Received: 1 June 2024 | Revised: 25 September 2024 | Accepted: 29 September 2024

DOI: 10.1111/1541-4337.70045

COMPREHENSIVE REVIEW

Comprehensive REVIEWS in Food Science and Food Safety WILEY

Smart conducting polymer innovations for sustainable and safe food packaging technologies

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Abstract

Biofilm formation on food packaging surfaces is a major issue in the industry, as it leads to contamination, reduces shelf life, and poses risks to human health. To mitigate these effects, developing smart coatings that can actively sense and combat microbial growth has become a critical research focus. This study is motivated by the need for intelligent packaging solutions that integrate antimicrobial agents and sensors for real-time contamination detection. It is hypothesized that combining conducting polymers (CPs) with nanomaterials can enhance antimicrobial efficacy while maintaining the mechanical integrity and environmental stability required for food packaging applications. Through the application of numerous technologies like surface modification, CP–nanoparticle integration, and multilayered coating, the antimicrobial performance and sensor capabilities of these materials were analyzed. Case studies showed a 90% inhibition of bacterial growth and a tenfold decrease in viable bacterial counts with AgNPs incorporation, extending strawberries' shelf life by 40% and maintaining fish freshness for an additional 5 days. Moreover, multilayered CP coatings in complex systems have been shown to reduce oxidative spoilage in nuts and dried fruits by up to 85%, while maintaining the quality of leafy greens for up to 3 weeks under suboptimal conditions. Environmental assessments indicated a 30% reduction in carbon footprint when CP coatings were combined with biodegradable polymers, contributing to a more transparent and reliable food supply chain. CP-based films integrated with intelligent sensors exhibit high sensitivity, detecting ammonia concentrations below 500 ppb, and offer significant selectivity for sensing hazardous gases. These findings indicate that CP-based smart coatings markedly enhance food safety and sustainability in packaging applications.

KEYWORDS

biofilm prevention, conducting polymers, food spoilage monitoring, intelligent food packaging, smart coatings

1 | INTRODUCTION

Microorganisms and their biofilms, which are very complex and resistant microbial communities, are serious threats to human health (Percival et al., 2011). Biofilms are a life-threatening risk across various domains, ranging from medicine to industrial processes, owing to their resilient biological composition (Muhammad et al., 2020). Biofilms composed of microbial cells and extracellular polymeric substances (EPSs), including polysaccharides, genetic material, proteins, lipids, and humic-like substances, exhibit challenging resistance (Percival et al., 2011). Microorganisms within biofilms often display reduced sensitivity to antimicrobial agents (Dutt et al., 2022), emphasizing the critical importance of addressing biofilm-related concerns, particularly within the food packaging industry and various other research fields (Srey et al., 2013). Infectious diseases, including blood and urinary tract infections, are frequently associated with biofilms. Consequently, given the widespread presence of microbial contamination and the corresponding risks of foodborne illnesses, it is imperative to implement precautionary measures for commonly used food packaging materials.

Antimicrobial agents encompass a vast array of natural and synthetic substances designed to inhibit or eliminate bacterial growth (Gyawali & Ibrahim, 2014; Moellering, 2011). These agents can be divided into two main categories: biocidal and biostatic (Gulati et al., 2022). Notably, a single agent can exhibit biostatic effects at lower concentrations and become biocidal at higher concentrations. These substances exert their effects by specifically targeting microorganisms and disrupting crucial steps in their development, such as wall synthesis, DNA replication, protein synthesis, or energy production. This disruption occurs when the antimicrobial agent binds to a specific molecule within the bacteria that plays a pivotal role in one of these essential metabolic processes.

Over the past few decades, the increasing challenge of identifying antibiotic-resistant bacteria has spurred intensive research into novel antimicrobial materials (Irkin & Esmer, 2015; Simoncic & Tomsic, 2010). Biocidal materials, which possess the capacity to either exterminate microorganisms or thwart their attachment to surfaces through the release of sterilizing ions, organic compounds, or metallic particles, have been a focal point of research. Organic polymeric materials with antimicrobial attributes are gaining significant attention from both academic and industrial perspectives, primarily attributed to their advantageous characteristics, including facile synthesis, flexibility, electrochemical stability, and potential for doping (Sumdani et al., 2022). However, the underutilized potential of conductive polymers in this critical field warrants further exploration and development.

Since their initial discovery in the late 1970s, conducting polymers (CPs) have emerged as a highly compelling and extensively explored field within materials science (Das & Prusty, 2012). Their distinctive attributes, including high electrical conductivity (up to 1000 S/m for doped CPs), electrochemical properties, mechanical resilience, ease of processing, and potential for both chemical and electrochemical synthesis, render them exceptionally versatile across a wide spectrum of applications (Namsheer & Rout, 2021). Countless scientists have dedicated their efforts to uncovering novel uses for these newly found CPs. The applications of CPs span a broad spectrum, including but not limited to thin-film transistors (Kim et al., 2016), organic light-emitting diodes (LEDs) (Koh et al., 2010), corrosion protection (El Guerraf, Ben Jadi, Aouzal et al., 2022), electromagnetic shielding (Wang et al., 2021), sensors (El Guerraf et al., 2020), molecular electronics (Brédas & Chance, 2012), supercapacitors (Han et al., 2020), and electrochromic devices (L. Zhang et al., 2019). By selecting specific molecular combinations, it becomes feasible to design multifunctional molecular structures that open up possibilities for nearly any desired application.

The appeal of utilizing CPs over existing solutions is multifaceted. First, these conjugated polymers can be readily synthesized, either chemically or electrochemically, often in a streamlined, single-step process. They are produced directly as uniform and adherent films with adjustable thicknesses. Moreover, these innovative materials exhibit remarkable resilience under extreme conditions: they maintain chemical stability in acidic solutions (Brožová et al., 2008) and display high thermal resistance (Dubey & Leclerc, 2011). Furthermore, their electroactivity and electrochemical stability render them attractive candidates for accessing bactericidal dopants. This unique feature allows for their reusability even after prolonged usage, which is achievable through a straightforward electrochemical re-doping procedure.

New processing techniques and creative packaging materials are being investigated in light of the increasing need for premium food products with longer shelf lives. The objective is to preserve the natural characteristics and appearance of these products without significant alterations. In this context, CPs offer an intriguing alternative (El Guerraf et al., 2023). Additionally, the utilization of nanomaterials, including silver and gold nanoparticles (Almatroudi, 2020; Tran et al., 2023), boron nitride nanotubes (Merlo et al., 2018), and graphene-based nanomaterials (Vasseghian et al., 2023), has become a point of great interest. These nanomaterials have played a critical role in revolutionizing the field of biotechnology, proving their effectiveness as antimicrobial agents and finding extensive

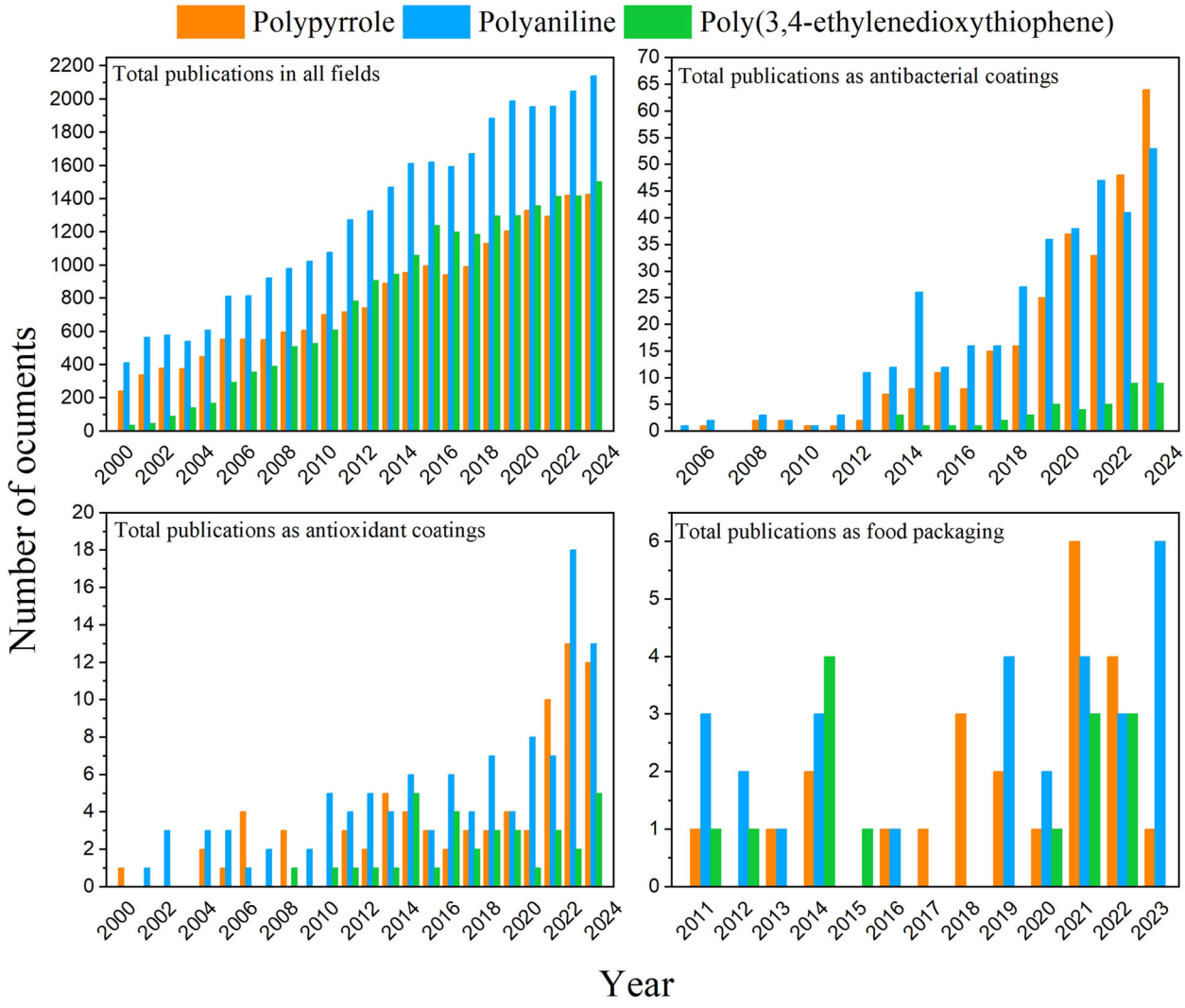


FIGURE 1 Published documents available in the Scopus database concerning the utilization of conducting polymers in diverse fields, including their applications as antibacterial, antioxidant, and food packaging coatings.

applications in the biomedical sector. Consequently, these nanomaterials can serve as promising bioactive agents within the polymeric matrix. Given their electroactivity and strong electrochemical stability, CPs can be readily doped with such bioactive substances, thereby enhancing their capacity to inhibit bacterial growth.

In Figure 1, we illustrate the publication trends related to CPs, initially across all fields and subsequently within the contexts of antibacterial, antioxidant, and food packaging coatings. Notably, significant growth in the number of published documents over the years underscores the considerable attention these polymers have garnered within the scientific community. However, the application of CPs for biofilm prevention remains underrepresented in the literature, as indicated by the limited number of published papers (less than six in 2023) in this specific domain.

On the other hand, smart and active food packaging systems incorporate tools to monitor changes in food quality, ensuring safety before reaching consumers. By providing real-time information about nutrition quality and safety, these systems eliminate the reliance on potentially inaccurate expiration dates (Azeredo & Correa, 2021). This not only helps prevent illnesses caused by consuming unsafe food but also significantly reduces food waste resulting from premature food recalls. This emerging packaging system ensures that food remains fresh and uncontaminated and extends the shelf life of packaged foodstuffs. It facilitates decision-making by monitoring and providing evidence of changes in food quality and warning of potential issues. Smart packaging technologies enhance communication about changes inside the package, displaying alerts about possible environmental problems that affect food quality, such as time, temperature, freshness indicators, and integrity (Thirupathi Vasuki et al., 2023).

This review describes the application of electronically CPs as a potential solution for preventing biofilm

formation, particularly within industrial contexts such as food packaging materials. The primary objective is to explore the practical implementation of such materials. The initial section of this comprehensive overview will address the various types of CPs, highlighting the unique challenges associated with their development and characterization. Particular attention will be directed toward the most prevalent polymers while also underscoring the significance of employing energy-efficient and environmentally friendly synthesis procedures. Subsequently, the discussion will focus on the doping of CPs with bactericidal species, an essential step in meeting the criteria for an ideal antimicrobial agent. The second section of this examination provides an in-depth examination of food packaging materials. The exploration of conventional packaging methods and their limitations will commence. This review will pivot to emerging research on the utilization of doped CPs as smart food containers. These insights are intended to guide future research endeavors in this domain.

2 | CONJUGATED CPs

Since their discovery, conventional organic polymers, which are typically electrically insulating materials, have played crucial roles in our daily lives. However, their insulating properties pose challenges when they are used in electrical environments. Toward the late 1970s, a pivotal breakthrough occurred with the discovery of polymers capable of conducting electric current (Guo & Facchetti, 2020). CPs represent a fascinating category of materials that bridge the gap between organic polymers and conductive metals. These unique materials are identified by their capacity to conduct electricity, similar to traditional metals while retaining the versatile and customizable properties of polymers. This discovery transformed these materials from their traditional applications as electrical sheaths, coatings, and paints into a broader and more intriguing realm of utility. Initial investigations focused on chemically synthesized polyacetylene, which, despite its relatively high conductivity, has the drawback of instability in the presence of air, rendering it impractical for many purposes (Guimard et al., 2007). Subsequently, numerous researchers have directed their efforts toward the development of alternative electronically CPs. Within this context, CPs have been categorized into three primary families based on their structural characteristics: the ***polyenic family (polyacetylene, and others), the poly heterocycle family (polypyrrole [PPy], polythiophene [PT], and others), and the polyaromatic family (poly(p-phenylene), polyaniline [PAni], and others). Additionally, there are mixed systems or copolymers, such as poly(p-phenylene vinylene). Table 1 provides various examples of CPs along with their corresponding conductivities, band gaps, and functionalities.

Unlike traditional semiconductors or metals, which have fixed electronic properties, CPs can be engineered to exhibit tuneable electrical conductance by modifying their chemical structure and doping levels. Materials can be created with a wide range of electrical, optical, and mechanical properties due to their versatility that makes them suitable for many applications. Because of their unique properties such as electrical conductivity, reversible doping–dedoping processes, controllable chemical and electrochemical characteristics, good environmental stability, ease of processing, and practical mechanical, optical, and electronic properties, many CPs have gained a great deal of notoriety in the fields of nanoscience and nanotechnology. In this introduction to CPs, the present study explored the fundamental principles behind their electrical conductivity, the methods of synthesis and doping that enable their customization, and their use as smart food packaging.

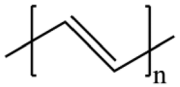
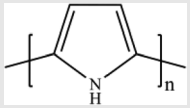
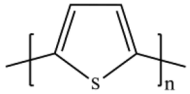
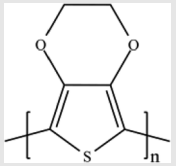
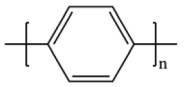
2.1 | Properties and conduction mechanisms

CPs possess several distinctive properties that make them particularly valuable in various applications. These materials not only demonstrate electrical conductivity but also exhibit a remarkable array of additional properties, including optical, mechanical, magnetic, wetting, and stability properties (K & Rout, 2021). These properties make CPs a fascinating class of materials with a broad range of potential applications in electronics, sensors, and other fields. Their versatility and ability to be tailored for specific requirements have contributed to their growing importance in materials science and technology.

2.1.1 | Optical properties

Numerous CPs have demonstrated interesting optical properties. They can absorb light in the visible and near-infrared (NIR) regions. When excited by photons, they undergo electronic transitions, which result in the emission of light. Because of this characteristic, they are useful in optoelectronic devices such as organic solar cells and LEDs (Khokhar et al., 2021). Additionally, the bandgap of CPs can often be adjusted by altering their chemical assembly. This adjustability allows for the fine-tuning of their optical characteristics, making them suitable for a diverse array of applications. The optical properties of CPs can be modulated by changes in their electrical conductivity. This

TABLE 1 Structures of common electronically conducting polymers with selected dopants, conductivities, band gaps, and functionalities.

Name	Structure	Procedure of synthesis	Doping agent	Conductivity (S/cm)	Band gap (eV)	Functionality	References
Polyacetylene (PAc)		Emulsion, suspension, precipitation, and dispersion polymerization	LiTFSI Na I	10^5	1.4	Polymeric electronics, asymmetric catalysis, and enantioselective crystallization	(Bi et al. 2013; Foyle et al., 2021; Kurzweil, 2009; Li et al., 2014; Wu et al., 2016)
Polypyrrole (PPy)		Chemical, microemulsion, electrochemical, and vapor-phase polymerization.	$FeCl_3$ APS $TEABF_4$ $LiClO_4$ $HAuCl_4$	Up to 105	1.9–2.8	Supercapacitors/electrodes, biosensors, drug delivery, protective coatings, actuators, and adsorbents	(Kaloni et al., 2016; Pang et al., 2021)
Polythiophene (PT)		Chemical, and electrochemical methods.	$FeCl_3$ APS SDS CTAB TEA	Exceeds 100	2.0	Resistive memory devices, photovoltaics and photoelectrochemistry, OLED, energy storage, and field-effect transistors	(Kadac & Nowaczyk, 2016; Kaloni et al., 2016, 2017; Mehmood et al., 2016)
Poly(3,4-ethylenedioxythiophen (PEDOT)		Chemical, electrochemical, and vapor-phase polymerization.	Metallacarborane ionic salts surfactants PSS	~0.2 (can be increased to higher than 2100)	1.5–1.6	Solar cells, energy harvesting and storage, sensors, OLED, smart textiles, optoelectronic devices, and bioelectronic medicine	(Fuentes et al., 2019; Li et al., 2021; Nie et al., 2021; Tseghai et al., 2020; Wang, 2009; Yu et al., 2016)
Poly(p-phenylene) (PPP)		Oxidative or electrochemical polymerization, and Suzuki coupling reaction	$TBAPF_6$ $LiClO_4$ ASF_6^- $FeCl_3$	Up to 1	2.8	LEDs, rechargeable batteries, supercapacitors, electrochemical sensing	(Giro et al., 2005; Phumman et al., 2009; Shacklette et al., 1982)

(Continues)

TABLE 1 (Continued)

Name	Structure	Procedure of synthesis	Doping agent	Conductivity (S/cm)	Band gap (eV)	Functionality	References
Poly(p-phenylene vinylene) (PPV)		Chemical routes using p-xylene intermediates	H_2SO_4 $FeCl_3$ CF_3SO_3H	Exceeds 100	2.0	LEDs, solar cells, sensors, biomedical, supercapacitors	(Ahlskog et al., 1997; Banerjee & Dutta, 2021)
Polyaniline (PAni)		Chemical, and electrochemical polymerization, electrospinning, enzyme assisted growth, DNA template method, and ultrasound-assisted polymerization	APS HCl H_2SO_4 DBSA PSS TFA CSA	2–10	2.8–3.2	Electrochromic glasses and electroluminescence devices, solar cells, sensors, supercapacitors, delivery systems and scaffolds in medicine, and anticorrosion materials	(Almasi et al., 2016; Bianchi et al., 2022; Chiolerio et al., 2014; Song & Choi, 2013; Zarrintaj et al., 2019)

property is utilized in sensors and devices for detecting changes in the environment or analyte concentrations.

