation techniques to synergistically optimize conductivity, mechanical properties, and stability. Current mainstream approaches include in situ polymerization composite doping, solution blending doping, surface modification/interface doping, and layer-by-layer self-assembly. To address the issues of low electrical conductivity and inadequate thermoelectric performance in pure PEDOT:PSS fibers, the Chen's team [61] first treated the fibers with dimethyl sulfoxide or ionic liquids to effectively reduce the insulating PSS component and construct efficient conductive pathways. Subsequently, they adjusted the carrier concentration using reducing agents or alkaline solutions, significantly enhancing the Seebeck coefficient. The resulting fibers not only exhibited excellent electrical and thermal properties but also demonstrated good flexibility and mechanical strength, capable of withstanding bending and twisting during textile processing. This provides a feasible solution for seamlessly integrating next-generation wearable self-powered electronic devices with textiles.

Overall, doping technologies for conductive polymers are advancing toward greater precision, stability, and functional diversity. Researchers are no longer confined to simply enhancing conductivity; instead, they aim to strike an optimal balance among high conductivity, superior stability, favorable mechanical properties, and processability. By combining conductive polymers with various functional materials, the application boundaries of these materials continue to expand.

4 | Wearable Health Monitoring: Application Domains

Chemically optimized CPs, characterized by high electrical conductivity and excellent functional properties, have emerged as ideal materials for constructing a new generation of wearable health-monitoring systems. They enable comprehensive and high-precision monitoring—from physiological signals within the body to environmental parameters externally—offering a novel technological pathway for personalized health management.

4.1 | Physiological Signal Detection

Chemically doped conductive polymers, with their unique flexibility, high biocompatibility, tunable electrical conductivity, and mixed ion–electron conduction capabilities, are demonstrating significant potential in physiological signal detection for wearable health monitoring. They are increasingly becoming a promising alternative to conventional rigid electrodes.

4.1.1 | Electrocardiogram and Heart Rate Monitoring

Chemically doped conductive polymers with high electrical conductivity—particularly PEDOT:PSS—have emerged as ideal materials for flexible dry electrodes. They form low-impedance, high-fidelity interfaces with the skin, enabling the acquisition of high-quality electrocardiogram (ECG) signals without the need for traditional conductive gels. This effectively avoids discomfort caused by gel drying or skin irritation, making them more suitable for long-term wear. When integrated into chest patches, wristbands, ECG vests, or smart garments, these electrodes enable long-term, continuous, and comfortable monitoring of cardiac activity. Such systems support the screening, diagnosis, and early warning of cardiac conditions such as arrhythmias (e.g., atrial fibrillation), myocardial ischemia, and heart rate variability analysis. Studies have shown that PEDOT:PSS electrodes doped with ionic liquids already match the SNR of clinically used Ag/AgCl gel electrodes while offering superior wearing comfort. The team led by Yang [62] developed a stretchable self-adhesive electrode based on PEDOT:PSS (Figure 4a). By blending PEDOT:PSS with elastomers and adhesive components such as polydopamine, the electrode adheres closely to the human body like a "second skin," maintaining stable low-impedance contact even during physical activity. This allows for the collection of ECG signals with an SNR as high as 38.85 dB and clinical-grade accuracy. This advancement represents a breakthrough technological pathway for the long-term management and early diagnosis of cardiovascular diseases. High-quality ECG acquisition requires stable low-impedance contact because the millivolt-level signal is highly susceptible to low-frequency drift and motion artifacts. Conductive polymer dry electrodes and conductive hydrogels can improve robustness by combining electronic conduction with mechanical compliance, thereby maintaining conformal contact and reducing impedance fluctuations during daily activities (Figure 4b) [63].

4.1.2 | Electromyography and Muscle Activity Monitoring

Flexible conductive polymer electrodes can closely conform to the undulating surface of muscles, accurately capturing microvolt-level electrical signals generated during muscle contractions while demonstrating excellent resistance to motion artifacts. This characteristic makes them highly valuable across multiple fields. In sports science, they enable analysis of muscle activation patterns, coordination, and fatigue states. In rehabilitation medicine,