On the other hand, some CPs can change color in response to an electrical stimulus. This change is due to chromophores (multiple bonding) that cause absorption in the visible and near-UV regions following π–π^* transitions (El Guerraf, Ben Jadi, Bakirhan et al., 2022). The unique optical attributes of CPs have been extensively studied for applications in electrochromic displays or nanophotonic devices because of their wide variation in colors. Moreover, the alteration in color has practical applications in food packaging, where it can be utilized to create coatings with desired colors or to serve as an indicator for assessing the condition of packaged products (freshness or expiration). To achieve this goal, various factors need to be controlled, including the oxidation level of the coating, the synthesis method, the choice of monomer, and the temperature.

2.1.2 | Mechanical properties

The mechanical properties of CPs are an essential aspect of their suitability for various applications, especially in the progress of flexible and wearable electronic devices. These properties include flexibility, stretchability, tensile strength (TS), elasticity, adhesion malleability, thickness variability, and ductility. Understanding and tailoring the mechanical features of CPs is essential to harness their full potential in applications that demand both electrical conductivity and mechanical flexibility. These properties have opened up opportunities in fields such as flexible electronics, wearable technology, sensors, and even medical devices, where traditional rigid materials may not be suitable. Additionally, in the context of food packaging, the mechanical characteristics of CPs, as well as their homogeneity and adherence, are determining parameters for their application as contact materials in such industries.

2.1.3 | Environmental stability

Generally, CPs are chemically stable in specific environments, such as acidic solutions, and can withstand certain conditions due to their strong intermolecular interactions. The environmental stability of CPs is a crucial consideration when assessing their suitability for various applications, especially those in outdoor or challenging environmental conditions, including food packaging. To enhance the environmental stability of CPs, several strategies have been employed, such as the development of protective coatings, encapsulation techniques, and the selection of polymer formulations that are inherently more resistant to environmental factors. The choice of CP and

the design of the specific application is critical for ensuring that the material can withstand the intended environmental conditions and remain functional over an extended period. Conversely, in cases where solubility is a prerequisite for certain applications, various factors, such as the doping rate and polymerization degree, can be fine-tuned to improve solubility. Additionally, solubility can be enhanced through approaches such as grafting side chains onto the primary polymer chain, doping with surface-active agents, or engaging in copolymerization.

2.1.4 | Wettability

Wettability denotes the capacity of a material's surface to interact with and be wetted by a liquid. It is one of the fundamental attributes of a solid surface and has been applied in diverse fields, such as self-cleaning surfaces (Tan et al., 2020), microfluidics (Mozammal Hossain et al., 2019), controlled drug delivery (Puiggalí-Jou et al., 2019), and bioseparation (Wang et al., 2020). In general, CPs exhibit hydrophilic characteristics. It is possible to create a superhydrophobic film of CPs by doping them with hydrophobic acids. By precisely monitoring the chemical composition of CPs, one can achieve a reversibly switchable surface that alternates between superhydrophobic and superhydrophilic properties (Das & Prusty, 2012).

2.1.5 | Electrical conductivity and mechanism

The electrical conductivity of CPs is a defining feature that differentiates them from conventional insulating polymers. CPs exhibit the ability to conduct electricity, albeit to varying degrees depending on their specific structure, doping level, and other factors. Unlike metals and semiconductors, conduction in these polymers occurs by jumps of charged defects, polarons and bipolarons and corresponds to the creation of energy states in the gap between the valence band and the conduction band during the doping process, as in the case of PT shown in Figure 2A. According to band theory, the overlapping π orbitals create bonding (π) and antibonding (π^*) molecular orbitals, forming valence and conduction bands, respectively, with a band gap of around 2.2 eV in undoped PT. The highest occupied molecular orbitals (HOMO), primarily π orbitals, make up the valence band, while the lowest unoccupied molecular orbitals (LUMO), primarily π^* orbitals, form the conduction band. The critical element that establishes the conduction characteristics of the polymer that is, whether it acts as an insulator, semiconductor, or conductor is the distance between these two bands or band gap (Le et al., 2017).

The electrical conductivity of such polymers is generally poor in its neutral, undoped state. However, the conductivity increases significantly upon doping. The introduction of dopants, either electron donors (n-type doping) or electron acceptors (p-type doping), changes the charge distribution in the polymer and facilitates conductivity. According to the findings of Rannou et al. (1999), the oxidation of conductive polymers, involving the removal of an electron, leads to a localized alteration in the polymer chain geometry, and the creation of localized charged defects known as polarons (spin ½ radical ions). According to calculations reported by Bredas and Street (1985), the creation of polarons is energetically favorable across all the conjugated polymers they investigated. Furthermore, when a second electron is extracted, it may lead to the generation of either a second polaron or a bipolaron, which is doubly charged and possesses zero spin. Notably, the structural relaxation around two charges is more pronounced than that around a single charge. This is why the bipolaron states are found to be closer to the center of the energy gap than the polaronic states. Remarkably, as indicated by Brédas' calculations, despite coulombic repulsion, bipolarons are more thermodynamically stable than two polarons.

Upon introducing a substantial quantity of charges to the structure, the overlapping of bipolaronic levels results in the emergence of bipolaronic bands within the energy gap. Consequently, bipolarons can become mobile when exposed to an electric field, elucidating the conductive nature of conjugated polymers. The mechanism of electronic conduction in CPs can be succinctly described as involving the creation of polarons and bipolarons during the doping process. These charged entities can traverse the polymer chain by reorganizing the single and double bonds within the conjugated system. By changing the chemical structure, choosing the right doping agents, or varying the doping level, CPs' electrical conductivity can frequently be modified, making them adaptable materials for numerous applications.

2.2 | Synthesis and characterization

In recent decades, researchers have directed their efforts not only toward comprehending the conduction mechanisms but also toward optimizing synthesis conditions to enhance the conductivity, ease of processing, and bolster the aging resistance of these conjugated polymers. Within this framework, various methods for crafting CPs have been documented (Xue et al., 2020). Among these, chemical oxidative polymerization, electropolymerization, lithography, template-assisted polymerization, and plasma techniques have been explored. However, the first two methods, chemical

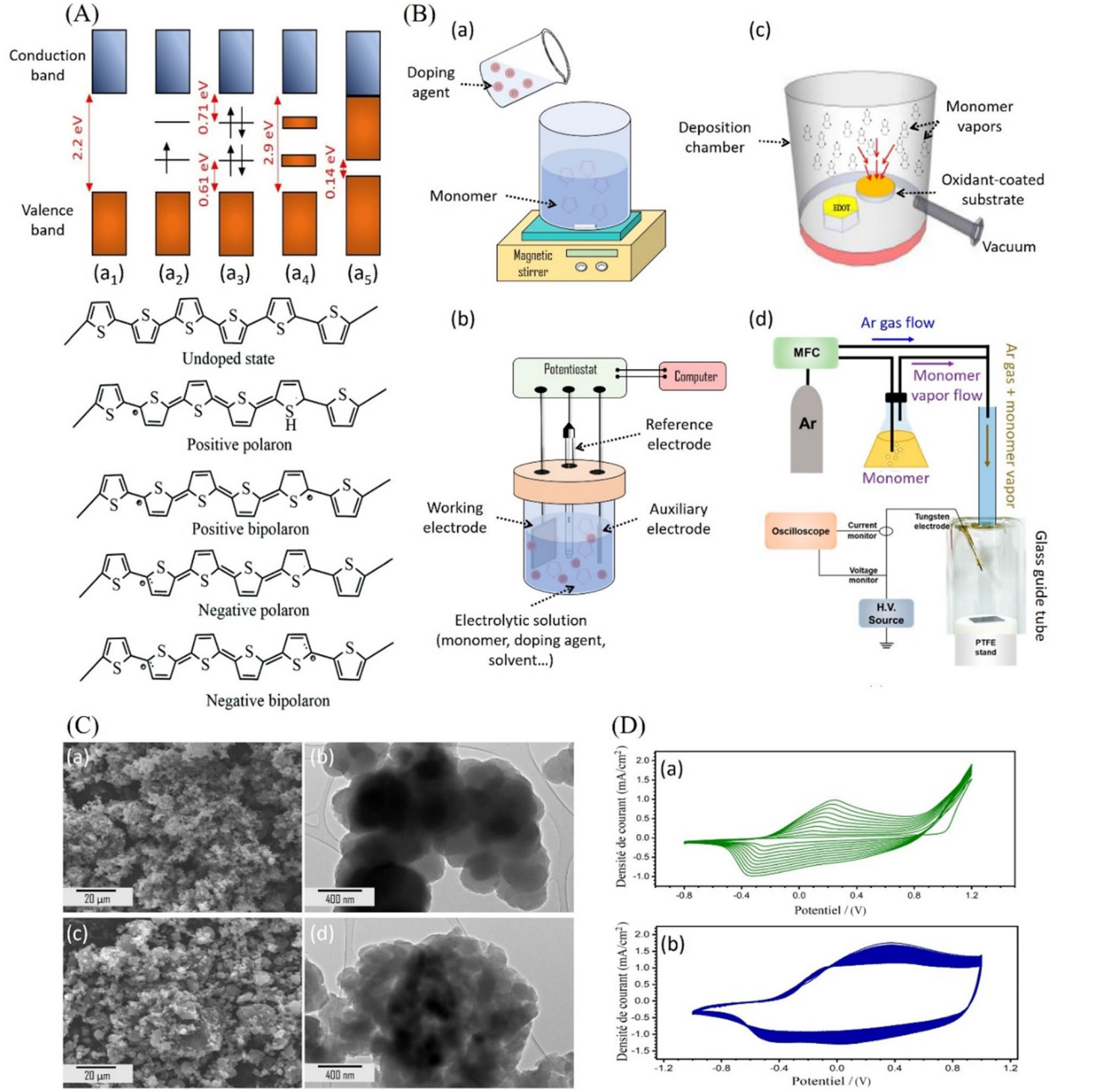


FIGURE 2 (A) Electronic bands and chemical structures of polythiophene showing: (a_1) an insulating film, (a_2) doped at <1%, polaron states in the gap, (a_3) doped at a few %, bipolaron states, (a_4) doped at 30%, overlap of bipolaron states and two bands, (a_5) hypothetical doped at 100%, and quasimetallic behavior. Adopted from Le et al. (2017) Copyright MDPI ©2017. (B) Schematic illustrations depicting the processes for the elaboration of CPs: (a) chemical oxidative polymerization, (b) electrochemical synthesis, and (c) dry vapor phase polymerization (adopted from Maziz et al. (2021) Copyright Elsevier ©2021), and (d) Atmospheric pressure plasma polymerization setup (adopted from Kim et al. (2021) Copyright MDPI ©2021). (C) SEM and TEM micrographs of chemically synthesized polypyrrole (a, b) and polyaniline (c, d). (D) Cyclic voltammograms of electrosynthesized PPy and PEDOT.

oxidative polymerization and electropolymerization (Figure 2B(a, b)), have emerged as the most widely utilized due to their accessibility, straightforward implementation, and cost effectiveness. Indeed, during the production of CP coatings, chemical deposition occurs on insulating substrates by oxidizing the monomer in the presence of an initiator, or alternatively, electrochemical deposition occurs on metallic electrode surfaces within an electrolyte medium containing the monomer.

The chemical synthesis process relies on the utilization of an oxidizing agent to initiate the polymerization reaction (Figure 2B(a)). Typically, this agent can take the

form of a potent acid (such as H_2SO_4, HNO_3, or $HClO_4$), a Lewis acid (such as BF_3, $AlCl_3$, or $FeCl_3$), or a Ziegler catalyst (Nalwa, 2001). This type of oxidation–reduction reaction yields polymers directly in the p-doped state with relatively low molecular weights. The chain length of the resultant polymer is significantly influenced by the oxidizing agent (Niemi et al., 1992). The synthesis involves the coupling of cation radicals, as illustrated in the work by Kovacic and McFarland (1979) in their study of the chemical polymerization of thiophene using the Lewis acid $AlCl_3$ or the strong acid CF_3CO_2H. Kassmehl and Chatzitheodorou (1981) proposed an alternative synthetic method based on radical oxidation through the introduction of AsF_5 vapors. Additionally, the Grignard-type polycondensation process, which utilizes dibrominated derivatives and nickel-based catalysts, is another well-established approach for the production of CPs (Yamamoto et al., 1980). However, chemically synthesized polymers often exhibit low conductivities due to the presence of oxidizing agents or catalysts in the reaction medium, which results in impurities and low molecular weights (Fukuda et al., 1993).

Conversely, the electrochemical synthesis (Figure 2B(b)) presents several advantages compared with the aforementioned approach. It is simple, cost effective, and can be done in a single-section glass cell. Additionally, this technique offers precise control over the deposition rate and the film's structure, as well as the ability to regulate the oxidation state of the polymer and the doping level of the resulting film (Bouabdallaoui et al., 2020). The most common electrochemical method for preparing CPs is the anodic oxidation of suitable electroactive monomers. In contrast, cathodic reduction is employed less frequently. During anodic oxidation, the polymer film is synthesized, and counter ions are doped simultaneously as a result of the oxidation process. The latter starts with selecting a monomer capable of forming a conductive polymer, such as pyrrole, aniline, or thiophene. This monomer is dissolved in an appropriate solvent, like acetonitrile or water, along with an electrolyte such as sodium sulfate or lithium perchlorate to facilitate the reaction. A three-electrode electrochemical cell is set up, consisting of a working electrode, where polymerization occurs, a counter electrode, and a reference electrode. By applying a controlled potential or current to the working electrode, the monomer undergoes oxidation or reduction, resulting in polymer formation. This process reduces contaminants and produces polymers of higher quality without the need for an external oxidizing agent. Additionally, the deposition of a polymer onto an electrode surface often simplifies subsequent analytical processes.

Key factors influencing the electrochemical synthesis of CPs include the applied potential, which dictates the polymerization rate and type of polymer formed, temperature, which affects both the rate and properties of the polymer, monomer and electrolyte concentrations, and polymerization time, which determines the thickness and length of the polymer chains. Postpolymerization, the resulting film is washed to remove residual monomer or electrolyte and then dried to stabilize the structure. Often, the polymer is doped with additional substances to enhance its conductivity and stability by inducing changes in the polymer's chain conformation and interactions between chains. Common dopants include protonic acids, such as hydrochloric acid (HCl), for p-type doping, or electron donors for n-type doping.

Other techniques for the elaboration of CPs include dry vapor phase polymerization (DVPP). Typically, in such process, the synthesis is achieved directly on the substrate through a two-step process. Initially, an oxidant such as iron tosylate is applied to the substrate using solvent-based coating techniques (Maziz et al., 2021). Subsequently, the chosen monomer, such as pyrrole, aniline, or thiophene, is vaporized and introduced into a deposition chamber where it is exposed to this substrate under controlled temperature and pressure conditions (Figure 2B(c)). Polymerization occurs as the monomer vapor reacts on the substrate, forming a thin, uniform polymer film. This method allows for precise control over film thickness and quality, producing high-quality, adherent coatings. The process benefits from the ability to produce clean and uniform films, reducing contamination risks and enabling deposition on various substrates, including those with complex shapes. It has been demonstrated that the polymerization of the ethylenedioxythiophene (EDOT) monomer using the DVPP method resulted in a poly(3,4-ethylenedioxythiophene) (PEDOT) film exhibiting conductivity of 3400 S/cm for a thickness of 60 nm, comparable to commercially available indium tin oxide (Fabretto et al., 2012).

On the other hand, atmospheric pressure plasma polymerization is a method used to synthesize thin polymer films onto substrates at atmospheric pressure, eliminating the need for vacuum chambers (Figure 2B(d)). This process involves generating plasma at atmospheric pressure by applying high voltage to a gas mixture, typically consisting of inert gases and reactive monomer vapors (Kim et al., 2021). The plasma generates ions, radicals, and other reactive species that initiate the polymerization of the monomer, leading to the deposition of a thin, uniform polymer film on a substrate. This method offers the advantage of operating at atmospheric pressure, which makes it more cost effective and scalable compared with vacuum-based techniques. It allows for precise control over film thickness and quality, resulting in high-quality, adherent coatings. The structures and physicochemical properties

of these coatings can be precisely controlled by modifying various experimental parameters of the plasma generation process. These parameters include the configuration of the plasma device, the type of discharge gas used, the gas flow rate, the plasma driving conditions (e.g., voltage and current waveforms), and any applied additional voltage bias.

Template-assisted polymerization is also a sophisticated technique used to synthesize CPs with precisely controlled structures and properties. This method involves utilizing a template either physical or chemical to guide the polymerization process. Physical templates, such as porous substrates or nanostructured materials, serve as scaffolds that influence the deposition and growth of the polymer, resulting in materials with specific morphologies. Chemical templates, on the other hand, are sacrificial or self-assembled structures that are removed after polymerization, leaving behind a polymer with the desired structural features (Su et al., 2021). The outcome of the polymerization process is highly dependent on the experimental parameters, such as the geometry and material of the template, monomer concentration, and polymerization conditions like temperature, pressure, and time. These factors collectively determine the final structure and properties of the CP.

Pyrolysis is another interesting method for preparing CPs. It is a high-temperature thermal decomposition process conducted in an inert atmosphere, such as nitrogen or argon, and can be employed to synthesize CPs or convert them into carbon-based materials with enhanced properties (Kumar et al., 2015). In the direct pyrolysis of precursor CPs like PAni or PPy, the polymer decomposes to form a carbon-rich material. This process often results in a high surface area and improved conductivity of the final product. For example, pyrolyzing PAni can yield carbon materials with excellent electrical conductivity and structural stability. Additionally, pyrolysis can be applied to polymer blends, where CPs are combined with other organic materials before pyrolysis, leading to the formation of composite carbon materials with tailored electrical and mechanical properties. The process can also produce carbon nanostructures such as nanotubes or nanorods, depending on the polymer type and conditions, further enhancing the material's conductivity. Furthermore, pyrolyzed CPs are valuable in the preparation of carbon-based electrocatalysts, serving as supports or catalysts in applications like fuel cells and batteries. Key parameters in pyrolysis include temperature, which typically ranges from 300 to 1000°C, the inert atmosphere to prevent oxidation, and the duration of the process, all of which influence the degree of carbonization and the properties of the final material.

The characterization of CPs, on the other side, is essential for understanding their structural, chemical, thermal, and electrical properties, which influence their performance in various applications. The morphology of CPs plays a critical role in determining their electrical, mechanical, and electrochemical properties, especially in applications such as energy storage, sensors, and electronics. Several techniques are used to analyze the morphology of these polymers, providing detailed insights into their surface structure, porosity, and overall architecture. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are common techniques used to visualize the morphology of CPs. They provide high-resolution images of the surface, revealing details such as roughness, particle size, and porosity. For instance, PPy and PAni synthesized electrochemically can exhibit smooth films, cauliflower-like structures, or nanofibers, depending on the electrolyte and voltage used (Figure 2C). While the polymerization of PEDOT leads to a nanofibrillar structure, which is crucial for its high conductivity and performance in energy storage devices.

X-ray diffraction (XRD) analysis is a key technique for investigating the crystallinity, phase structure, and molecular arrangement of CPs, which are typically semicrystalline with both ordered and amorphous regions (El Guerraf et al., 2023). Higher crystallinity generally improves conductivity by facilitating charge transport along the aligned polymer chains, a phenomenon observed in materials like PAni and PEDOT. XRD also provides insights into polymer chain packing and orientation, allowing the determination of interchain spacing, which influences electron hopping between chains. Smaller interchain distances lead to better charge transfer, improving the electrical properties, as seen in polyacetylene. Additionally, XRD is invaluable for studying the effects of doping, which alters the polymer's crystalline structure by introducing dopant molecules that modify interplanar spacing. For instance, doping PPy with iodine can shift or broaden XRD peaks, reflecting changes in the polymer's packing and crystalline order. XRD also helps monitor phase transitions, such as those induced by thermal annealing or doping, where increased crystallinity is often observed through the appearance of sharper peaks. Polymorphism, where a CP can exhibit multiple crystalline forms depending on synthesis or processing conditions, is another area where XRD proves useful by identifying distinct diffraction patterns for each form, which often correlate with variations in electrical properties. Moreover, for nanostructured CPs, such as nanofibers or thin films, XRD combined with grazing incidence XRD can be employed to examine surface structures and thin films, often revealing enhanced crystallinity at the nanoscale due to better polymer chain alignment. For example, in doped PAni, a

broad peak at $2\theta = 20–25°$ corresponds to the periodicity along the polymer chain, while sharper peaks after doping or annealing indicate increased structural order (Sutar et al., 2007). Similarly, in PEDOT, lamellar structures and π–π stacking interactions appear in the XRD pattern, with peaks at $2\theta = 6–10°$, directly linked to improved electrical conductivity (Sharma et al., 2018).

CPs have delocalized π-electrons along their backbone, allowing electronic transitions between molecular orbitals, typically from the HOMO to the LUMO. UV–Vis analysis reveals the energy required for these transitions, which is often related to the polymer's bandgap. For example, PAni in its different oxidation states (leucoemeraldine, emeraldine, and pernigraniline) shows distinct absorption bands in the UV–Vis spectrum. For the emeraldine salt form, an absorption peak is typically observed around 350–400 nm, corresponding to π–π^* transitions, while a peak near 600 nm indicates polaron transitions related to its conductivity (Dhivya et al., 2019). UV–Vis spectra can be used also to estimate the optical bandgap of CPs. The onset of absorption gives a direct measure of the energy gap between the HOMO and LUMO, which is related to the polymer's electrical conductivity and its potential for electronic applications.

Furthermore, CPs exhibit redox activity due to the reversible oxidation and reduction of their conjugated polymer chains. Cyclic voltammetry is a vital tool for characterizing this redox activity, as well as the charge storage capacity, and the electrochemical stability of CPs (El Guerraf, Ben Jadi, Aouzal et al., 2022). By analyzing the shape, peak positions, and current response of the voltammogram over repeated cycles, researchers can assess the polymer's suitability for applications such as energy storage, sensors, and electrochemical devices. For a polymer like PPy, a typical cyclic voltammogram may show well-defined oxidation and reduction peaks corresponding to the polymer's redox transitions. In organic solvent such as acetonitrile, during the first scan, the oxidation peak may occur around 0.25 V versus a standard reference electrode (e.g., Ag/AgCl), while the corresponding reduction peak occurs around −0.3 V on the reverse scan (Figure 2D(a)). A well-defined, stable CV profile with minimal peak shift and current decay over time is indicative of a robust, electrochemically stable material capable of long-term performance (Figure 2D(b)).

2.3 | Doped and self-doped CPs

A novel category of materials known as doped CPs combines the manufacturing flexibility and simplicity of use of polymers with the electrical conductivity of metals. Dopants or charge carriers must be added to the polymer matrix to create these materials. When used in this sense, "doping" refers to adding foreign atoms or molecules to the structure of a polymer to boost the polymer's electrical conductivity. Molecular doping, electrochemical doping, and ion-exchange doping are the three main techniques used to dope semiconducting polymers. The most popular method is called "molecular doping," which uses redox-active tiny molecules as dopants for organic semiconductors (Figure 3A(a)). In principle, small molecules or atoms are introduced into the polymer matrix to either donate or accept electrons, creating charge carriers. For p-type doping, electron acceptors (such as iodine or halogens) remove electrons from the polymer's conjugated backbone, generating positive charge carriers (holes). In n-type doping, electron donors introduce electrons into the polymer, forming negative charge carriers. Molecular doping can modify the polymer's electrical, optical, and mechanical properties by directly altering its electronic structure. This method has several inherent limitations arising from the dual role of the dopant molecule. p-Type doping works primarily through a reversible electron transfer reaction to start as an oxidizing agent for the dopant. The final product is then added to the film as an ionized dopant to balance out the positive charge in the polymer (Salzmann et al., 2016). Demanding a single chemical species to fulfil both of these functions is challenging.

On the other hand, electrochemical doping is a process that relies on the exchange of charge carriers using an electrode (Figure 3A(b)). Such method occurs by applying an external electrical potential to the polymer, typically in an electrochemical cell, where the polymer is immersed in an electrolyte. The applied potential drives either oxidation (p-doping) or reduction (n-doping) reactions in the polymer. While the requirement to coat the film onto a working electrode does impose limitations, electrochemical doping offers a significant advantage over molecular doping: it allows for the selection of ions from an extensive range of readily accessible salts. Recently, ion-exchange doping has been introduced, which operates on the principle of ionic substitution, where ions from a dopant source are exchanged for ions of a similar charge within the host material (Figure 3A(c)) (Yamashita et al., 2019). This process typically occurs when the CP is exposed to a solution containing ions that can substitute the ions initially present in the polymer. Only the electrolyte counterion stays in the film when the exchange process is very efficient, so producing a composition that is the same as that produced through electrochemical doping (Jacobs et al., 2022). Consequently, ion exchange serves as a connecting link between molecular and electrochemical doping (Figure 3B) and combines the advantages of both techniques. This method is particularly important for

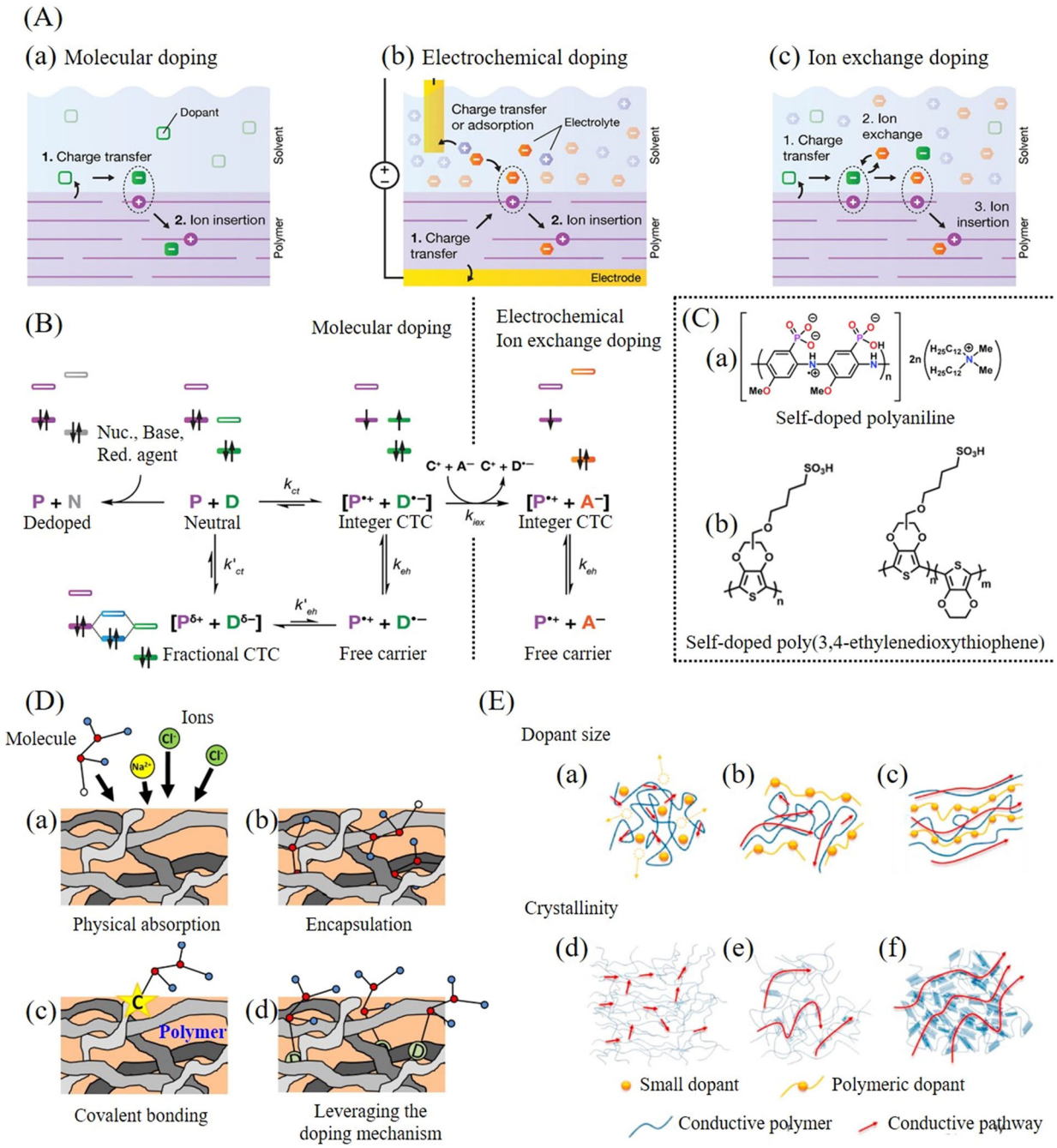


FIGURE 3 (A) Doping mechanisms: (a) molecular doping from a separate solvent, (b) electrochemical doping, and (c) ion exchange doping. (B) Reaction pathway for p-type molecular doping through ion exchange. Illustrative electron configurations are displayed above or below, with reorganization effects excluded for clarity. Adopted from Jacobs et al. (2022) Copyright Wiley ©2021. (C) Example of self-doped polyaniline (a) (adopted from Amaya et al. (2016) Copyright RSC ©2016), and poly(3,4-ethylenedioxythiophene), (b) (adopted from Beaumont et al. (2021) Copyright ACS ©2021). (D) The four approaches for functionalizing CPs include (a) physical absorption, (b) encapsulation, (c) covalent bonding, and (d) leveraging the doping mechanism. Adopted from Balint et al. (2014) Copyright Elsevier ©2014. (E) Schematic representations of the molecular structures of conducting polymers demonstrating (a–c) interactions with counterions or dopants and (d–e) delocalized charge pathways, as well as variations in crystal domain sizes. (a) Interaction with small molecules, (b) oligomeric dopants, and (c) polymeric dopants, (d) amorphous, (e) low-crystalline, and (f) high-crystalline conjugated areas within the conductive matrix. Adopted from Lee et al. (2020) Copyright Elsevier ©2020.

applications where the ionic conductivity of the material is critical, such as in sensors or batteries.

Overall, charge transfer doping within CPs involves the infusion of charge into the extended pi-electron arrangement. This process necessitates the diffusion of dopants or counterions into the polymer to maintain charge neutrality. Reversible large-anion exchange between the electrolyte and the active polymer mass limits a number of important characteristics, including charging rates and electrochromic switching. Consequently, considerable research efforts have been directed toward self-doped CPs. To put it simply, these polymers contain a significant amount of negatively charged, ionizable functional groups that are covalently bound to the monomers, acting as stationary and stable dopant anions.

The concept of self-doping in CPs operates by expelling smaller, mobile protons or monovalent cations from the polymer into the electrolyte while immobilizing larger anions through the process of oxidation (Freund & Deore, 2007). Generally, self-doped CPs have been developed to enhance the solubility of such polymers. It was claimed that didodecyldimethylammonium bromide and poly(2-methoxyaniline-5-phosphonic acid) salt production was used to generate soluble self-doped conducting PAni (Figure 3C(a)) (Amaya et al., 2016). Furthermore, the production of water-soluble self-doped PEDOT has been accomplished through direct (hetero)arylation polymerization (Figure 3C(b)) (Beaumont et al., 2021). Significant improvements were made to the polymer's solubility and solution stability by adding a counterion covalently bound to the polymer backbone.

Four main chemical techniques can be employed to boost the characteristics of CPs (roughness, porosity, hydrophobicity, conductivity, and degradability) and make it easier for biological molecules to bind, making such materials promising for industrial applications (Balint et al., 2014) (Figure 3D): (a) Through absorption (Figure 3D(a)), a solution containing the functionalizing agent is brought into contact with the synthesized polymer. The biomolecule is physically absorbed through electrostatic interactions between the polymer matrix and the molecule's charge (Ahuja et al., 2007). Although simple to perform, this route gives a product whose conductivity is very pH sensitive, with biomolecules that can potentially leach out, thereby weakening the conductivity of the polymer. (b) Entrapping the molecule inside the polymer involves combining the functionalizing molecule with the monomer, dopant, or solvent of the polymer before synthesis (Balint et al., 2014). During the electropolymerization process, the molecules of the functionalizing agent near the electrode become integrated into the developing polymer (Figure 3D(b)). This technique is predominantly employed for the immobilization of macromolecules, such as enzymes or DNA, as their large size prevents their diffusion out of the polymer matrix once encapsulated. (c) One method involves covalently bonding the molecule to the polymer chain (Figure 3D(c)). This approach ensures strong binding of biological molecules, increasing the long-term stability of the polymer (Lee et al., 2009). (d) By leveraging the inherent doping process that confers conductivity to polymers (Figure 3D(d)), a varied array of biomolecules can be bonded as long as they carry a charge (Lee et al., 2009). Nevertheless, this approach has drawbacks: doping to host bioactive compounds limits the number of molecules that can be bound while also adversely affecting the conductivity of the polymer more than covalent bonding does (Balint et al., 2014).

Notably, the electrical conductivity of CPs can be significantly influenced by the use of various types of dopants (Lee et al., 2020) (see Figure 3E). Electrically active doped CPs can exhibit a wide range of complex microstructures, from completely amorphous to somewhat crystalline, which are explained by the conformational freedom of weakly linked polymer chains. The morphological characteristics, crystallinity, orientation, and size and connectedness of macroscopic domains are all important elements that affect how much charge-carrier movement there is. The size, mobility, and chemical compatibility of the dopant play crucial roles in determining conductivity. Small, mobile dopants diffuse more easily through the polymer matrix, leading to better charge transport, whereas larger dopants may remain more localized, affecting the distribution of charge carriers. Additionally, the dopant's chemical stability and interaction with the polymer matrix can affect the long-term performance and stability of the doped polymer. To sum up, the electronic and ionic hybrid conductivities of CPs are significantly influenced by the molecular weights of the conjugated backbones, the sizes of the π–π stacked crystalline domains, interactions with p-type doping counterions, proton transport pathways, hydrogen bond-facilitated electron transfer, and molecular ordering (Lee et al., 2020).

2.4 | Toward real applications of doped CPs

In light of their application, doped CPs have garnered substantial attention across diverse fields, such as electronics, sensors, and energy storage, owing to their exceptional blend of characteristics. The creation of composite films for electromagnetic interference (EMI) shielding was investigated by Zhang et al. (2019). HCl, PAni codoped with dodecylbenzenesulfonic acid (DBSA), and a few-layered Ti_3C_2Tx were used to create these films. Ionic intercalation and then sonication were used to create the Ti_3C_2Tx

material. The doping of PAni was then achieved through a vacuum-assisted filtration procedure (Figure 4A). The electrical conductivity, EMI shielding efficacy, and TS of the doped PAni improved noticeably as the mass fraction of Ti_3C_2Tx rose. This is attributed to the sheet-like structure of Ti_3C_2Tx. The latter demonstrates potential application in cutting-edge industries needing ultrathin, light-weight, and flexible EMI shielding materials.

A highly biocompatible polymer composite based on poly(ethylene glycol) (PEG) and gold nanoparticle-doped PEDOT was synthesized through electrochemical polymerization (Cui et al., 2016). Owing to their excellent biocompatibility, the doped CPs demonstrated ultrasensitive and selective sensory characteristics for alpha fetoprotein (AFP), a crucial biomarker for liver cancer. AuNPs were trapped inside the polymeric matrix to enhance the anchoring of antibodies due to their distinctive affinity for thiol groups (Figure 4B). This AuNP-modified PEDOT/PEG substrate proved to be an excellent platform for immobilizing various biomolecules, including antibodies specific to AFP, a critical biomarker for liver cancer. The developed AFP biosensor exhibited excellent selectivity, high sensitivity, and an ultra-low detection limit. Furthermore, the presence of highly hydrophilic PEG polymers in the PEDOT skeleton contributed to its strong antifouling properties, enabling the reliable detection of AFP in human serum samples.