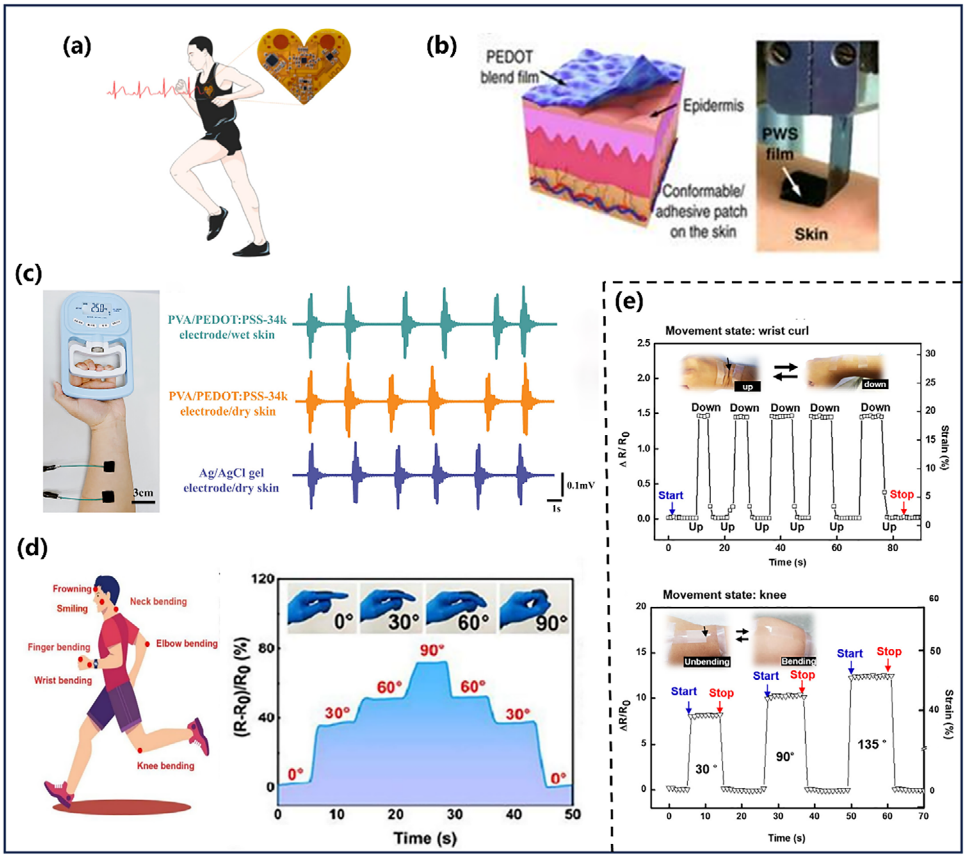

FIGURE 4 | (a) Self-adhesive PEDOT:PSS electrode used as an ECG patch on the chest [62]. Copyright 2025, American Chemical Society. (b) A self-adhesive, stretchable dry electrode film based on a PEDOT:PSS/WPU/D-sorbitol blend [63]. Copyright 2020, The Author(s). (c) Photograph of the electrode attached to the arm during a grip strength test, and the corresponding EMG signals collected on wet or dry skin [64]. Copyright 2025, American Chemical Society. (d) Real-time resistance changes of liquid metal nanoparticles (LMNPS) hydrogel when used for monitoring finger, elbow, neck, wrist, and knee movements, as well as facial expressions and knuckle bending [65]. Copyright 2024, Elsevier B.V. (e) Photographs of the 3D stress sensors mounted on the wrist and knee, along with the time-dependent resistance changes [66]. Copyright 2017, American Chemical Society.

they provide objective assessment of neuromuscular functional recovery, offering data-driven guidance for rehabilitation training. In cutting-edge human–computer interaction, they further support high-precision control of prostheses, exoskeletons, or neural interfaces by accurately recognizing users' movement intentions. For example, one study precisely regulated the molecular weight of polyvinyl alcohol (PVA) to construct an optimized hydrogen-bonding network within a PVA/PEDOT:PSS composite [64]. This led to the development of a high-performance electrode suitable for long-term stable epidermal electromyography (EMG) monitoring. When attached to forearm skin, the electrode clearly captures EMG signals even during gestures such as fist clenching or finger extension, effectively suppressing motion artifacts (Figure 4c). This breakthrough material solution provides a reliable and durable platform for long-term human–machine interaction and health monitoring.

4.1.3 | Joint Motion and Biomechanical Stress Sensing

Based on the piezoresistive effect (resistance change under pressure) and strain-sensing properties (resistance change under deformation) of doped CPs, flexible sensors can be fabricated and attached to joints (such as the knee, wrist, or finger joints) or integrated into insoles and smart shoe soles. By monitoring real-time resistance variations, these sensors can accurately capture critical biomechanical parameters, including joint flexion angles, range of motion, gait cycles, and even ground reaction forces and plantar pressure distribution. The team led by Ye [65] successfully developed a multifunctional conductive hydrogel based on PEDOT:PSS and liquid metal (Figure 4d). This material combines high stretchability, excellent conductivity, self-adhesion, and self-healing capabilities. When fabricated into a strain sensor and attached to joints such as fingers, elbows, or knees, it stably outputs resistance change signals that closely correspond to joint bending angles. This technology provides a reliable tool for quantitative rehabilitation training assessment and precise motion posture capture, demonstrating broad application potential in smart healthcare and sports analysis. In strain- and motion-sensing, conductivity stability under repeated deformation is as important as the peak conductivity value. Conductive polymer composites and hydrogel architectures can provide percolated conduction pathways that remain continuous under large strain, enabling repeatable resistance and impedance modulation with reduced hysteresis and improved durability for joint motion tracking (Figure 4e) [66, 67].

4.2 | Environmental Sensing for Personal Safety

Chemically doped CPs have emerged as promising sensing materials for environmental safety monitoring, owing to their unique electrical properties, tunable molecular structures, and excellent processability for flexible applications.

4.2.1 | Detection of Hazardous Gases (e.g., NO_x, CO, and VOCs)

The core mechanism of such gas sensors lies in the "chemiresistive effect," where the diffusion and adsorption of target gas molecules onto the surface of doped CPs induce significant changes in electrical resistance. Specifically, oxidizing gases (e.g., NO_2, Cl_2, and O_3) typically cause a decrease in resistance, while reducing gases (e.g., CO, NH_3, H_2S, and volatile organic compounds (VOCs)) lead to an increase in resistance. A team led by Kang [68] developed an alternating- and direct-current (ADC)-electropolymerization technique that enables direct growth of conductive polymer films on microelectrodes as gas-sensing layers (Figure 5a). The resulting NO_2 sensor not only exhibits ultrahigh sensitivity and rapid response but also operates at room temperature with excellent flexibility, offering a feasible technological pathway for next-generation high-performance, wearable environmental monitoring devices. Another innovation comes from Dong et al. [69], who created a flexible sensor capable of directly adhering to plant surfaces (such as leaves or stems). This device enables in situ, real-time, and continuous monitoring of specific volatile organic compounds (e.g., methanol) released by plants, achieving a detection limit at the sub-ppm level (Figure 5b). This technology provides a novel research tool for gaining deeper insights into plant physiological status, advancing smart agriculture, and enhancing food security.