A "doping-then-gelling" approach was utilized to produce a supramolecular hydrogel by combining poly(acrylic acid) (PAA) and PAni into an interconnected network (D. Liu et al., 2022). At first, PAni was doped with an acrylic acid (AA) monomer, which improved the polymer's conductivity and allowed it to dissolve in water. Afterward, AA polymerization produced PAA/PAni hydrogels with an elevated density of electrostatic contacts as dynamic bonds (Figure 4C). The carboxyl group of AA acts as a counterion to the dopant, facilitating the protonation of imine groups in PAni, while the carbonyl group improves the its solubility, leading to a uniform dispersion of polymer chains. The resultant PAA/PAni hydrogel showed outstanding characteristics, such as high breaking strength (120 Kpa), amazing stretchability (up to 2830%), and quick self-healing speed. During cyclic stretching, it showed strong conductivity-based sensing performance, a fast response time (222 ms), and a high sensitivity to strain (gauge factor = 12.63). Furthermore, a range of strain sensing applications was demonstrated, showing its potential for precise monitoring of human movements and suggesting promising applications in wearable devices. Comparably, Wang et al. (2016) used an electrochemical immunosensor to identify the carcinoembryonic antigen (CEA), a cancer biomarker made of PEDOT doped with hyaluronic acid (HA). Additionally, the authors in this instance showed the doped CPs' porous architecture, exceptional sensitivity to CEA, and low detection limit (0.3 pg/mL).

The thermoelectric characteristics of poly[2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-b]thiophene ($C14$-PBTTT) were investigated using a newly established ion exchange doping technique, with a focus on the size of the doped counterion. This method has been demonstrated efficient for tuning the charge concentration of CPs over a wide range, extending to the degenerate limit. Chen et al. (2023) used three chemically homologous, closed-shell anions of diverse sizes, namely, tris(trifluoromethylsulfonyl)methide anion ($TFSM^-$), bis(trifluoromethylsulfonyl)imide anion ($TFSI^-$), and trifluoromethanesulfonate (TFO^-). Three steps are involved in the doping process (Figure 4D): (1) At the boundary between the polymer film and the dopant solution, a positive polaron is created by charge transfer from the PBTTT polymer to an oxidizing agent ($FeCl_3$). (2) Ion exchange between the anion of an ionic liquid in the dopant solution ($TFSM^-$, $TFSI^-$, TFO^-) and the dopant anion ($FeCl_4^-$). This process is primarily propelled by a notable concentration gradient between the dopant ions and the anions of the ionic liquid, leading to an increase in entropy. (3) Diffuse into the bulk of the polymer film are the positive polaron and the ionic liquid anion that was induced on the polymer in step (1). As already stated, in contrast to conventional molecular doping, ion exchange doping provides the advantage of decoupling the processes of initial electron transfer and the incorporation of charge-stabilizing counterions. This approach allows for the selection of counterions from a broad range of stable, closed-shell anions, rather than being limited to a narrow range of unstable radicals.

To achieve higher conductivity at lower doping levels, the authors demonstrated that it is essential to distribute dopant ions more evenly within the polymer film. This strategy has the potential to substantially enhance thermoelectric power aspects and overall efficiency. These outcomes deliver important new understandings of the relationship between the structure and characteristics of conjugated polymers doped with ion exchange, and they encourage a methodical approach to doping that can efficiently control charge and thermoelectric transport in polymer structures for thermoelectric applications. Doped CPs also have diverse applications in the energy sector, spanning from energy storage and conversion to energy harvesting and efficiency enhancement. While CPs theoretically possess a high redox capacity, their practical capacity tends to be quite limited and gradually decreases over charge–discharge cycles (Zhou et al., 2011). This decline is caused by the diffusive dispersion of anions into the electrolyte and the low p-doping levels of the counter anions in the polymeric matrix.

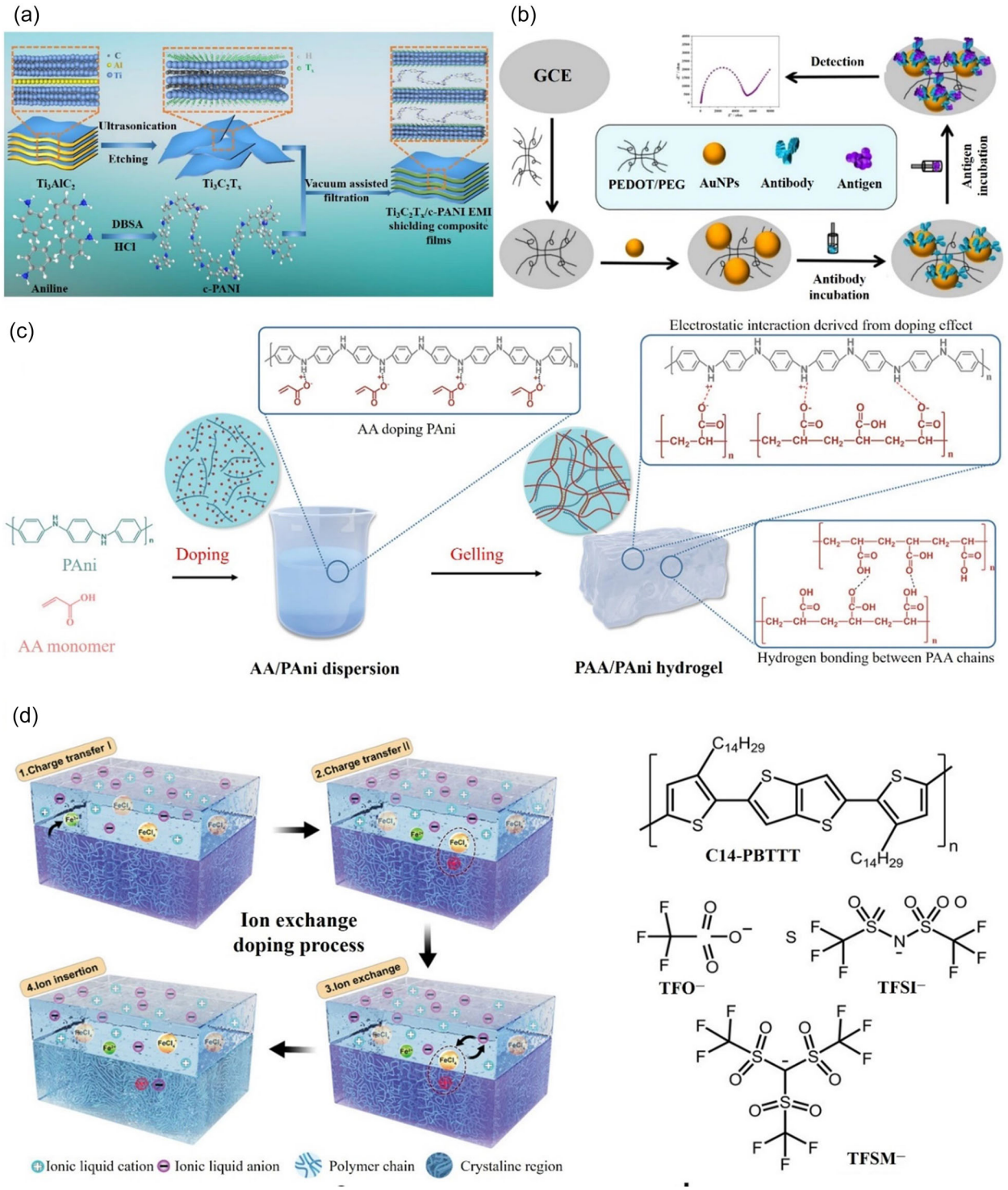


FIGURE 4 (A) Diagram illustrating the fabrication process of Ti_3C_2Tx-doped PAni. Adopted from Zhang et al. (2019) Copyright Elsevier ©2019. (B) The step-by-step fabrication process of poly(ethylene glycol)-doped conducting PEDOT. Adopted from Cui et al. (2016) Copyright Elsevier ©2016. (C) The synthesis procedure of hydrogels based on acrylic acid-doped polyaniline. Adopted from Liu et al. (2022). Copyright Wiley ©2022. (D) The ion exchange doping mechanism and the structures of the C14-PBTTT conducting polymers doped with different anions. Adopted from Chen et al. (2023) Copyright Wiley ©2023.

One possible way to tackle this problem is to introduce redox-active anions into CPs matrices. Because the CP is both ionically and electrically conductive, the embedding of redox-active species inside its bulk increases its energy storage capacity by facilitating effective transport to the integrated redox species (Chhin et al., 2019). In this context, graphene quantum dots (GQDs), recognized for their exceptional electrical conductivity and extensive surface area, were integrated into PAni CPs to create high-performance supercapacitor electrode materials (Mondal et al., 2015). GQDs with an approximate size of 6.0 nm were prepared from graphene oxide (GO) flakes, then used for the elaboration of PAni composite (Figure 5A). The resulting GQD–PAni material exhibited an impressive specific capacitance, with the highest recorded value attaining approximately 1044 F/g at a current density of 1 A/g. Moreover, these composites demonstrated notable stability, retaining 80.1% of their capacitance after 3000 charge–discharge cycles.

Considering the improvement achieved in various composite materials through the integration of GO, leveraging its various advantages, Tian et al. (2014) studied the electrochemical deposition of GO-doped PEDOT. As depicted in Figure 5B, the monomer EDOT underwent electrochemical oxidation to initiate the formation of CP chains. These positively charged PEDOT chains are then combined with the negatively charged groups on GO through ionic bonds. In this manner, the particles were dispersed in a disordered fashion, serving as the structural material that shaped a 3D interconnected network. Concurrently, PEDOT acted as a stable medium for charge transfer, permeating the gaps within the graphene framework. As a result, enhanced electrochemical performance was demonstrated due to an increased effective surface area, along with improvements in impedance, charge storage capacity, and charge injection limits. Additionally, extensive testing, including repeated usage assessments and examinations of cell proliferation and attachment, has confirmed the stability and biocompatibility of this biomaterial.

Furthermore, based on the ionic mobility of counterions within CPs, these polymers can be categorized into permanent and impermanent dopants (Figure 5C). Permanent dopants are chemically incorporated into the polymer structure, creating long-lasting effects by covalently bonding or strongly associating with the polymer backbone. These dopants provide sustained conductivity and stability, making them ideal for applications requiring consistent performance, such as organic electronics or sensors. In this context, a remarkable capacitive performance was achieved with thick PPy films electro synthesized onto an exfoliated graphite substrate with the use of an inorganic heptamolybdate anion ($Mo_7O_{24}^{6-}$) as the permanent dopant (M. Zhang et al., 2021). In contrast, impermanent dopants are weakly associated with the polymer matrix through ionic or physical absorption, and their effects are temporary and reversible. These dopants, such as halide ions or organic compounds, can be added or removed through electrochemical processes, making them useful in applications where conductivity needs to be dynamically controlled, such as in batteries or electrochromic devices. The charging and discharging of the polymer involve the enclosure and removal of these ions from the electrolyte.

In the process of pyrrole polymerization, $Mo_7O_{24}^{6-}$ anions were introduced as permanent poly-counterions within the polymer structure to offset the positive charges present on the PPy chains (Figure 5C). These anions have a substantial cell volume of approximately 715 $Å^3$, enabling them to become immobilized within the polymer matrix, primarily owing to steric hindrance. The PPy electrode doped with the heptamolybdate anion demonstrated exceptional capacitive effectiveness with an extraordinarily increased mass loading of approximately 192 mg/cm^2 and a thickness of approximately 2 mm. At a current density of 2 mA/cm^2, this included a volumetric capacitance of 235 F/cm^3 and a gravimetric capacitance of 235 F/g. The interaction between the PPy chains and poly-counterions significantly enhances the electrical conductivity of the polymer. Additionally, poly-counterions with substantial steric hindrance can function as structural pillars, imparting CPs with open frameworks that facilitate efficient ion transport. This overarching approach of redox-active poly-counterion doping has the potential to significantly advance the practical utilization of CPs across various domains, including food packaging.

As an alternative to conventional chemical and electrochemical doping methods that depend on redox or acid–base interactions, controlled doping by solid-state diffusion has been successfully achieved thanks to the coding location of solution-processable π-conjugated polymers with a strong molecular acceptor. Without disturbing the conjugated layers, 2,3,5,6-tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F4-TCNQ) was diffused into layers containing side chains of a thiophene-based CP (PBTTT) that were solubilizing (Kang et al., 2016). F4-TCNQ was allowed to evaporate, and then edge-on stacking of PBTTT was carried out with the F4-TCNQ molecules scattering into the interdigitated cross-chain region (Figure 5D). Like diffusion-based doping methods used in inorganic semiconductors, solid-state diffusion introduces dopant molecules while maintaining and enlarging the highly semicrystalline microstructure of the undoped CP. This makes it possible to add dopants selectively to electrically inactive areas of the film, which are usually inhabited by flexible, insulating side chains. This process also preserves the polymer's highly ordered lamellar microstructure, with the dopant effectively integrated

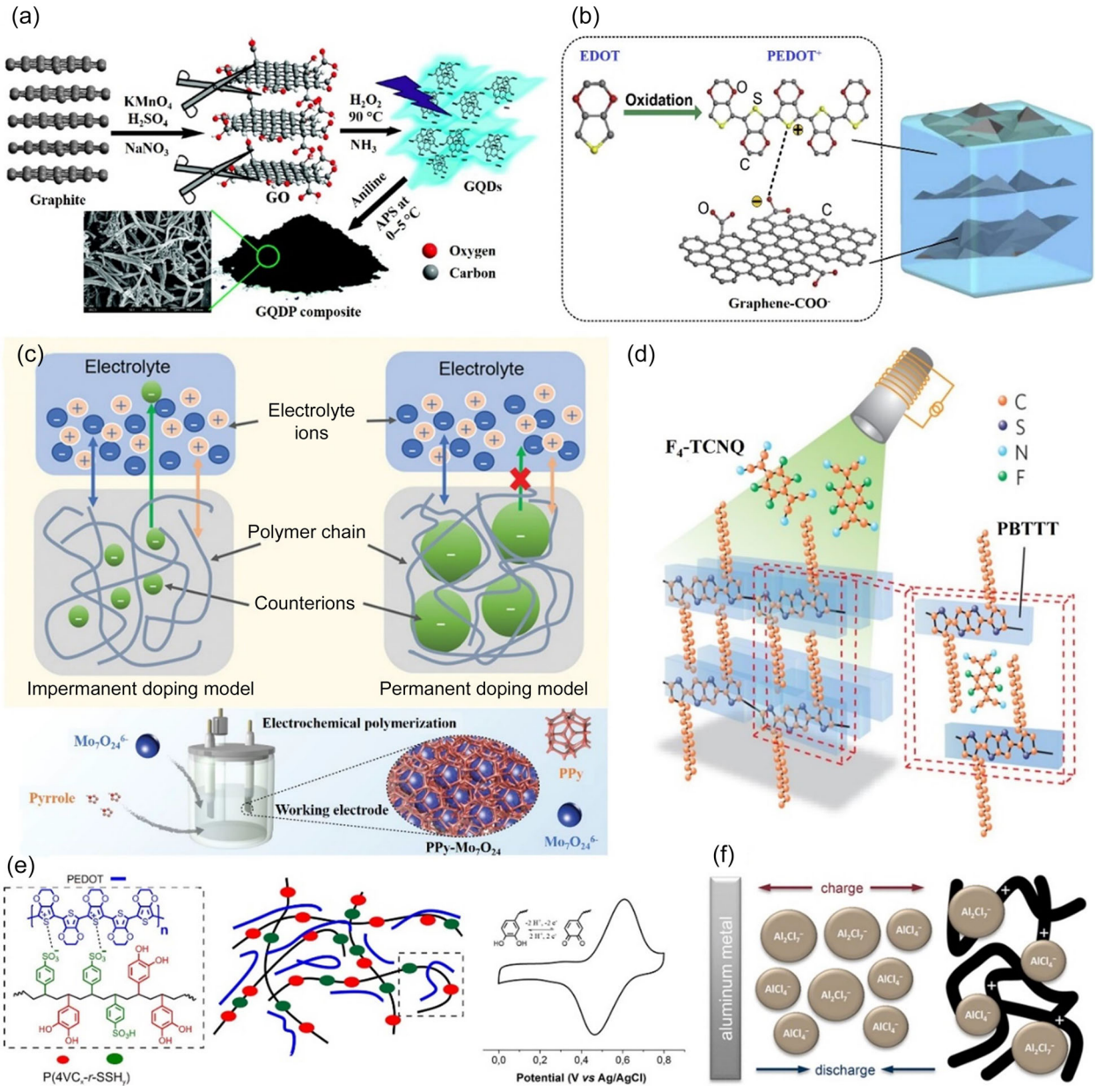


FIGURE 5 (A) Diagram illustrating the elaboration of graphene quantum dot-doped polyaniline composites. Adopted from Mondal et al. (2015) Copyright RSC ©2015. (B) Representation of the chemical structure of a PEDOT/graphene oxide. Adopted from Tian et al. (2014) Copyright Elsevier ©2014. (C) Diagram depicting the impermanent and permanent doping models and the synthesis procedure of $Mo_7O_{24}^{6-}$-doped polypyrrole. Adopted from Zhang et al. (2021) Copyright Wiley ©2020. (D) Doping procedure for the evaporation of F_4-TCNQ into PBTTT. Adopted from Kang et al. (2016) Copyright Nature ©2016. (E) Schematic representation of the use of PEDOT with poly(4-vinylcatechol-r-styrenesulfonic acid) for improving organic batteries. Adopted from Chhin et al. (2019) Copyright ACS ©2019. (F) Chloroaluminate-doped CPs used as anodes in rechargeable aluminum batteries. Adopted from Hudak (2014) Copyright ACS ©2014.

into the side chain layers. Utilizing this solid-state diffusion technique, electrical conductivity, reaching up to 248 S/cm was achieved.

A modest, yet very flexible technique of altering CPs was described in the work of Chhin et al. (2019). This method involves using a bifunctional copolymer that can behave as a redox-active dopant. During the electropolymerization of PEDOT, a copolymer containing styrenesulfonic acid and 4-vinylcatechol moieties functioned as the dopant and ion source, respectively (Figure 5E). The composite polymer exhibited an enhanced capability attributed to the catechol faradaic reaction (52 mAh/g) compared with the use of poly(4-styrenesulfonate) (PSS) as a dopant (18 mAh/g).