4.2.2 | Radiation and Other Environmental Hazards

Environmental radiation and other hazardous factors are diverse, primarily including ionizing radiation (such as α, β, γ rays, and neutrons, commonly found in nuclear facilities or medical environments) and nonionizing radiation (such as ultraviolet light and electromagnetic fields), along with chemical hazards (toxic gases, VOCs, particulate matter, and heavy metals), physical hazards (noise and extreme temperatures), and biological hazards (pathogenic microorganisms). These factors can threaten human health by directly damaging cells, inducing cancer, or causing chronic diseases. In the field of radiation monitoring, CPs can be utilized to detect UV radiation intensity by incorporating radiation-sensitive monomers or specific dopants. This capability helps in preventing skin damage from sun exposure and supports the development of smart sunburn warning devices. A team led by Hur [70] developed a ZnO/conductive polymer bilayer UV sensor that combines the advantages of organic and inorganic materials, demonstrating excellent sensitivity, response speed, and stability. This sensor is suitable for various scenarios requiring precise UV intensity monitoring, including real-time environmental UV index measurement, industrial UV curing process control, flame detection, and personal UV exposure alerts in wearable devices (Figure 5c). This research provides an advanced material solution for achieving reliable and efficient ultraviolet detection. For UV and radiation-related hazards, wearable sensing should be dose-aware rather than purely qualitative. Skin-conformal UV patches coupled with smartphone readout provide an experimentally validated route to quantify exposure during daily activities and under sunscreen use. This highlights a practical "hazard-to-action" workflow where mechanics, sensing chemistry, and calibration jointly determine usable safety feedback (Figure 5d) [71].

4.3 | Integration with Data Acquisition and Processing Systems

System integration often limits wearable performance via power/data links, packaging, and motion-robust readout rather than the sensing material alone. Battery-free near-field communication (NFC) sensing is attractive for long-term wear, but range constraints hinder multisite monitoring. Textile-based near-field relays have been demonstrated to extend NFC connectivity across garments, enabling multinode, smartphone-readable sensing during motion (Figure 5g) [74].

4.3.1 | Compatibility With Wireless and Flexible Electronics

Traditional electronic components (such as chips and batteries) are typically rigid, leading to a significant mechanical mismatch with flexible sensors. In contrast, chemically doped conductive polymers not only possess inherent flexibility and stretchability but can also be readily integrated as sensing materials into flexible systems. Achieving effective compatibility with wireless flexible devices relies on the systematic integration of multiple technical aspects, including materials, mechanics, circuitry, and communication. Doping engineering optimizes electrical conductivity and stability, enabling polymers to be seamlessly combined with flexible substrates via printing or spinning processes, thereby ensuring consistent performance during deformation. Low-power-circuit design and edge computing are employed to process weak sensing signals, reducing the burden on wireless transmission. Coupled with low-power-communication protocols such as bluetooth low energy (BLE) and NFC, efficient data transmission is realized. This multilevel collaborative design ultimately enables the creation of intelligent systems that can be worn closely to the body, sense in real time, and interact wirelessly, laying the foundation for the widespread adoption of wearable technology. A team led by Yu [72] developed a high-performance sensor based on p-toluene sulfonate hexahydrate (PTS)-doped PANI for detecting food spoilage. Designed as a passive LC resonant circuit, the sensor allows noncontact monitoring of frequency changes via an external radio frequency (RF) reader, enabling real-time and nondestructive assessment of food freshness (Figure 5e). When used to monitor the spoilage process of fish or poultry in packaging under room-temperature or refrigerated conditions, the sensor consistently reflected spoilage trends that aligned closely with traditional microbial counts and amine concentration measurements, demonstrating its effectiveness as an early-warning system for food spoilage.