It is evident that both ionic and redox properties are active in the bifunctional copolymer, demonstrating its potential to function as a dopant and thereby extend

the capabilities of CPs. On the other hand, the use of chloroaluminate-doped PPy and PT as active materials within the positive electrodes of rechargeable aluminum-based batteries has been previously reported (Hudak, 2014). The cycling of the CP electrodes involved the electrochemical enclosure and removal of chloroaluminate anions (Figure 5F). For both CPs, exceptionally stable galvanostatic cycling was shown, with electrode capacities that ranged from 30 to 100 mAh/g, almost reaching theoretical levels and coulombic efficiencies that were close to 100%.

Redox-active $Fe(CN)_6^{4-}$ anion-doped PPy, PTh, and PEDOT polymer backbones have been reported as cathode materials for Li-ion batteries (Zhou et al., 2011). In addition to having a redox capacity that is three times greater than undoped PPy—140 mAh/g—the $Fe(CN)_6^{4-}$-doped PPy material also exhibits good cycling stability and efficient electrochemical activation. Furthermore, the $Fe(CN)_6^{4-}$-doped PTh and PEDOT also exhibit this capacity augmentation, suggesting a wider use of the doping technique to create additional kinds of high-capacity CPs. All of these findings highlight the intricate interplay between a CP and its dopant. The potential for fine-tuning the composition, structure, and polymerization strategy holds promise for enhancing energy storage performance and the creation of new functional materials that leverage characteristics inherent in molecular units.

Self-doped CPs have also been explored for their potential applications in the energy sector. The specific applications and performance of such polymers depend on their chemical composition, structure, and synthesis methods. To create a hybrid asymmetric electrochemical supercapacitor, two varied nanostructured CPs were combined: PPy and self-doped PAni (Ghenaatian et al., 2012). With a total electrode material capacitance of more than 97 F/g, this supercapacitor displayed an amazing maximum operating prospective window of 1.3 V. Furthermore, the system showed high values for specific energy, specific power, and maximum power at a current density of 5 mA/cm^2, reaching 22.87 Wh/kg, 570 W/kg, and 45,193 W/kg, respectively. In various contexts, organic-inorganic hybrid perovskite solar cells have been developed using water-soluble, self-doped CPs based on PSS–g-PAni (PSS–g-PAni) as an efficient hole-extraction layer (HEL) (Lim et al., 2016). PSS–g-PAni molecules are water soluble due to the covalent bonding of the polymeric dopant with PAni; consequently, they can maintain their initial solution state effectively over extended periods and across a broad pH range, facilitating the creation of HELs with fewer surface defects. Because PSS–g-PAni's surface energy is lower than the Fermi energy, its integration significantly increased the device's built-in potential and characteristics. Power conversion efficiency significantly increased as a result of this technological breakthrough, rising from 7.8% in perovskite solar cells using PEDOT:PSS to 12.4% in those using PSS–g-PAni.

3 | FOOD PACKAGING MATERIALS

3.1 | Navigating complexities in modern food packaging solutions

In today's food industry, packaging serves vital functions, including protection, convenience, and communication. It ensures the secure transportation and shielding of food products from environmental elements such as water, gases, and microorganisms. Packaging materials, ranging from glass and metals to paper and plastic polymers, offer unique advantages tailored to specific needs (Mirza Alizadeh et al., 2022). Glass containers provide durability and heat resistance, while aluminum cans offer robust protection, particularly for beverages. Paper packaging, such as aseptic cartons, is commonly used for products such as milk and fruit juices, while plastic polymers such as poly(ethylene terephthalate) (PET) bottles offer versatility across various food items (Tamizhdurai et al., 2024). Sustainable packaging practices aim to mitigate environmental concerns by minimizing waste generation and resource consumption, often guided by life cycle assessment (LCA) methodologies (Thomassen et al., 2024). Ongoing efforts are directed toward defining and enhancing sustainable practices within the packaging industry.

A thorough examination of studies on beverage packaging reveals a plethora of challenges, including environmental impact, material degradation, viral transmission, nanoparticle migration, and organic compound leaching. The study conducted by Amienyo et al. (2013) revealed significant environmental ramifications of carbonated soft drinks, with packaging emerging as the primary contributor to environmental impact, accounting for 59–77%, followed by ingredients (7–14%), manufacturing (5–10%), refrigeration (up to 33%), and transport (up to 7%) (Amienyo et al., 2013). A study by Momeni et al. (2023) revealed that while pure poly(lactic acid) (PLA) degrades slowly over months to years, composting with biomass can accelerate decomposition to only 3–4 weeks. For viral transmission, Gopal and Muthu (2023) reported that HuCoV-229E survived on various surfaces, including PVC, PTFE, glass, ceramic tiles, and stainless steel, for up to 5 days. In addition, SARS-CoV-2 survives on steel and plastic for 2–3 days but not on copper or cardboard, with extended survival at lower temperatures, while a study noted virus inactivation at higher temperatures, suggesting that temperature plays a role in transmission dynamics.

Additionally, studies have reported discrepancies in inorganic leachates from glass bottle materials, highlighting substantial differences in contaminant levels between PET and glass bottles (Kabir et al., 2023). Notably, Sharma et al. (2023) reported aluminum migration from clay packaging, reaching levels of up to 51.65 ng/cm^2, while Punia Bangar et al. (2023) observed significant migration of silicon and aluminum into acidic food simulants, with Si exhibiting a migration ratio 23% greater than that of Al. Additionally, studies have provided insights into the migration behavior of organic compounds from PET materials, with migration levels comparable to those of beverages under specific conditions, underscoring the necessity of accurate testing parameters to ensure reliable assessments (Díaz-Galiano et al., 2024). Furthermore, several researchers revealed variable concentrations of BPA in canned beverages, with levels extending from 0.032 to 4.5 µg/L, emphasizing the importance of continued monitoring and regulation in ensuring consumer safety (Fabjanowicz et al., 2024). These findings collectively underscore the complexity and criticality of addressing diverse challenges inherent in beverage packaging, necessitating integrated approaches encompassing sustainability, safety, and regulatory compliance considerations.

3.2 | Intelligent nano antibacterial compounds for food packaging technologies

Integrating intelligent nanoantibacterial compounds into biopolymer-based nanocomposite films and coatings offers an innovative solution to the challenges of preserving fruits and vegetables (Sagar et al., 2022). These advanced materials, which are derived from diverse natural sources, are enriched with nanomaterials, enhancing their properties. This integration imparts an array of enhanced physicochemical, mechanical, and barrier properties that are indispensable for safeguarding perishable produce against a gamut of microbial, biochemical, and physical deterioration (Saberi Riseh et al., 2023). The incorporation of intelligent antibacterial functionalities enables targeted release of agents, efficiently hindering microbial evolution and prolonging shelf life (Luo et al., 2024). Real-time monitoring of bacterial activity within the packaging environment ensures enhanced food safety throughout the supply chain (Ziani et al., 2024). This convergence represents a significant leap forward in postharvest preservation, promising sustained quality and longevity while minimizing contamination risks.

In a previous study, Sani et al. (2021) composite film, which involved blending chitin nanofibers (CNFs) and methylcellulose (MC) with red barberry anthocyanins (RBAs), demonstrated significant improvements in various properties. The addition of CNFs and RBAs enhanced the mechanical properties, moisture resistance, and UV–vis screening capabilities. Moreover, RBAs increase the film thickness to 0.130 from 0.098 mm for MC alone while reducing the transparency from 19.35 to 12.04 (log T600/mm). The water vapor permeability decreases notably from 6.50 for MC to 2.35 for MC/CNFs3%/RBAs3%. As the TS rises from 45.05 to 61.11 MPa and the elongation at break (EAB) rises from 7.04 to 16.05%, the mechanical characteristics also rise. Additionally, the film demonstrated robust antibacterial capacity against *Staphylococcus aureus* (16.8 mm) and *Escherichia coli* (18.3 mm), suggesting that food packaging may benefit from its use. RBAs have also the potential to serve as colorimetric indicators for food spoilage detection due to their sensitivity to variations in pH and ammonia gas production. Figure 6A highlights the film's utility as a halochromic material, showing a color change from reddish to pale pink with increasing pH during fish fillet storage, offering a straightforward visual freshness indicator.

Amaregouda and Kamanna (2024) study developed cellulose-based intelligent packaging for chicken meat. Films derived from carboxymethyl cellulose (CMC) and starch (ST) polymers, reinforced with chitosan nanoparticles (CS NPs), were produced using the solution casting method. The prepared film showed high biocompatibility (>90% cellular viability) and low migration rates (<1000 µg/dm^2) against food simulants. Chickens wrapped in these films maintain a stable pH, preventing oxidation. Total volatile basic nitrogen (TVB-N) levels correlate with food deterioration, enabling reliable freshness monitoring. Figure 6B illustrates the extended freshness of the CSC-4 film-wrapped chicken, which enhanced its antioxidant activity (~42.35%) and shelf life by up to 56 h. CSC-4 improved the mechanical strength (~81.08%) and UV blocking ability (~34.50%) and reduced oxygen (~45.93%) and water vapor permeability (~68.62%). The incorporation of CS NPs into CMS/ST matrices not only improved the physicomechanical properties of the composite films but also augmented their bioactivity. These nanofiber films offer promising smart containers for improved food quality and protection.

Rehim et al. (2023) study on active packaging films with *Lepidium sativum* extract, hyperbranched polyamide amine, and polyvinyl alcohol (PVA) revealed significant findings (Figure 6C). Film A3 (5% PVA, 1.2 ratio PVA:LS gum) displays strong antimicrobial ability against *E. coli* and *Listeria monocytogenes*, extending cheddar cheese preservation for up to 4 weeks and preventing trans-fat formation during storage (Rehim et al., 2023). The fat oxidizability in various cheese samples ranged from 0.40 to 0.98, indicating resistance to oxidation. Moreover, cheese

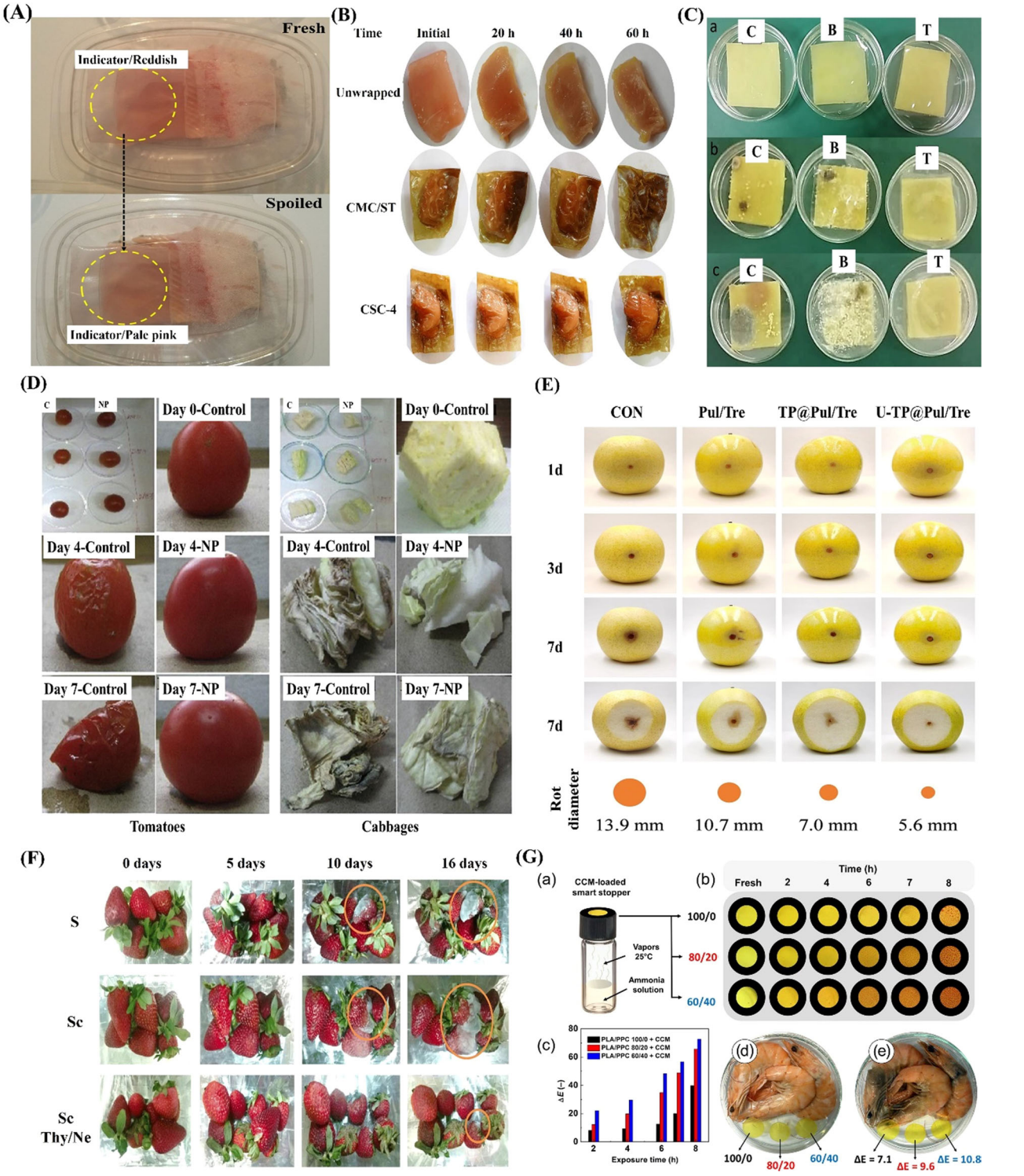


FIGURE 6 (A) Monitoring fish fillet freshness and spoilage using intelligent halochromic film. Adopted from Sani et al. (2021) Copyright Elsevier ©2021. (B) Evaluation of chicken packaging at room temperature using the CMC@ST-CSNP film. Adopted from Amaregouda and Kamanna (2024) Copyright Springer ©2024. (C) Visual spoilage development on cheese surfaces: control cheese (C), cheese wrapped with PVA film (B), and cheese wrapped with A3(T) film at time zero, after 2 weeks, and after 4 weeks of refrigerated storage. Adopted from Rehim et al. (2023) Copyright Springer©2023. (D) Challenge test demonstrating the preservative action of AgNP-infused cellulosic packets on tomatoes and cabbages stored for 4 and 7 days at room temperature. Negative controls were packed in standard cellulosic packets. Adopted from Singh and Sahareen (2017) Copyright Elsevier ©2017. (E) Morphological images of the control (CON), Pul/Tre-packed, TP@Pul/Tre-packed, and U-TP@Pul/Tre-packed pears over 1–7 days. Adopted from (Kang et al., 2023) Copyright Elsevier ©2021. (F) Appearance of uncoated (S) and BAlbion-coated strawberry plants with a quinoa protein/chitosan coating (Sc) and a Thy-nanoemulsion

(Continues)

FIGURE 6 (Continued)
quinoa protein/chitosan coating (Sc-Thy/Ne) throughout storage at 5°C. Adopted from Robledo et al. (2018) Copyright Springer ©2018. (G) Schematic illustration of the food spoilage testing setup of PLA/PPC Film (a), digital photographs (b) and corresponding color changes (c) represented as ΔE values of CCM-loaded PLA/PPC indicators at various exposure times to NH_3 vapors, and shrimps sealed in a Petri dish at the start of the test (d) and on day 5 (e). Adopted from Cvek et al. (2022) Copyright ACS ©2022.

samples coated with the treated films were protected from the formation of trans fats, underscoring the effectiveness of the modified films in providing antioxidant, antimicrobial, and preservative functions. Moreover, Singh and Sahareen (2017) demonstrated the efficacy of AgNP-impregnated cellulosic food packets in increasing shelf life by inhibiting microbial contamination and minimizing moisture loss in vegetables. Specifically, on day 0, tomatoes had 91.075% moisture, and cabbage had 81.275%. By day 4, the control samples lost moisture, with tomatoes at 79.42% and cabbage at 70.975%, while the AgNP-treated samples retained higher moisture levels, with tomatoes at 89.575% and cabbage at 81.3%. This trend continued through day 7, with the control samples further losing moisture (tomatoes: 62.5%, cabbage: 37.8%), while the AgNP-treated samples maintained elevated moisture levels (tomatoes: 89.15%, cabbage: 80.5%). Figure 6D highlights the preservation benefits of AgNP-impregnated packets, emphasizing their ability to extend shelf life compared with cellulose alone.

Extending this line of inquiry, Kang et al. (2023) engineered TP@Pul/Tre and U-TP@Pul/Tre films by blending tea polyphenols into pullulan/trehalose. These films were subjected to ultrasound-assisted treatment using dual-frequency (20/35 kHz, 40 W/L) for 15 min to evaluate its physicochemical and mechanical properties. The inclusion of TP diminishes the oil oxidation potential (OP), effectively deterring oil oxidation. Figure 6E shows that these films minimize the decay diameter in pears, with the TP@Pul/Tre (7 nm) and U-TP@Pul/Tre (5.6 nm) films demonstrating the smallest decay diameter. When antibacterial efficacy was evaluated, both films showed strong inhibition rates (100% for *E. coli* and 99.47% for *S. aureus* after 4–6 h). Moreover, the TP@Pul/Tre film shows exceptional UV light screening properties, absorbs UV light at 280 nm, has enhanced transparency, and significantly delayed moisture loss, oxidative browning, decay, and deterioration in fresh-cut apples and pears, thereby extending their shelf life. This demonstrates that ultrasound is an effective technique for enhancing the quality of food packaging films, with broad applicability.

Similarly, spontaneous emulsification was employed to prepare a thymol nanoemulsion, which was then incorporated into quinoa protein/CS coatings and used for prolonging the shelf life of strawberries under commercial storage environment (Robledo et al., 2018). Coated strawberries showed 58.3% damage on day 10 compared with 100% damage in uncoated strawberries. By day 16, the damage had decreased to 41.7%, showing enduring protection. After 16 days, the coating thickness reduced to 0.162 ± 0.033 and 0.151 ± 0.018 mm, respectively, due to moisture loss. The starting values of the coating thickness were 0.224 ± 0.020 mm for the coatings without Thy/Ne and 0.245 ± 0.016 mm for the coatings with Thy/Ne. Furthermore, the application of these biocoatings on strawberries significantly reduced weight loss compared with the control over 16 days of storage at 5°C and 90% relative humidity. Additionally, the biocoatings did not affect the quality parameters, including pH, titratable acidity, and soluble solids percentage. As visual comparisons showed that storage at 5°C had protective effects (Figure 6F), thymol/nanoemulsion-loaded edible films is in fact effective strategy for extending the shelf life of highly perishable products such as strawberries.

In another study, Wang et al. (2019) blended poly(ε-caprolactone) (PCL) with CS and grapefruit seed extract (GFSE) to create films with varying antimicrobial properties. Initially, the PCL/CS film had a thickness of 0.12 ± 0.00 mm, with a Young's modulus of 364.23 ± 11.66 MPa, a UTS of 13.31 ± 0.91 MPa, and an EAB of 421.80 ± 38.37%. However, the mechanical properties decreased with increasing GFSE content. PCL/CS/GFSE films displayed potent antimicrobial capacity against *E. coli* and *Pseudomonas aeruginosa*, reducing bacterial populations on surfaces. In salmon packaging, antimicrobial effectiveness was limited, with *E. coli* populations reaching 7.77 ± 0.10 log CFU/g after 6 days. In bread packaging, compared with PE films, films delayed mold development, with a higher GFSE preventing mold growth by the 7th day. PCL/CS/GFSE films showed promising antifungal characteristics, suggesting that they could be used to prolong the shelf life of bread, with a GFSE content of 1 mL/g.

Scalable procedures were recently used to create a material that is a combination of PLA and poly(propylene carbonate) (PPC) loaded with curcumin (CCM) (Cvek et al., 2022). Owing to their structural similarities, PLA and PPC exhibited significant compatibility and established hydrogen bonding interactions within their blends. The samples' adjustable release of CCM was shown to give efficient antioxidant action by the 2,2-diphenyl-1-picrylhydrazyl (DPPH•) assay, while PPC enhanced the

barrier qualities of the PLA/PPC blends according to studies of water vapor and oxygen permeability. Additionally, the film was effectively used as a sticker indication to track the deterioration of prawns over time, exhibiting a discernible color shift from yellow to light orange noticed by the naked eye (Figure 6G), especially in blends that contain PPC. Table 2 provides an overview of additional studies exploring various intelligent methodologies for preserving foods, further enriching our understanding and expanding the repertoire of innovative solutions in food packaging and preservation.

3.3 | 2D materials revolutionizing intelligent food packaging

Two-dimensional materials (2DMs) offer unique attributes, such as a large surface area, strong mechanical performance (Sher et al., 2024), and notable electrocatalytic ability, making them ideal for diverse food packaging applications (Furlan de Oliveira et al., 2022). Graphene, hexagonal boron nitride (h-BN), graphitic carbon nitride (g-C3N4), hexagonal metal dichalcogenides, layered double hydroxides, and transition metal carbides and nitrides (MXenes) are notable examples (Yu et al., 2021). They enhance dynamic packaging, elevating barrier properties, strength, thermal stability, and antimicrobial activity. The integration of smart features such as sensors and displays capitalizes on the properties of 2DMs, enabling functionalities such as leak detection, pH monitoring, and time–temperature tracking and ensuring heightened safety and quality standards during the food supply chain (Cheng et al., 2022). The synergistic potential of 2DMs and intelligent packaging technologies promises further innovations, reshaping food packaging solutions.

Numerous investigations have been conducted to explore the prospective applications of 2DMs in intelligent food packaging (IFP) systems. Waldhans et al. (2023) introduced an innovative android-compatible application-based digital color readout system for time–temperature indicators (TTIs), aiming to track temperature fluctuations along the supply chain and forecast the remaining shelf life by analyzing TTI discoloration. Their research successfully yielded a highly sensitive android app capable of detecting and measuring individual R, G, and B values of the TTI, reflecting color variations over time. Storage tests highlighted variations in the raw color values within the blue dot of the label, which could be alleviated through a white balance correction feature integrated into the app. Furthermore, a kinetic shelf life model based on app-generated measurements accurately predicted the TTI's remaining shelf life based on its color transformation. Specifically, the initial and corrected color values of the blue dots ranged from 94.46 to 183.29 and 230.21 to 270.46, respectively, and initially increased to 217.46 to 312.58 and 362.01 to 414.84, respectively, after 360 h of storage at 7°C. This study underscores the potential of android-based TTI monitoring systems for enhancing food quality and protection during the supply chain.

Moreover, Zhang et al. (2020) synthesized a 3D covalent organic framework (COF) from 2D materials using hexadecyl trimethylammonium bromide (CTAB) micelles. A flower-like COF structure was produced by adding CTAB, and this structure demonstrated good adsorption performance for UV filters and alkylphenols, which are frequently present in materials used to make food containers. The concentrations of these substances in the food packaging materials ranged from 4.8 to 6.2 μg/dm^2, with the maximum concentration detected at 37.2 μg/kg, which is well below the European Union-defined level of 6 mg/kg. Additionally, the synthesized COF displayed fluorescence properties, suggesting its potential for metal ion detection. This COF presents a promising solution for removing harmful substances from food packaging materials, thereby enhancing food safety measures. Moreover, its fluorescence capabilities offer avenues for the advanced analysis and detection of hazardous components within food packaging materials.

Furthermore, Han et al. (2023) investigated the potential use of silk fibroin (SF) films incorporated with 2D COFs as smart packaging materials for food spoilage detection. The optical properties, sensitivity to environmental changes, and antimicrobial capacity of the SF–COF films were evaluated. The results indicated that the SF–COF films exhibited excellent transparency in the visible region, with a light transmittance of roughly 60%, albeit they were translucent due to the presence of wrinkles. The optical properties were also influenced by the COF type. Furthermore, SF–COF films demonstrated high sensitivity, with a response time of 0.4 s, and a fast colorimetric response to alterations in pH and the presence of organic amine vapors, which is indicative of meat spoilage. Reversible color changes suggest the potential for regeneration and reuse as sensors. Evaluation of antimicrobial activity revealed that COF-incorporated films were not acutely toxic to brine shrimp, with minimal expected migration into food. Overall, this study suggested that SF–COF films have potential as smart packaging materials for food spoilage detection, offering fast, accurate responses to environmental changes in safe packaging options.

Li et al. (2019) investigated PHBV nanocomposites comprising cellulose nanocrystals (CNCs) and 2D graphene oxide (GO), examining their morphologies, mechanical properties, water absorption, water vapor transmission rate, thermal properties, and antibacterial activity. The findings revealed that the enclosure of CNCs and GO

TABLE 2 Comprehensive assessment and critique of intelligent polymer-based coatings for food preservation.

Polymer matrix	Bioactive compounds	Coating methods	Fruit/vegetable	Functionality	Effects on produce quality	References
Starch/cellulose	Gallic acid	Casting method	Cut apples	The film shields food from UV radiation, preventing color and flavor changes, and lipid oxidation.	Young's Modulus increased from 1.2 to 2.0 GPa, and tensile strength rose from 23 to 39 MPa. The 10% BNC and 1% GA film showed high oxygen barrier. 4.5 log10 CFU/mL reduction of *Staphylococcus aureus* colonies in 48 h.	(Almeida et al., 2023)
Chitosan/starch	Lippia gracilis Schauer essential oil	Dipping method	Guavas	Chitosan-cassava starch-essential oil film extended guava shelf life by delaying ripening and inhibiting microbial growth, preserving color.	TA varied from 0.31 to 1.05% over time. TSS content fluctuated between 8.16 °Brix and 13.33 °Brix throughout storage. Reduced browning and color development in guavas. The coatings helped maintain the firmness of the guavas during storage.	
Cellulose/chitin/chitosan	Wood nanocrystals (WCNCs)/chitosan nanofibers (CSNFs)	Spraying method	Strawberry	The film preserves color, reduces weight loss, boosts antimicrobial activity, and prolongs fruit shelf life.	The nanomaterial coating reduced weight loss to less than 5% by day 8, compared with 8.37% in the control. Coated strawberries remained mold-free even after 13 days.	(Sun et al., 2021)

(Continues)

TABLE 2 (Continued)

Polymer matrix	Bioactive compounds	Coating methods	Fruit/vegetable	Functionality	Effects on produce quality	References
Cellulose	Rosemary/green tea/pomegranate peel extracts	The incorporation of herbal extracts into bacterial cellulose (BC) active membranes	Button mushrooms	The film serves as an active membrane, gradually releasing compounds to control microbial growth and preserve phenolic compounds and ascorbic acid in mushrooms.	The active membrane with 50% RE exhibited the highest antioxidant. PPE50% yielded the lowest microbial count (6.5 log CFU/g). PPE and RE in active packaging preserved vitamin C. Active membranes reduced weight loss by 30% during storage.	(Moradian et al., 2018)
	Naringin	Drop-casting	In vitro test	The film offers UV blocking, acts as a plasticizer, and exhibits antioxidant and antibacterial properties, aiding in food preservation. Serves as a barrier, reducing water vapor and oxygen transmission.	UV-A was 100% for CN-0 and approximately 85% for CN-20, while UV-B was 100% for CN-0 and approximately 90% for CN-20. Films decomposed well in seawater: CN-20 lost ~19%, CN-0 ~39% weight in 30 days.	(Guzman-Puyol et al., 2022)
	ZnONPs	Hydrothermal method	In vitro test	ZnO film boosts mechanical strength, barriers, and fire resistance, with printability and UV resilience. Biodegradable, with minimal Zn^{2+} migration, and potent antimicrobial properties.	Tensile strength exceeds 39.0 MPa, with elongation at break surpassing 7.3%. Good water solubility, with values ranging from 0.5 to 1.5%. Antimicrobial capacity against *S. aureus*, *E. coli*, and *C. albicans*, with bactericidal ratios varying from 3 to 24%.	(Xie et al., 2022)

(Continues)

TABLE 2 (Continued)

Polymer matrix	Bioactive compounds	Coating methods	Fruit/vegetable	Functionality	Effects on produce quality	References
	Chinese Chives root extract	Sputter-coating	In vitro test	Enhances antioxidant activity, biodegradability, barrier properties, and bacteria inhibition	CMC-CRE5 film had the maximum biodegradability at 58.14%. Film thickness improved from 43 to 84 μm. Water solubility decreased from 77.51 to 52.91%. Swelling degree decreased from 55.74 to 40.37%. DPPH and ABTS radical scavenging capacity of CMC-CRE films increased significantly, by 58 and 82%, respectively.	(Riaz et al., 2020)
Chitosan	Polyvinyl alcohol (PVA)/citric acid (CA)	–	Strawberries and cherry tomatoes	The film breaks down naturally, reducing environmental pollution from nonbiodegradable plastics. Prevents condensation, maintains transparency for food observation, and inhibits bacterial growth to extend shelf life.	PVA/CMCS/CA composite films prolonged the shelf life of fresh strawberries and cherry tomatoes by decreasing weight loss, indicating delayed water evaporation.	(Wen et al., 2021)

(Continues)

TABLE 2 (Continued)

Polymer matrix	Bioactive compounds	Coating methods	Fruit/vegetable	Functionality	Effects on produce quality	References
	Acrylamide/acrylonitrile	Microwave initiated graft copolymerization	Apple and guava	Antimicrobial packaging material protects against environmental factors and inhibits bacteria.	Antimicrobial film kept fruits fresh for 18 days at 40–45°C, inhibiting *Escherichia coli* (24.5%), *Staphylococcus aureus* (26%), and *Pseudomonas aeruginosa* (26%).	(Kumar et al., 2018)
	Beeswax-pollen grains	Dipping	Conte pear	The film extends shelf life by reducing respiration and water loss while enhancing fruit resistance to pathogens and improving water resistance and stiffness.	Chitosan films self-healed efficiently (83.03–92.00%). Adding beeswax and pollen grains increased chitosan film's contact angle (79.8° to 109.7°). Chitosan-beeswax/pollen grain films had WVTR of 1038.07 g/m^2/day, half that of chitosan film (2065.23 g/m^2/day). With 14.09% elongation at break, it is less than half of chitosan film's (35.81%).	(Sultan et al., 2021)

(Continues)

TABLE 2 (Continued)

Polymer matrix	Bioactive compounds	Coating methods	Fruit/vegetable	Functionality	Effects on produce quality	References
	Aloe vera	Dip coating	Blueberry	Aloe vera-infused chitosan coating enhances blueberries, preserving their quality and extending shelf-life by minimizing water loss.	The coated blueberries experienced 50% less weight loss after 25 days. Mold was delayed 7 days, extending shelf-life by 5 days.	(Vieira et al., 2016)
	TiO_2/SiO_2NPs	–	Ginkgo biloba seeds	The film offers antimicrobial action under light and provides oxygen and oil barrier properties for food packaging, reducing gas permeability to maintain packaging integrity and prevent spoilage.	The membrane permeability increased markedly in all treatments (CT, and CS) from, 11.47, 12.37, and 19.42% with low doses of nano-TiO_2. CT and CS treatments significantly reduced $O2^{*-}$ production rate ($p < .05$), maintaining higher SOD and CAT activities, with increased POD activity in CT and CS groups.	(Tian et al., 2019)
Starch	Polyurethane/lavender essential oil	Interfacial polymerization	Blueberries and raspberries	Packaging film offers strength, transparency, and UV shield. EOs@PU microcapsules combat *E. coli* and *S. aureus*. Eco-friendly films, passes cytotoxicity and degradation tests.	EOs@PU microcapsules extended fruit shelf life by over 7 days. Films degraded 95% in soil within 8 days, promoting environmental protection.	(Wang et al., 2023)

(Continues)

TABLE 2 (Continued)

Polymer matrix	Bioactive compounds	Coating methods	Fruit/vegetable	Functionality	Effects on produce quality	References
	Foams/grape stalks	–	Cake	Cassava starch-based film with grape stalks is a biodegradable food wrap, suitable for low-moisture storage, serving as a green alternative to EPS for short-term use.	Cassava starch foams with grape stalks fully degraded in 7 weeks. Grape stalk-added foams showed ideal flexural properties (3.3–17.1 MPa).	(Engel et al., 2019)

enhanced the PHBV matrix's dispersion and compatibility, which in turn produced better mechanical strength, less water absorption, UV-shielding qualities, and antibacterial activity against *S. aureus* and *E. coli*. Specifically, the water vapor transmission rate decreased by 72.6%, the TS improved by 170.2%, the EAB decreased by 52.1%, and the melting temperature (Tm) decreased by 26.3°C compared with the reference values. Moreover, significant antibacterial activity was observed, with inhibition zones of 3.49 mm for *E. coli* and 3.32 mm for *S. aureus*. These findings underscore the promising potential of PHBV–CNC–GO nanocomposites as multifunctional materials for various packaging applications. Overall, these studies collectively underscore the significant role of 2DMs in advancing IFP technologies, emphasizing the importance of integrating advanced materials with intelligent design to guarantee food safety, quality, and sustainability throughout the supply chain.

3.4 | Smart CPs for novel functionalities in the food industry

3.4.1 | Antibacterial and antioxidant-doped CPs

Conductive polymers are multipurpose materials with antibacterial, antioxidant, and electrical conductivity that make them useful in a variety of sectors. Their electrical conductivity facilitates the development of advanced materials and devices in electronics, energy storage, and sensors. Furthermore, their antibacterial qualities are essential for use in food packaging, healthcare, and preservation. Furthermore, the antioxidant properties of these substances aid in prolonging the durability of goods and preserving the integrity of delicate substances. By encompassing these diverse functionalities, conductive polymers have emerged as innovative materials driving progress in materials science and engineering.

Maruthapandi et al. (2019) investigated a novel composite material based on PPy and copper oxide (PPy@CuO), focusing on its potent antibacterial properties (Figure 7A). A straightforward one-step sonochemical process, which involved combining the carbon dot initiated PPy and CuO composite was adopted. When the composite was tested at different concentrations, it was shown to completely eradicate *S. aureus* and *E. coli*, essentially stopping the evolution of bacteria. Notably, after 8 h of exposure, the composite showed 100% mortality of both bacterial strains at a dosage of 1 mg/mL with 0.234 mg/mL CuO. Through electron paramagnetic resonance (EPR) measurements, substantial growth in reactive oxygen species (ROS) production was detected in the PPy@CuO composite compared with the

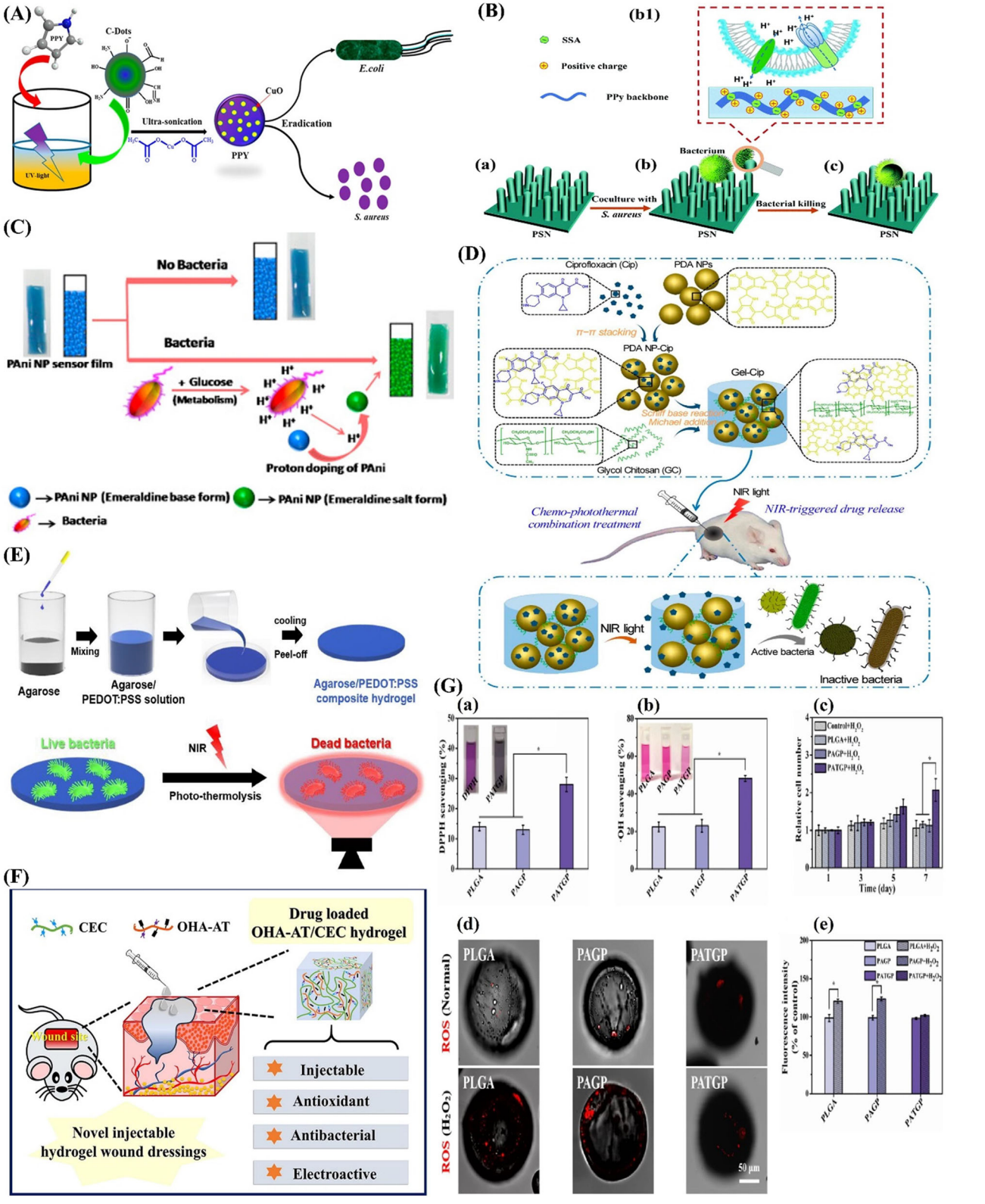


FIGURE 7 (A) Elaboration of PPy@CuO micro/nanoparticles with improved antibacterial capacity using carbon dot initiation. Adopted from Maruthapandi et al. (2019) Copyright ACS ©2019. (B) Potential interaction mechanism between PSNs and bacteria: (a) representation of the PSN substrate, (b) bacteria closely adhered to the PSNs when cocultured with *S. aureus*, (b1) microbial thiol groups undergo oxidation on positive PSN surfaces during bacterial culture, this oxidation leads to proton outflow from the bacteria's intracellular space, (c) disrupting the proton transfer stability and eventually causing cell death. Adopted from Zhou et al. (2018) Copyright RSC ©2018. (C) Illustration of the proposed mechanism for controlling bacterial evolution using PAni–Pec NPs-based colorimetric sensor. Adopted from (Thakur et al., 2015)