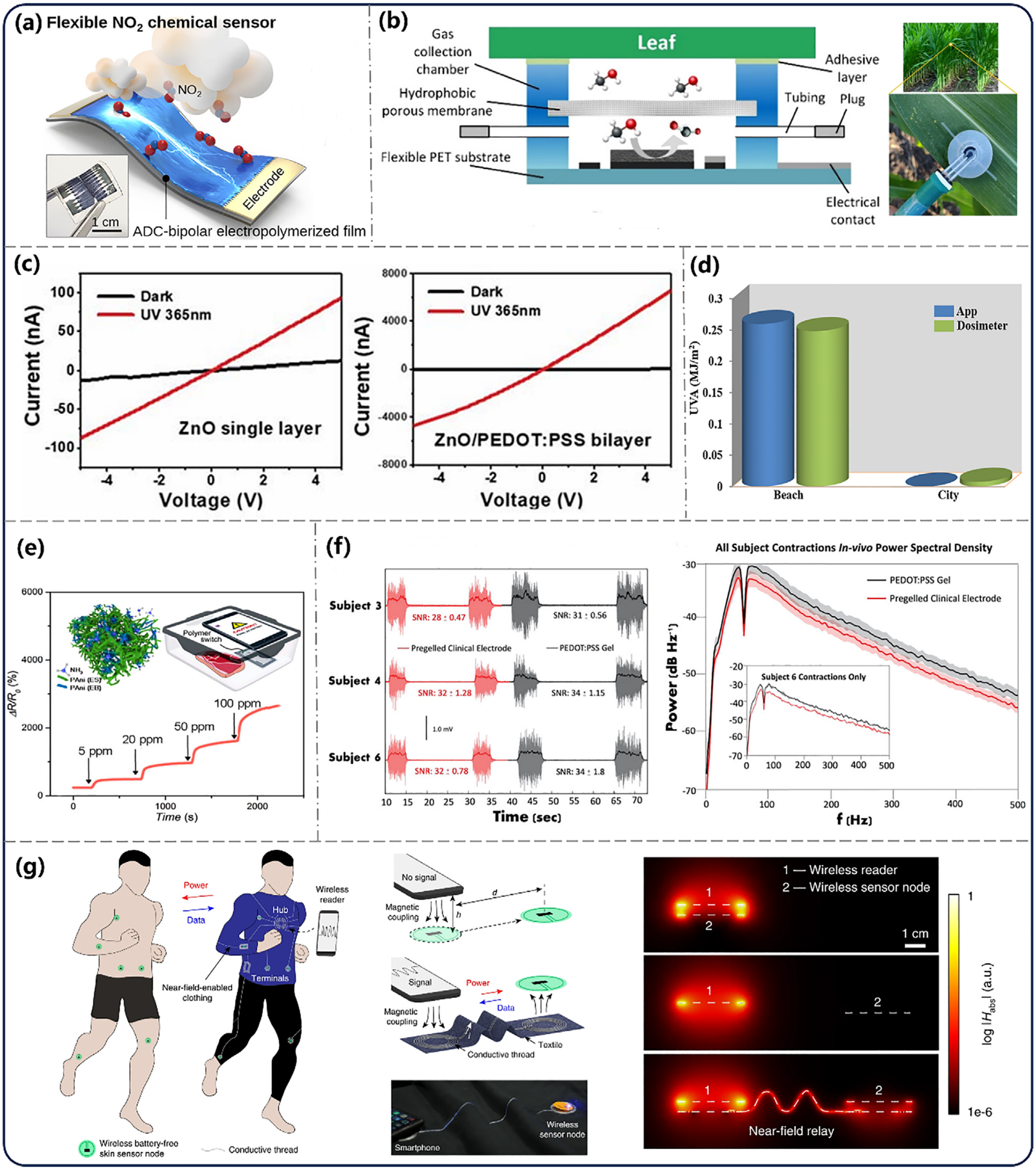

FIGURE 5 | (a) PEDOT-based gas sensor prepared via ADC bipolar electropolymerization [68]. Copyright 2025, American Chemical Society. (b) Cross-sectional view of the methanol sensor, and photograph of a VOC sensor mounted on a leaf surface [69]. Copyright 2022, American Chemical Society. (c) Comparison of the electrical properties of ZnO monolayer and ZnO/PEDOT:PSS bilayer structures under dark and ultraviolet (365 nm) illumination conditions [70]. Copyright 2020, The Korean Institute of Chemical Engineers. (d) Comparative data showing UV exposure during daily activities and the significant reduction in exposure when sunscreen is applied [71]. Copyright 2018, The Authors. (e) Real-time response curves of the sensor to different gas concentrations, monitoring food spoilage processes [72]. Copyright 2018, American Chemical Society. (f) Recorded electromyography signals from subjects with annotated signal-to-noise ratios, and power spectral density plots of contractions from all subjects [73]. Copyright 2023, Wiley-VCH GmbH. (g) Multiple battery-free sensor nodes are mounted on the skin and connected to a wireless reader via near-field enabled clothing [74]. Copyright 2020, The Author(s).

4.3.2 | Signal Fidelity and Noise Challenges

The conductivity σ determines the electrode/interconnect resistance $R_s \approx L/(\sigma A)$, thereby directly affecting signal attenuation and the Johnson noise floor $v_n = \sqrt{4kTR_s\Delta f}$, and ultimately the SNR [75]. We further relate σ to bandwidth and transient fidelity through the RC time constant $\tau \sim (R_s + R_{load})C_{eff}$, explaining that insufficient σ increases the effective filtering effect and aggravates motion-induced artifacts [76]. In dynamic and variable real-world wearable environments, ensuring high-fidelity physiological signals remains a core challenge for flexible sensing systems. Noise interference typically arises from multiple sources, including interfacial noise, motion artifacts, environmental electromagnetic interference, and internal circuit noise. To suppress noise at the source, researchers often employ highly doped CP electrodes. Such materials not only exhibit extremely high interfacial capacitance and excellent mixed ionic–electronic conductivity but also form stable, low-impedance interfaces with the skin, effectively reducing the impact of interfacial noise and motion artifacts. Additionally, their high electrical conductivity and robust bending resistance help maintain signal integrity and stability during deformation. A team led by Howe [73] developed a pure conductive polymer hydrogel that does not contain any external conductive fillers, its conductivity relies entirely on the self-constructed three-dimensional conductive network of the polymer (Figure 5f). When used as an epidermal electrode, the material significantly reduces electrode–skin interface impedance due to its outstanding mixed ionic–electronic conductivity and soft, skin-conformable texture. This improvement not only enhances the strength of useful bioelectrical signals but also effectively suppresses motion-induced noise, thereby fundamentally improving the signal-to-noise ratio. This material offers an innovative solution that surpasses traditional gel electrodes and dry electrodes for long-term, high-fidelity physiological monitoring.

5 | Device Fabrication and System Integration

5.1 | Material Processing and Device Architectures

Chemical doping of conductive polymers not only imparts exceptional electrical properties to the material but, more importantly, preserves its excellent solution processability. This offers significant advantages in device manufacturing compared to conventional rigid materials. Through precise control of material characteristics via doping engineering, combined with advanced techniques such as solution processing and electrospinning, these materials can be fabricated into sensing units with tailored microstructures. These units can then be integrated into resistive or transistor-based device architectures to achieve efficient signal conversion, collectively determining the overall performance of the sensor.

5.1.1 | Printing, Coating, and Fiber-Spinning Techniques

Printing, coating, and fiber-spinning technologies represent core-manufacturing strategies for transforming chemically doped conductive polymers from functional materials into practical devices. By precisely tuning the solution properties (such as viscosity and surface tension) of dopants and polymers, techniques like inkjet printing and screen printing can be employed to efficiently fabricate high-precision circuits and electrodes on flexible substrates. Coating processes such as spin-coating and blade-coating enable the rapid formation of large-area, uniform sensing films. Meanwhile, electrospinning and wet-spinning techniques allow the construction of one-dimensional nanofibers or continuous macroscopic fibers with high specific surface areas, offering ideal platforms for gas sensing and electronic textiles. A team led by Chen [77] successfully developed a conductive polymer ink with outstanding air stability, overcoming the atmospheric sensitivity limitations of conventional materials and enabling the direct printing of high-performance micro-supercapacitors in ambient air (Figure 6a). Suitable for screen printing and other processes, this ink can produce ultrathin, flexible energy storage devices on soft substrates. Its exceptional environmental stability not only simplifies the manufacturing process but also significantly enhances device reliability, providing key technical support for the development of self-powered “electronic tattoo” systems that seamlessly integrate with skin or textiles. This advancement holds significant implications for high-throughput, low-cost progress in personalized health monitoring and smart fabrics. Liu et al. [78] created an ultraconductive, patternable 40-nm polymer film that serves as an innovative hardware platform for emotion recognition (Figure 6b). With its extremely low interfacial impedance, the film captures weak physiological signals such as electroencephalogram (EEG) and skin conductance with high fidelity. Its patternable nature also supports the construction of multichannel sensing arrays for synchronous monitoring of multimodal physiological parameters. Combined with machine learning (ML) algorithms, this technology enables accurate extraction of emotional features from high-quality data, strongly advancing the practical application of wearable devices in mental health monitoring and human–computer interaction.