(Continues)

FIGURE 7 (Continued)
Copyright Elsevier ©2015. (D) Representations of the synthesis pathway of Gel-Cip and NIR light-induced Cip release from Gel-Cip for bacterial inactivation. Adopted from Gao et al. (2019) Copyright Elsevier ©2019. (E) The fabrication process of PEDOT:PSS/agarose nanocomposite hydrogels and illustration of the photothermolysis of surface bacteria. Adopted from Ko et al. (2019) Copyright Elsevier ©2019. (F) Degradable conductive injectable hydrogels for antibacterial and antioxidant wound dressings and enhanced healing. Adopted from Qu et al. (2019) Copyright Elsevier ©2019. (G) Assessment of the antioxidant ability of PATGP using PLGA and PAGP as controls via DPPH and ·OH scavenging assays (a, b), CCK-8 assay measuring cell proliferation on microspheres over 7 days in the presence of H_2O_2 (1 μM) with TCPs as a control (c), DHE staining depicting intracellular ROS levels (d), and quantitative analysis of DHE fluorescence intensities in cells cultured on microspheres with or without H_2O_2 treatment (e). Adopted from Huang et al. (2020) Copyright Elsevier ©2020.

individual components, with 3.5-fold and 2-fold increases relative to those of PPy and CuO alone, respectively. This enhanced antibacterial effect can be attributed to the conductive nature of PPy, which facilitates increased ROS production that is detrimental to bacteria. Additionally, the composite's positive charge and unique chemical structure enhance its antibacterial activity by disrupting bacterial cell walls and inducing cell death.

Furthermore, sulfosalicylic acid (SSA) is a crucial dopant for enhancing the antibacterial efficacy of CPs, such as PPy. SSA makes it easier for PPy micelles to electrically assemble into a nanostructure that resembles the extracellular matrix of bacteria because it has a large number of negatively charged functional groups (Zhou et al., 2018). The SSA produces CPs with remarkable antibacterial activities by altering the surface electrical characteristics of PPy, hence increasing the positive charge on SSA-assisted PPy. A schematic representation of the contact mechanism between bacteria and the positively charged PPy surface is presented in Figure 7B. Positive charges are concentrated on PPy by the high negative charge of SSA, upsetting the proton transfer equilibrium in bacteria and eventually causing cell death. The strong negative charge of SSA concentrates positive charges on the PPy, thereby increasing the surface charge density. The positively charged PPy then captures electrons from the bacterial cell membrane, disrupting proton transfer balance and leading to bacterial cell death. This illustration highlights how bacterial contacts and surface potential modulation by SSA contribute to the polymer's enhanced antibacterial qualities. This innovative approach highlights the potential of SSA as a dopant for enhancing CP functionality and emphasizes the use of biomolecules such as SSA for advanced materials with superior antibacterial capabilities. Antimicrobial assessments revealed a significant decrease in *S. aureus* viability on the PSN sample compared with PSI and PCI, with PSN exhibiting a remarkable 93% antibacterial ratio per surface area. The enhanced antibacterial efficacy of PSN suggests a synergistic effect from nanofunctionalized PPy with increased surface potential.

A simple and novel colorimetric sensor based on PAni nanoparticles for detecting bacterial growth was reported previously (Thakur et al., 2015). The films clearly changed color from blue to green when used to track bacterial development in real-time. Since no specialist antibodies or receptors are used, the generic sensor has potential for use in real-world applications as a patch sensor on cartons to track the integrity and freshness of food products and drinks in real-time. Figure 7C illustrates the fundamental concept of the colorimetric assay. When bacteria such as *E. coli* grow, they metabolize simple carbohydrates like glucose into various end products such as lactate, acetate, ethanol, succinate, and formate, via pathways like glycolysis. The acidic environment that these metabolic processes create surrounding the bacteria can be observed with pH-sensitive nanosensors such as PAni–Pec NPs. The PAni undergoes a clear, visually discernible color change from its emeraldine base form (blue) to its emeraldine salt form (green) when acidic metabolic byproducts are present.

In addition to these studies, the synergy between CPs and metal nanoparticles in nanocomposites has led to remarkable antimicrobial properties. For example, polyindole/Ag–CeO_2 nanocomposites have shown superior activity against various pathogens by disrupting bacterial cell walls and inducing cell death (Pradeep et al., 2022). Comparably, the minimum inhibitory concentration (MIC) values of several polymer-based nanocomposites, including PPy–Pd, PPy–Zn@CuO, PAni–Zn@CuO, PPy–NT Ag–NPs, and PAni/Pt–Pd, have shown a variety of antibacterial properties against various bacterial strains: The results showed that PPy–Zn@CuO was effective against *E. coli* (MIC: 0.078 mg/mL), PAni–Zn@CuO was successful against both *E. coli* and *S. aureus* (MIC: 0.144 mg/mL), and PPy–Pd nanocomposites was effective against *S. aureus* (MIC: 5.78 mg/mL, MBC: 23.12 mg/mL). Moreover, research on the antioxidant activities of conductive polymers, particularly PPy, has revealed significant findings (Elango et al., 2018). PPy exhibits strong antioxidant properties, scavenges free radicals and reduces oxidative stress. The incorporation of the polymer into materials, such as hydrogels, has improved the conductivity and efficiency of light-to-heat conversion under NIR laser irradiation.

Additionally, conductive polymer-based nanoparticles, such as conductive poly(p-phenylenediamine)/Fe_3O_4

nanocomposites, play a crucial role in extending the shelf life of products owing to their antioxidant capacity. In addition, a quantitative evaluation of the antioxidant activity of conductive PPy/zinc oxide/CS bionanocomposites revealed that, in less than a 100 min, the antioxidant activity rose from 74.814 to 79.169 as the ZnO NP concentration increased (Ebrahimiasl et al., 2014). The potential of these bionanocomposites to shield products from oxidative damage and prolong their shelf life is highlighted by the time-dependent nature of their antioxidant activity and their effective scavenging of DPPH radicals. The DPPH inhibition percentages ranged from 52.597 to 58.912% for different time intervals and compositions of the bionanocomposite, showing the time-dependent nature of the antioxidant activity. Manufacturers can leverage the antioxidant properties of these innovative materials to develop products with improved stability and longevity, benefiting industries such as food packaging, pharmaceuticals, and cosmetics.

Furthermore, reports of the use of polydopamine-based gels, such as hydrogels and cryogels, for wound healing and photothermal treatment-induced bacterial inactivation (Gao et al., 2019). The development of an injectable thermosensitive hydrogel (Gel-Cip) involved the integration of glycol chitosan (GC) with PDA nanoparticles loaded with ciprofloxacin (Cip) (Figure 7D). This hydrogel was created to regulate the release of Cip to fight bacterial infections.

On one hand, the positive charge of GC and the adsorption capacity of PDA NPs facilitated the efficient capture of bacteria on the surface of Gel-Cip. On the other hand, while Gel-Cip showed minimal leakage under physiological conditions, it enhanced ciprofloxacin release when exposed to NIR light. In the meantime, PDA NPs caused a rise in temperature due to the photothermal effect after irradiation by NIR light that brought on localized hyperthermia to take the integrity of bacteria away and consequently resulted in bacterial inactivation through a synergistic effect. The visual representation highlights the strategic combination of several functionalities within the PDA CPs, demonstrating their potential as effective solutions for combating microorganisms and oxidative processes.

In a separate study, a straightforward aqueous solution-based strategy was employed to fabricate an effective photothermal nanocomposite composed of PEDOT:PSS and agarose (Figure 7E). This nanocomposite exhibits thermo-processability, light-triggered self-healing properties, and outstanding antibacterial activity under NIR irradiation (Ko et al., 2019). The hydrogel achieved nearly 100% bacterial eradication within just 2 min of NIR irradiation at a light intensity of 2 W/cm^2. This performance was comparable to that of iron oxide@PEDOT-based photothermal nanoparticles, which required 5 min of exposure to achieve similar results. Furthermore, live/dead staining studies on fibroblasts cultured on the PEDOT:PSS/agarose composite gels for 4 days revealed a thriving cell population with minimal signs of cell death, indicating excellent biocompatibility for supporting cell growth and proliferation. Hemocompatibility tests showed that the PEDOT:PSS/agarose composite hydrogels (20% v/v and 40% v/v) exhibited negligible hemolysis percentages below 6%, showing outstanding compatibility with blood components. Considering its simple production, flexibility, thermo-processability, localized self-healing, excellent biocompatibility, and effective antibacterial properties, PEDOT:PSS/agarose nanocomposite holds promise for advancing the development of antimicrobial platforms for practical applications in biomedical and biotechnological fields.

Furthermore, Qu et al. and (2019) highlighted the strategic combination of antibacterial and antioxidant functionalities within degradable conductive injectable hydrogels (Figure 7F), offering effective solutions for microbial control and oxidative stability. Conductive antioxidant hydrogels, designated oxidized HA-graft-aniline tetramer (OHA-AT)/CEC, were synthesized by mixing the biocompatible polymer N-carboxyethyl chitosan (CEC) with OHA-AT under physiological conditions. The hydrogels demonstrated stable rheological properties, a high swelling ratio, appropriate gelation time, favorable in vitro biodegradation, electroactivity, and effective free radical scavenging capacity. This scavenging ability (reaching a value of up to 89%) was attributed to electron transfer or hydrogen atom donation from the AT fragments. In contrast, the OHA/CEC hydrogels had a minimal impact on the DPPH radical scavenging ability. Following the incorporation of the antibiotic amoxicillin, the hydrogel demonstrated robust antibacterial activity, effectively preventing wound infection. In vivo studies revealed that the hydrogel with AT addition (OHA-AT/CEC hydrogels) significantly accelerated wound healing, as evidenced by increased granulation tissue thickness, enhanced collagen deposition, and greater angiogenesis in a full-thickness skin defect model.

An AT and glycine ethyl ester cosubstituted polyorganophosphazene (PATGP) was synthesized, designed to meet the desired requirements. The AT moieties provide antioxidant properties, while the phosphorus-rich phosphazene segments ensure osteocompatibility. The incorporation of AT into PATGP endowed the material with conductivity, aligning with the electrophysiological properties of bone tissues. Through in vitro cell culture and in vivo evaluations, PATGP microsphere-type scaffolds were systematically assessed for their capabilities, including ROS-scavenging effect, cytotoxicity, and osteoinductivity, with nonconductive poly[(ethylalanato)(ethylglycinato)]phosphazene (PAGP)

and poly(lactide-co-glycolide) (PLGA) microspheres used as control groups. PATGP microspheres exhibited the most significant effects in enhancing cellular activities and accelerating neobone formation in rat calvarial defects. As highlighted in Figure 7G, the antioxidant activity of conductive PATGP was demonstrated through its superior scavenging efficiency compared with that of other materials, with values of 28.3 ± 2.4% (DPPH) and 48.1 ± 1.5% (·OH), indicating that PATGP is a promising material for applications in bone regeneration and tissue engineering (Huang et al., 2020).

In another setting, the extraordinary potential for enhanced functional materials can be achieved by mixing a synthetic polymer with a naturally occurring biodegradable polymer. For this reason, the increasing need for high-performance textiles has led to a great deal of interest in the improvement of cellulosic matrix coated with CPs in recent years. In the effort of Nazarzadeh Zare et al. (2014), PPy combined with dextrin was synthesized, characterized, and tested for its antibacterial and antioxidant capacities. The outcomes showed that the conductivity and antioxidant activity of the nanocomposite matrix were both improved by adding more PPy. The results further demonstrated the efficiency of the nanocomposites against both Gram-positive and Gram-negative bacteria. It was also shown that natural soil microorganisms may biodegrade the nanocomposite, breaking it down to as much as 74.52%. Comparable work was carried out by Maráková et al. (2017), using PPy and PAni-coated cotton fabric and with the addition of silver nanoparticles. Both materials exhibited decent antibacterial activity against *S. aureus* and *E. coli*, along with minor cytotoxicity.

Recently, we have worked in a similar vein in which multifunctional smart PPy (El Guerraf, Ben Jadi, Bakirhan et al., 2022), PAni and PEDOT (El Guerraf et al., 2023) combined with AgNPs were coated on top of a cellulosic paper obtained from Tetra Pak food packaging. The developed materials have demonstrated the ability to inhibit biofilm formation and reduce the oxidation rate of foodstuffs while also detecting toxic gases produced by spoiled food. These formulations have a great chance to become an appealing substitute for conventional food containers thanks to this creative method. The synthetic composites' clever and unique qualities make them perfect for use in industrial applications down the road. They offer the best protection possible, preventing product degradation, and they create an atmosphere that prolongs the shelf life of foodstuffs. In conclusion, conductive polymers represent a class of innovative materials with diverse applications and promising prospects in various fields. Their exceptional combination of electrical conductivity, antimicrobial efficacy, and antioxidant properties marks them invaluable for addressing contemporary challenges and driving progress in materials science and engineering.

3.4.2 | CPs as intelligent food containers

Food packaging has made widespread use of synthetic polymer materials like polyethene because of its outstanding gas and grease barrier qualities, flexibility, and ease of processing. However, these nondegradable materials have led to significant waste pollution. Intelligent and active packaging is becoming more and more popular as a reaction to society's demands for more environmentally friendly solutions. This kind of packaging ensures product quality during storage, distribution, and transit by keeping an eye on changes that take place while food is being stored and by giving information on the product's state. As a result, the food packaging sector is looking for bio-based alternatives for the upcoming generation of packaging. Because of its biodegradability and recyclability, cellulose has been thoroughly investigated as one of these novel alternatives. The strongly intertwined fiber network of cellulose nanofibers provides outstanding mechanical capabilities as well as oxygen barrier properties. Nevertheless, cellulose's strong affinity for water results in poor water vapor barrier qualities because of its hydrophilicity, which is a significant disadvantage for packing.

Addressing this issue, the group led by Loranger (Bideau et al., 2017, 2018) has introduced a combination of a cellulosic matrix and CPs. This approach aims to enhance the physicochemical properties of the packaging and impart smart characteristics to the containers. The first study looked at the extra advantages of PPy coating and TEMPO-oxidized cellulose nanofibers (TOCN) on the characteristics of paperboard (PB) packaging (Bideau et al., 2018). This coating considerably enhanced the mechanical characteristics of the PB, increasing Young's modulus from 0.93 to 2.92 GPa for the uncoated and coated PB, respectively. It also greatly reduced the gas permeability, decreasing it from 12.5 to 1.0 mL/min for the uncoated and coated PB, respectively. Moreover, a qualitative test was also achieved by placing cherry tomatoes in an uncoated and coated PB box. After 10 days, as shown in Figure 8A, all of the control tomatoes were extremely wrinkled and in a mature stage, rendering them undesirable to many consumers. Although a few stayed steady, most of the tomatoes in the PB box were in a similar state. All of the tomatoes in the PPy/PB boxes, on the other hand, kept their appealing appearance and steady texture for ingestion. The mechanical properties and reduced gas permeability of the coated PB were notably enhanced due to the formation of a dense network comprising TOCN and PPy particles.