Furthermore, the application of conductive polymers in textiles is evolving from single-function systems to multifunctional integrated platforms. The team led by Persson [79] made a breakthrough by developing a conductive polymer artificial muscle fiber suitable for continuous production (Figure 6c). Using commercial textile fibers as substrates, they designed a continuous process for in situ polymerization and doping, successfully producing doped conductive polymer muscle fibers tens of meters long with uniform performance. This method overcomes the length and scale limitations of traditional batch laboratory preparation, enabling the resulting fibers to be directly woven and integrated using existing textile technologies. This lays an industrial foundation for the practical application of artificial muscles in large-scale soft robotics and smart textiles.

5.1.2 | Design Considerations for Wearable Comfort and Durability

Device design must remain human-centered, and in the development of wearable technology, comfort is always a key factor determining user acceptance. Factors such as material breathability and moisture permeability, appropriate weight and thickness,

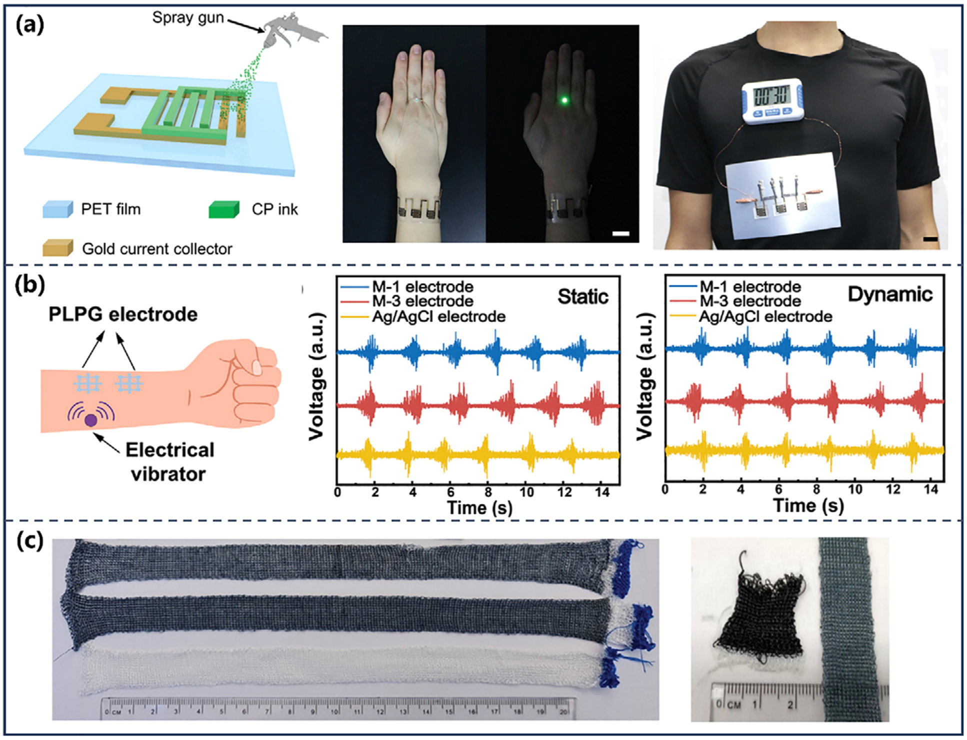

FIGURE 6 | (a) Mask-assisted spray coating for fabricating printed micro-supercapacitors (MSCs); the prepared integrated circuit can power a green light-emitting diode (LED) and drive a liquid crystal timer [77]. Copyright 2021, Wiley-VCH GmbH. (b) Recording of electromyography (EMG) signals on the skin under vibrations induced by an electric vibrator, measuring EMG under both dynamic and static conditions [78]. Copyright 2024, Wiley-VCH GmbH. (c) 1 × 1 rib-knitted fabric produced on an industrial flat knitting machine (Stoll ADF 530 ki) [79]. Copyright 2024, The Author(s). Macromolecular Materials and Engineering published by Wiley-VCH GmbH.

soft tactile properties, and gentle, nonirritating skin contact collectively determine whether a device can be as comfortable and durable as everyday clothing or a bandage. To achieve this goal, researchers have pursued innovations in both structural and material designs. To prevent the issue of traditional continuous films blocking sweat evaporation, CPs can be engineered into porous or mesh-like structures, or patterned and integrated with textile substrates. These approaches enhance breathability while preserving electrical performance. A team led by Huo [80] developed a composite bioelectrode based on natural leather and polypyrrole. The soft leather substrate not only conforms closely to skin contours but its inherent porous structure also effectively promotes sweat evaporation and air circulation (Figure 7a). This enables stable electrical signal acquisition while significantly improving comfort during long-term wear. Beyond comfort, mechanical durability is another critical hurdle for the practical application of wearable devices. Under repeated bending, stretching, and other dynamic stresses, polymer films are prone to microcracks, delamination, or separation from electrodes, ultimately leading to performance degradation. To address this challenge, Fang et al. [81] designed and synthesized a polyaniline analog featuring a rigid "ladder-type" backbone (Figure 7b). This structure significantly suppresses segmental motion and undesirable conformational changes of the polymer chains, resulting in exceptional stability during electrochemical cycling. The material retained nearly 100% of its capacitance after 10,000 cycles and still maintained over 90% even after 100,000 cycles. In contrast, conventional polyaniline retains only about 40% of its initial capacitance under the same conditions. This breakthrough provides a new molecular design strategy for developing conductive polymers that combine high electrical conductivity with outstanding mechanical durability.

5.2 | Biocompatibility and Stability

5.2.1 | Long-Term Skin Contact and Toxicity Aspects

In the design of wearable health devices, biocompatibility is a critical factor determining whether the device can safely contact the skin over extended periods. It not only affects wearing comfort but also directly relates to the potential for skin irritation, allergic reactions, or other adverse toxic effects. Although many conductive polymers (such as PEDOT, PPy, and PANI) are generally considered to have good biocompatibility, the safety of their long-term in vivo degradation products still requires systematic evaluation. In practical applications, potential risks may arise from multiple sources. Small-molecule dopants (e.g., $FeCl_3$) or metal nanoparticles may leach out from the polymer under the influence of sweat, causing cytotoxicity. Residual reactive monomers (e.g., pyrrole and aniline) from the synthesis process may also persistently irritate surrounding tissues due to their high reactivity. Additionally, surface roughness and rigidity of the material may damage the skin barrier through mechanical friction, while dense structures that trap heat and moisture can promote dermatitis and microbial growth. These risks fundamentally stem from complex interactions among the material's chemical composition, physical morphology, and the bio-interface, and must be systematically

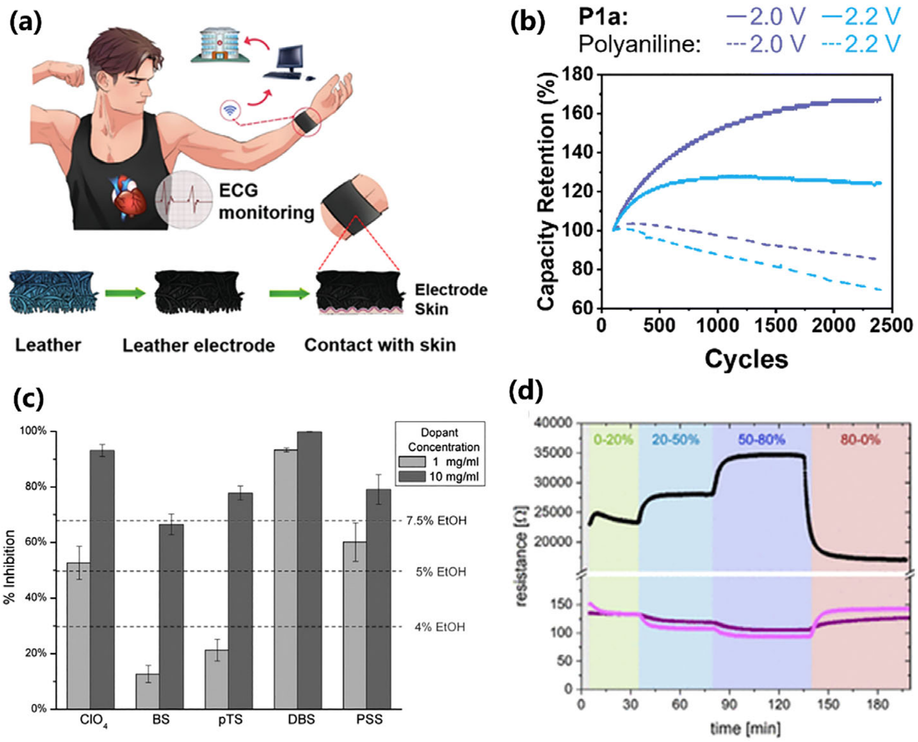

FIGURE 7 | (a) Composite bioelectrode for real-time monitoring of ECG signals and telemedicine in patients with cardiovascular diseases [80]. Copyright 2020, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim. (b) Relationship between cycle number and capacity for polyaniline and P1a dual-electrode devices [81]. Copyright 2023, Royal Society of Chemistry. (c) Percentage of cell growth inhibition for each dopant at concentrations of 1 and 10 mg/mL [82]. Copyright 2013, Wiley Periodicals, Inc. (d) The resistance of PEDOT:PSS films gradually increases with rising environmental relative humidity [83]. Copyright 2023, American Chemical Society.

managed through dopant optimization, interface engineering, and structural design. Among these risks, the choice of dopant is particularly crucial. Small-molecule inorganic dopants (e.g., perchlorate) can effectively enhance electrical performance but are prone to leaching in physiological environments, leading to localized high concentrations and cytotoxicity. In contrast, macromolecular or polymeric dopants (such as PSS or certain biopolymers) can be more stably anchored within the polymer network, reducing the risk of leaching and thereby demonstrating superior biocompatibility (Figure 7c) [82].

5.2.2 | Environmental and Operational Stability

Wearable devices must maintain stable performance under real-world, dynamic environmental conditions and during long-term operation, posing significant challenges for CP materials. In practical application scenarios, the conjugated backbone of CPs is prone to oxidative degradation when exposed to air and ultraviolet radiation over extended periods, leading to a gradual decline in electrical conductivity. Moisture from sweat can penetrate the material, causing swelling and accelerating the leaching of dopants. Temperature fluctuations also introduce thermal stress, affecting the material's structural integrity and interfacial adhesion. Taking PEDOT:PSS films as an example, they exhibit notable surface chemical instability during prolonged atmospheric aging, characterized by a transition from hydrophilic to hydrophobic wetting behavior over time (Figure 7d). This phenomenon stems from the metastable nature of the material itself. To reach a more stable energy state, polymer chains undergo surface reconstruction, causing hydrophobic PEDOT segments to gradually migrate and accumulate on the surface while masking the hydrophilic PSS components [83]. This inherent, environmentally driven phase-separation process makes it difficult to maintain stable surface properties, thereby posing a fundamental challenge to the long-term reliability of devices that depend on consistent interfacial characteristics, such as biosensors.

5.3 | Powering and Wireless Communication

5.3.1 | Energy Harvesting, Low-Power Design, and Integration with Internet of Things

To achieve fully wireless wearable systems capable of long-term operation, a stable and sustainable power supply remains a critical challenge to address. Energy harvesting, low-power design, and Internet of Things (IoT) integration collectively form the key technological pillars that enable conductive polymer devices to become self-powered, intelligent, and long-lasting. The relationship among these three can be likened to an organic living system: energy harvesting acts as the system's "blood," continuously infusing it with energy; low-power design ensures that every unit of energy is used with maximum efficiency, allowing the system to operate reliably even under minimal power input; and IoT integration provides "intelligence" and "connectivity," enabling the analysis of collected data to generate value, while its flexible scheduling and management capabilities can in turn optimize the system's energy consumption.

For example, organic artificial neurons leverage their unique ion–electron coupling characteristics to simulate the dynamic behavior of biological neurons at ultralow power consumption levels as low as femtojoules [84]. Their event-driven operation mode, combined with the intrinsic properties of the materials, allows efficient integration with energy harvesters such as piezoelectric or photovoltaic devices. These harvesters capture energy from body movement or ambient light, gradually moving toward energy self-sufficiency. This integration fully unleashes the potential of conductive polymers in the bioelectronic IoT—driving the development of battery-free, long-term implantable or wearable intelligent systems for applications such as real-time health monitoring, neural rehabilitation, and distributed sensing. Ultimately, this facilitates deep integration of intelligent technology with living organisms and the physical world. In practical applications, researchers have developed fully integrated sensor arrays that adhere to the skin like a bandage [85]. These devices can synchronously, in situ, and in real time analyze dynamic changes in multiple components of sweat, such as glucose, lactate, and electrolytes. With built-in circuits for signal processing and Bluetooth for wireless transmission to smartphones, this technology has for the first time enabled continuous, noninvasive, and multiplexed analysis of complex sweat composition. It provides a novel technological platform for personalized health management and exercise physiology research.

Looking ahead, the development of truly wireless wearable systems requires further advances in compatible flexible power solutions. These may include integrating flexible batteries, energy harvesting devices (such as triboelectric nanogenerators and flexible solar cells), or adopting ultra-low-power designs. Ultimately, through IoT technology, seamless and efficient transmission of data to smart terminals and cloud platforms will be realized.

6 | Challenges, Opportunities, and Future Perspectives

6.1 | Current Limitations

Despite substantial achievements in the laboratory stage and continuous breakthroughs in various performance metrics, the path toward true commercialization and large-scale clinical application still faces severe challenges. One major issue is the significantly lower efficiency of n-type doping compared to p-type doping, rooted in thermodynamic instability and fundamental materials science hurdles. N-type dopants are typically strong reducing agents (such as alkali metals), which are inherently unstable in air, making them difficult to handle and store. Effective n-type doping requires polymers with low LUMO energy levels to stabilize the injected electrons. However, most conductive polymers possess relatively high LUMO levels, which limit the overall efficiency and stability of n-type doping.

6.1.1 | Long-Term Durability, Reproducibility, and Large-Scale Manufacturing

In large-scale production, ensuring the uniformity of material and device performance as well as batch-to-batch reproducibility remains a critical challenge to be addressed. The morphology, dimensions, and doping levels of conductive polymer nanostructures (such as nanofiber networks) are highly dependent on synthesis conditions. Even minor fluctuations in processing can lead to performance variations, posing difficulties for product standardization. The long-term stability of materials also presents a significant challenge. Under prolonged exposure to environmental factors such as oxygen, moisture, or elevated temperatures, conductive polymers are prone to a decline in electrical conductivity and degradation in sensing performance, resulting in signal drift and reduced device lifespan. Furthermore, after repeated gas adsorption or mechanical stress, the structural integrity of nanostructures may be compromised, affecting their functional reliability [86].

6.1.2 | Stability Under Mechanical Deformation and Environmental Exposure

In dynamic wearable environments, the long-term mechanical and chemical stability of materials is crucial to their practical applicability. Conductive polymers remain susceptible to fatigue failure under repeated bending, stretching, and other mechanical stresses. Beyond mechanical stress, environmental factors such as sweat, sebum, and ultraviolet radiation collectively pose significant challenges to material stability. Taking PEDOT:PSS thin films as an example, under high-humidity conditions, the material absorbs a significant amount of moisture, causing the insulating PSS phase to soften and exhibit enhanced viscoelasticity. This change slows down the dynamic response of the conductive network—its breakdown and reconstruction—during deformation. Macroscopically, this manifests as a severe lag in resistance change relative to the actual strain, leading to significant signal distortion and measurement inaccuracy [87].

6.2 | Emerging Trends

6.2.1 | Multifunctional Sensing (Simultaneous Detection of Multiple Signals)

Future wearable devices will evolve beyond single-function sensors into integrated systems that combine multiple sensing units. These advanced platforms can simultaneously capture a variety of physiological and biochemical signals—such as ECG, EMG, temperature, and sweat composition—to provide a more comprehensive view of an individual's health status. A team led by Javey [86] developed a highly integrated sensor array capable of in situ, synchronous, and real-time monitoring of multiple key physiochemical substances in sweat. The array not only includes amperometric metabolite sensors (for detecting glucose and lactate) but also incorporates potentiometric electrolyte sensors (for sodium and potassium ions). Innovatively, it also integrates a skin temperature sensor to calibrate the responses of the biochemical sensors, thereby improving quantitative accuracy. This high-density integration, achieved through micro-nanofabrication techniques, ensures that all data points are collected from sweat at the same spatial and temporal location. For the first time, this enables synergistic analysis and correlated interpretation of dynamic changes in multiple sweat components, offering a powerful tool for comprehensively evaluating exercise physiology, metabolic status, and hydration levels.

6.2.2 | Self-Healing and Self-Powered Wearable Systems

The development of CPs with self-healing capabilities—enabling automatic restoration of structure and function after wear or fracture—holds great potential for significantly extending device lifespan. By embedding conductive fillers (such as PEDOT:PSS and carbon nanotubes) or liquid metals into a self-healing polymer matrix, the dynamic network reconstruction of the matrix can drive the reconnection of conductive pathways [88]. This approach is expected to address performance degradation caused by mechanical damage in flexible electronic devices, substantially enhancing their durability and reliability in applications such as wearable technology and soft robotics. Integrating such materials deeply with energy harvesting technologies to build fully self-powered, recharge-free wearable systems has become a key objective in the field. A team led by Yu [89] developed an interpenetrating network composite based on PEDOT and thermoplastic polyurethane (TPU), which can be used to construct triboelectric nanogenerators for efficient harvesting of water droplet mechanical energy and its conversion into electricity. This system has been successfully applied to power LEDs and small electronic devices, offering a novel electrode solution for environmental energy harvesting systems. Moving forward, efforts should focus on developing wearable electronic devices that combine self-healing properties with sustained self-powering capability, thereby advancing the realization of intelligent, durable, and energy-autonomous next-generation flexible systems.

6.2.3 | Integration With Artificial Intelligence for Personalized Health Analytics

The massive volume of continuous monitoring data must be analyzed with the aid of artificial intelligence (AI) and ML algorithms. AI not only filters out noise but also extracts deep health insights, enabling early disease prediction, personalized health recommendations, and closed-loop interventions (such as automated drug delivery), thereby achieving a true leap from simple “monitoring” to proactive “management.” A new paradigm for personalized health analysis is emerging: highly biocompatible doped conductive polymer-based flexible sensors unobtrusively and continuously capture multimodal physiological signals—such as ECG, sweat biochemical markers, and mechanical deformations—providing high-quality data sources for analysis. AI deeply mines these dynamic data streams, leveraging temporal modeling to establish individual health baselines, integrating multimodal information to decode physiological correlations, and applying federated learning to enable adaptive algorithm iteration. This end-to-end framework ultimately forms an intelligent closed loop—from early anomaly detection and root cause analysis to personalized intervention—driving the evolution of health management from generalized monitoring toward precise, forward-looking decision-making [89].

6.3 | Outlook for Translation to Clinical and Consumer Applications

6.3.1 | Regulatory Considerations

Any new material intended for long-term contact with the human body must be accompanied by comprehensive biocompatibility test reports (according to ISO 10993 standards), including in vitro cytotoxicity, skin irritation and sensitization, and systemic toxicity [90, 91]. These form the foundation for regulatory approval. The commercialization of wearable devices requires a clear distinction between medical-grade and consumer-grade applications. Medical devices (such as diagnostic patches) must undergo approval from regulatory bodies like the Food and Drug Administration (United States) (FDA) and National Medical Products Administration (China) (NMPA), involving extensive clinical validation trials to demonstrate their safety, efficacy, and reliability—a process that is both time-consuming and costly. Consumer-grade products (e.g., health management wristbands) face relatively lighter regulatory requirements but still need to comply with electronic device safety and electromagnetic compatibility standards. In recent years, a trend of “transitioning from consumer grade to medical-grade” has emerged [92]. For example, the ECG feature of the Apple Watch has received Class II medical device clearance from the FDA.

6.3.2 | Pathways for Commercialization

Successful commercialization requires interdisciplinary collaboration, involving materials scientists, engineers, clinicians, and business developers—all playing indispensable roles. Cost control, user-friendly industrial design, robust supply chains, and a clear business model—whether the product is positioned as a medical device or a consumer electronic—are all decisive factors in determining whether a technology can ultimately reach the market and benefit the general public. The clinical pathway centers on medical device certification, requiring breakthroughs in three key areas: biocompatibility certification, large-scale clinical trials, and integration into healthcare reimbursement systems. This pathway enables value transformation—from flexible electrodes and smart dressings to precision drug delivery systems. In contrast, the consumer pathway relies on a rapid-iteration model of hardware plus data services. By achieving low-cost mass production and integrating into broader ecosystems, it fosters user loyalty in areas such as health monitoring and sports rehabilitation. These two pathways ultimately converge at the node of “data valorization.” Leveraging continuously collected multidimensional physiological data as a foundation, algorithm upgrades drive the evolution of consumer-grade devices into auxiliary diagnostic tools. This process builds a comprehensive business ecosystem spanning “materials–devices–data–services.”

7 | Conclusion

7.1 | Summary of Key Advances

Through innovative doping strategies, the electrical conductivity of these materials has successfully been elevated to the range of 10^2–10^4 S/cm while maintaining excellent flexibility. Multifunctional sensing platforms capable of simultaneously monitoring physiological signals such as ECG and EMG, as well as environmental risk factors, have been developed. Leveraging printed electronics and fiber-spinning technologies, large-scale device fabrication has been achieved, while flexible hybrid electronics have addressed key system integration challenges. Furthermore, the integration of artificial intelligence algorithms with self-powering technologies is driving the evolution of systems toward greater intelligence and long-term operational autonomy. These breakthroughs have transformed chemically doped conductive polymers from functional materials into a core technological platform supporting a new generation of wearable health-monitoring systems, laying a solid foundation for the realization of personalized health management.

7.2 | Outlook on the Continued Development and Impact of Chemically Doped Conductive Polymers in Wearable Health Monitoring

Chemically doped conductive polymers, leveraging their unique flexibility, biocompatibility, and tunable electrical properties, are driving wearable health-monitoring technology to deeper levels of capability: from single physiological signal detection toward multimodal sensing integration, enabling comprehensive and simultaneous monitoring of electrocardiograms, biochemical markers, and environmental factors. Through molecular engineering that optimizes doping systems, significant improvements in material stability and biocompatibility have been achieved, laying the foundation for long term and comfortable wear. Looking ahead, this field will increasingly converge with artificial intelligence, utilizing edge computing for real-time data analysis and disease prediction, while flexible hybrid electronics will help overcome system integration bottlenecks. Ultimately, chemically doped conductive polymers will form the backbone of a new generation of seamlessly connected "hospital-to-home" intelligent health networks. This will catalyze a shift in healthcare from reactive treatment to proactive, personalized management, establishing these materials as a key enabling platform for the core infrastructure of smart medicine.

Author Contributions

J.S., L.Zhe., L.Zha., and C.H.L. conceived the structure and scope of the review. M.Z. and H.H. conducted the literature survey, data compilation, and figure preparation, and drafted the initial manuscript. All authors contributed to critical revision, discussion, and refinement of the manuscript. J.S., L.Zhe., L.Zha., and C.H.L. supervised the project and secured funding. All authors reviewed and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The authors have nothing to report.

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