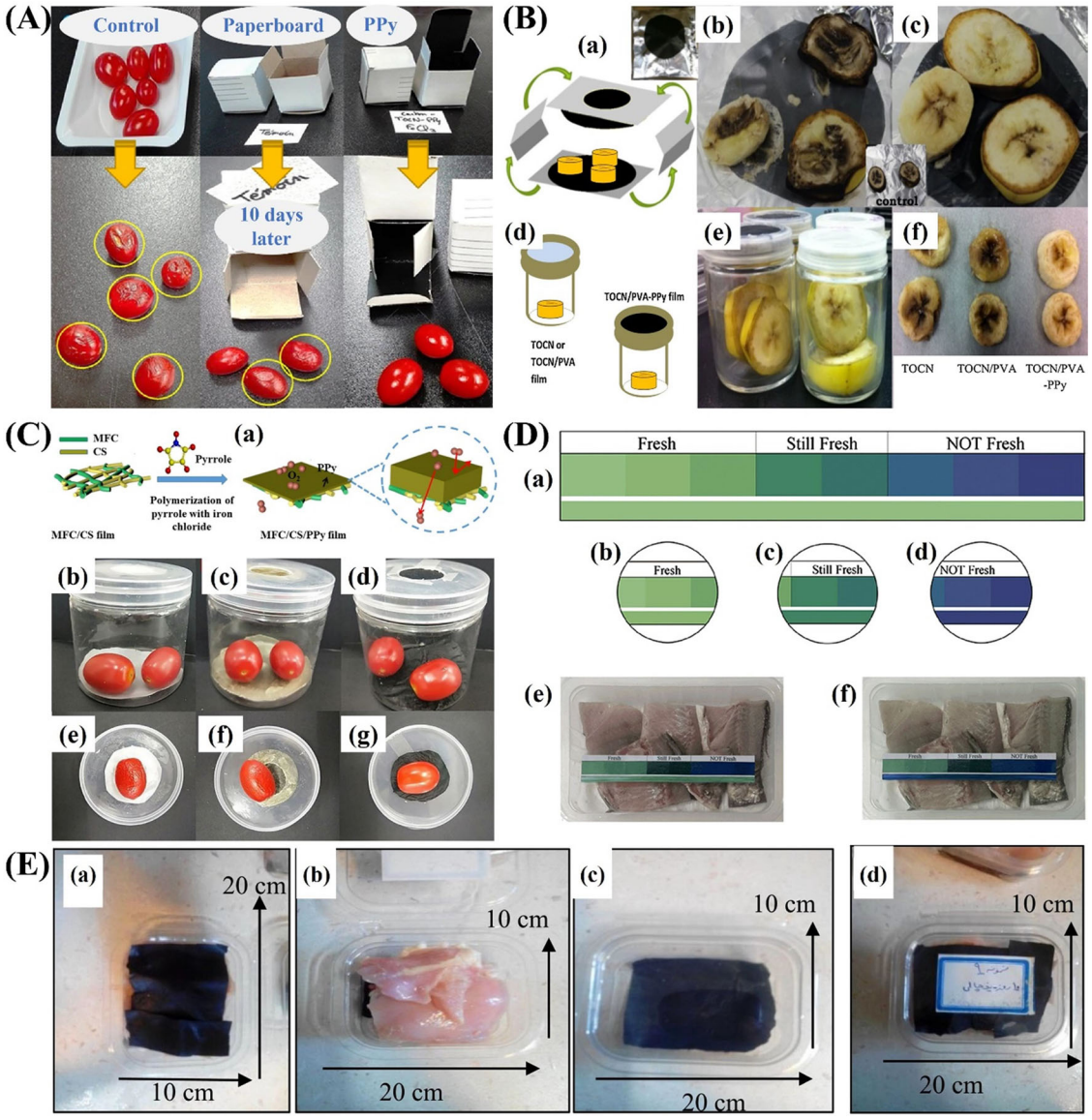


FIGURE 8 (A) Simulation of cherry tomatoes packing after 10 days using paperboard and PPy-coated paperboard. Adopted from Bideau et al. (2018) Copyright Elsevier ©2018. (B) Diagrams of bananas packing test by contact (a), food simulation after 5 days with TOCN film (b), and TOCN/PVA–PPy film (c); diagram of bananas packing test by noncontact (d); food simulation containers (left: TOCN/PVA–PPy film and right: TOCN/PVA film) (e); piece of banana after 5 days (f). Adopted from Bideau et al. (2017) Copyright Elsevier ©2017. (C) Representation of the elaboration process of MFC/CS/PPy film (a), and the corresponding simulation of cherry tomatoes after being covered for 10 days with the MFC film (b and e), the MFC/CS film (e and f), and the MFC/CS/PPy film (d and g). Adopted from Gao et al. (2020) Copyright Elsevier ©2020. (D) A suggested PAni display for assessing the freshness of tilapia and its indication procedure: (a) PAni-based freshness indicator for tilapia, (b–d) indicator displaying different statuses corresponding to the freshness levels of tilapia: (b) fresh; (c) slightly spoiled; (d) spoiled, and (e, f) application of the indicator in packaged tilapia: (e) fresh; (f) spoiled. Adopted from Wang et al. (2018) Copyright RSC ©2019. (E) Chicken thigh meat packaging by conducting BC–PPy–ZnO film: (a) placing the film on the bottom of the container, (b) placing the chicken thigh meat on the film, (c) adding the BC–PPy–ZnO film on top of the meat, and (d) sealing the package. Adopted from Pirsa and Shamusi (2019) Copyright Elsevier ©2019.

The group's other project involves combining TEMPO-oxidized nanofibrillated cellulose (TOCN), PVA, and PPy (Bideau et al., 2017). The objective was to create packaging that combines the physicochemical characteristics of PPy with the gas barrier and biodegradability of cellulose. The TOCN/PVA–PPy films' water vapor permeability and oxygen barrier are as high as those of synthetic polymers found in retail stores. To evaluate the potential industrial application of the TOCN/PVA–PPy composite, food simulation by contact was conducted (Figure 8B). In the presence of the cellulose film, bananas remained hydrated but began to show signs of deterioration, as evidenced by the browning

of the fruit due to oxidation (Figure 8B(b)). This oxidation contributed to the degradation of the bananas. However, as shown in Figure 8B(c), banana pieces were retained after 5 days, demonstrating the significant barrier properties of the composite.

Noncontact food simulation was also conducted in this study (Figure 8B(e)). As shown in Figure 8B(f), bananas preserved with the TOCN/PVA–PPy film exhibited superior preservation compared with those stored with either the TOCN or TOCN/PVA films. The absence of browning indicates that oxidation was effectively prevented in the TOCN/PVA–PPy treatment, unlike in the other two conditions. In both situations, the films' inclusion of barrier and antioxidant qualities allows them to protect perishable foods from impurities like dust, grime, and oxygen while also extending their shelf life. Additionally, the PPy dark color protects against light-induced degradation of food. Moreover, the biodegradable nature of these films offers the potential to decrease packaging waste typically produced by plastics. This method in both cited articles demonstrated the feasibility of producing PB-based food packaging that significantly outperforms conventional PB packaging, resulting in an extended shelf life for perishable foods.

The aim of an inquiry conducted by Gao et al. (2020) was the incorporation of CS and PPy into microfibrillated cellulose (MFC) for enhanced antioxidant, antibacterial and oxygen barrier features. The incorporation of CS and PPy enhanced the surface uniformity and effectively filled the pores, suggesting that the channels were blocked. This modification resulted in a significant reduction in oxygen transmission to 32.38 cm^3 (m^{-2} day^{-1}). In addition, the resultant MFC/CS/PPy film successfully suppressed DPPH free radicals and showed strong bactericidal action against *E. coli*, attaining a 5.43 log CFU/mL decrease. The synergistic effect of protonated amino groups (in acidic conditions) in CS combined with the positively charged PPy chains enhances the antimicrobial performance of MFC/CS/PPy. The positively charged ions can interact with the negatively charged bacterial cell walls, leading to the disruption of the cell wall and ultimately resulting in bacterial cell death. Furthermore, fresh cherry tomatoes were effectively packaged using the composite film. Tomatoes covered with the MFC/CS/PPy film showed less morphological alterations and retained their vibrant color for up to 10 days when compared with the MFC and MFC/CS films (Figure 8C). The MFC/CS/PPy composite film effectively decreased oxygen exchange and delayed the ripening of tomatoes, thereby extending their shelf life.

Conversely, a PAni-based colorimetric indicator label was created to determine the tilapia's freshness by measuring the total amount of released TVB-N (Wang et al., 2018). The proposed indicator label, shown in Figure 8D(a), comprised of a printed reference color bar above and a PAni bar below. The PAni bar's color shifted from green to dark blue as the product progressively spoiled, as revealed in Figure 8D(b–d). The corresponding color showed the tilapia's immediate freshness in the packaging. The label's actual use for ensuring the freshness of packed tilapia is seen in Figure 8D(e, f). The polymer bar became green when the fish was still fresh. The PAni bar deepened as the fish started to go bad and finally turned dark blue when the dish was ruined beyond recognition. A regenerated PAni film, treated with HCl, exhibited a distinct color change from green to peacock blue when TVB-N levels approached the critical value. This film demonstrated the capability for at least three cycles of reuse. The proposed design based on PAni could assist consumers in assessing the freshness of tilapia and ensuring the safety of the products.

Following a similar vein, bacterial cellulose (BC) film was adjusted with a PPy–zinc oxide (PPy–ZnO) nanocomposite and utilized for packaging chicken thigh meat (Pirsa & Shamusi, 2019). The outcomes showed that the pH level and microbial evolution in the meat of chicken thighs were successfully regulated by the BC–PPy–ZnO film. Furthermore, during the storage time at different temperatures, the film maintained the chicken thighs' sensory qualities in a positive state. As an antioxidant-active film, the BC–PPy–ZnO film successfully shielded the meat from oxidizing agents, increasing the meat's shelf life (Figure 8E). The total microbial count in the samples packaged with the BC–PPy–ZnO film was lower than in the control samples. The odor and sensory quality of the control samples declined over time, whereas the decline occurred much more slowly in the samples packaged with the BC–PPy–ZnO film. The results indicate a strong correlation between changes in film electrical resistance and both storage time and temperature. This relationship could be utilized to estimate the storage duration and temperature of chicken thighs, thereby enabling the development of intelligent packaging solutions.

In another context, Maskey et al. (2020) developed a thermistor for near-field communication (NFC)-enabled intelligent packaging systems to enhance temperature monitoring in the food logistics chain (Figure 9A). A functionalized graphene oxide–polyvinylidene fluoride (FGO–PVDF) composite as an encapsulation layer was introduced to validate the reliability of PEDOT thermistors under high-humidity conditions. The authors successfully employed this thermistor to monitor temperature ranges relevant to the cold chain. Figure 9A(a) provides a detailed overview of the process, from mask printing to encapsulation with the FGO–PVDF composite, for fabricating the FGO–PEDOT thermistor. A single-step roll-to-roll (R2R) gravure system was employed to print antenna and

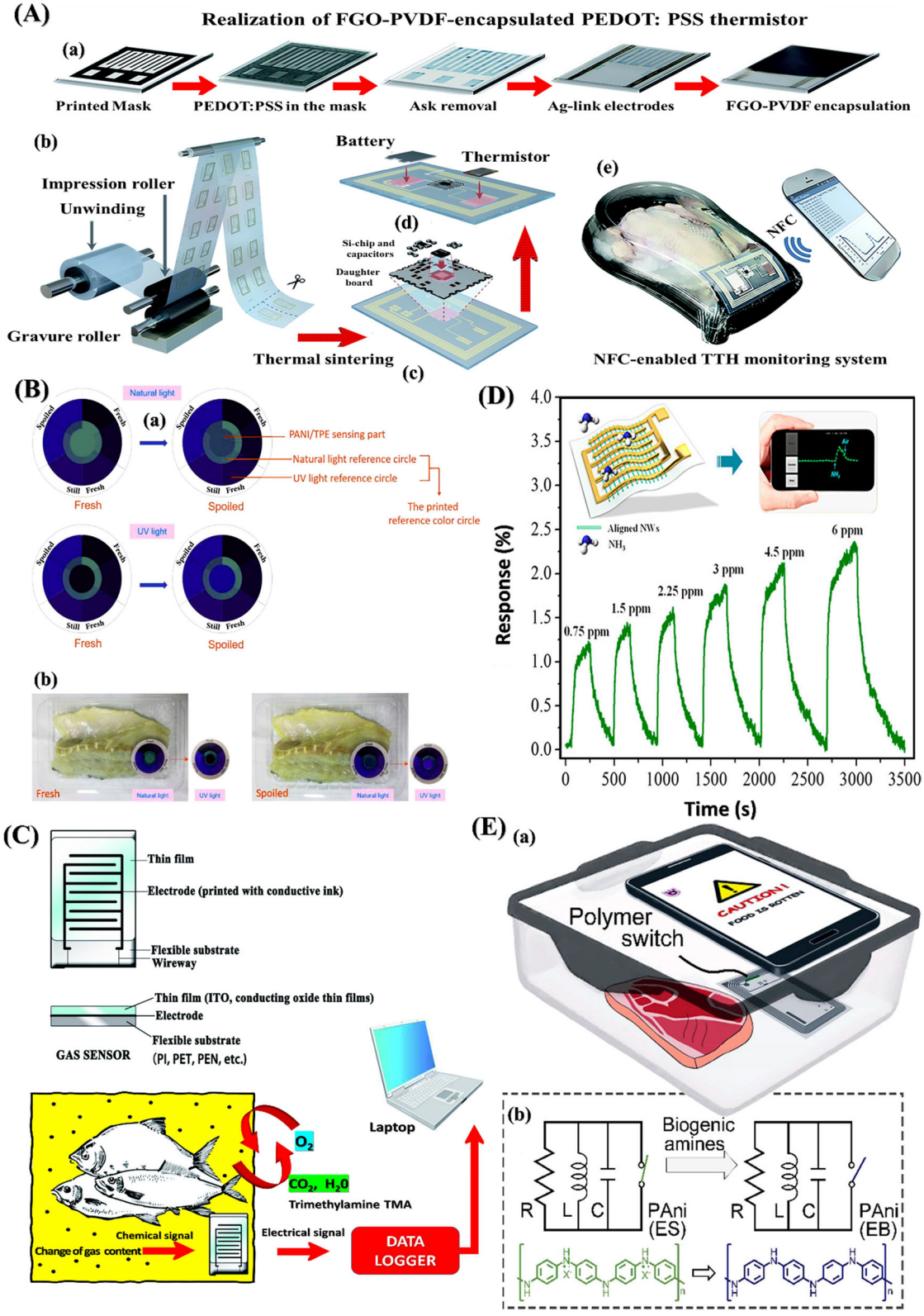


FIGURE 9 (A) Diagram depicting the implementation of a time–temperature history (TTH) monitoring system: (a) creation of the FGO–PVDF-encapsulated PEDOT:PSS thermistor via a straightforward printing method, (b) illustration of the R2R gravure printing apparatus, (c) integration of Si-chip components via a daughter board, (d) incorporation of a printed battery and thermistor into the printed circuit, and (e) idea of employing the NFC-enabled TTH monitoring system within a chicken package. Adopted from Maskey et al. (2020) Copyright RSC ©2020. (B) Smart packaging utilizing tetraphenylethylene-functionalized PAni: (a) a proposed indication process and (b) practical application of a PAni/TPE sensing label on a fish sample in packaging. Adopted from Liu et al. (2020) Copyright Elsevier ©2020. (C)

(Continues)

FIGURE 9 (Continued)
A representation of an intelligent food packaging system utilizing gas sensors. Adopted from Liao et al. (2019) Copyright RSC ©2019. (D) Real-time response of a bendable nanowire gas detector based on PEDOT:PSS, ZnO, GO, and $In(NO_3)_3$ to NH_3. Adopted from Tang et al. (2019) Copyright ACS ©2019. (E) Diagram demonstrating the wireless badge for detecting food decomposition: (a) utilization of PTS−PAni as a switch to alter an NFC tag for spoilage detection, and (b) modified circuitry of the NFC tag. Spoiled meat emits amine gas, which deactivates PTS−PAni, increasing device resistance and improving NFC tag readability. Adopted from Ma et al. (2018) Copyright ACS ©2018.

interconnect lines onto PET and polyimide (PI) rolls, respectively (Figure 9A(b)). Each antenna underwent thermal treatment before being assembled with a Si-chip transponder using a daughter board (Figure 9A(c)). Following this, the printed battery and FGO–PEDOT thermistor were integrated (Figure 9A(d)). The fully assembled tag was affixed to a chicken package to monitor temperature–time history (TTH). Data were retrieved via the NFC functionality of a smartphone and analyzed using a custom-developed android application (Figure 9A(e)). Excellent linearity, stability, and a resolution of 1272.57 U/°C were displayed by the thermistor. Encapsulation prevents water permeation, ensuring reliability. This cost-effective solution offers estimated label costs below $1, highlighting its potential for widespread implementation in temperature-sensitive industries.

Similarly, the investigation by Liu et al. (2020) focused on the development and application of a novel PAni/tetraphenylethylene (PAni/TPE) sensing label integrated into smart packaging for identifying the freshness of fish products. The PAni/TPE sensing label demonstrated a linear response to TVB-N concentrations within specific ranges, with ΔE values reflecting this relationship. Under room temperature conditions, the sensing label showed sensitivities within 25.2 mg/100 g (UV light) and 29.63 mg/100 g (natural light), as well as at chilled temperatures. The proposed indication process is illustrated in Figure 9B. The sensing label comprises a printed reference color circle on the outer section and a PAni/TPE sensing portion at the center. The reference color circle includes an area that transitions from black to bright blue under UV light, serving as the UV reference, and another area that shifts from emerald green to peacock blue under natural light, serving as the visible light reference. As the fish product spoils, the PAni/TPE sensing portion undergoes a corresponding color change. The fluorescent signal of the label transformed from black to bright blue under UV light, while visible color changes from emerald green to peacock blue indicated fish spoilage. The nanostructured morphology of the PAni–TPE sensing label, with wires approximately 100 nm in diameter, supported its effectiveness in detecting changes in freshness. Additionally, based on ΔE values taken from the detecting label images, producers and merchants might use the label to quantify TVB-N levels in fish items, allowing for a quantitative evaluation of fish freshness.

Moreover, the PPy/nanocellulose composite demonstrates exceptional performance as an intelligent food container (Bideau et al., 2017), as evidenced by various key values obtained from the study. The oxygen transmission amounts of the TOCN films, with a thickness of 31 mm, were 83.8 ± 0.6 cm^3/m^2/day at 85% relative humidity after 400 min, showing their excellent barrier properties. In comparison, the TOCN/PVA–PPy films exhibited even lower oxygen transmission rates at 16.5 cm^3/m^2/day, emphasizing the enhanced barrier efficiency of the composite. In addition, the antioxidant capacity of the compound was notable, with the PPy component showing 28% inhibition of antioxidants after 15 min, increasing to 63% inhibition after 1 h, and reaching a maximum inhibition of 68.8% after 5 days. These results underscore the aptitude of the composite to extend the shelf life of perishable foods by providing a protective atmosphere and shielding against external factors. Additionally, the water vapor transmission rates further support the composite's potential for IFP, with the TOCN films exhibiting a water vapor transmission rate of 276 g/m^2/day, the TOCN/PVA films showing a rate of 207.4 g/m^2/day, and the TOCN/PVA–PPy films demonstrating a significantly reduced rate of 18.1 g/m^2/day.

Similarly, Pirsa and Shamusi (2019) focused on the improvement and application of an active and smart packaging solution using a BC–PPy–ZnO film for freshly chopped chicken thigh meat. The BC–PPy–ZnO film exhibited varying antioxidant activities across different experimental runs, with values ranging from 3.54 to 68.60%. The electrical resistance characteristics of the films were characterized by initial resistance ($R0$) values between 480 and 710 kΩ, final resistance (R) values ranging from 19 to 410 kΩ, and percentage changes in resistance ($R - R0/R0$) ranging from −0.969 to −0.166. A mathematical model was developed to predict the electrical resistance change based on time and temperature, with coefficients indicating the relationship between these variables. These results underscore the potential of the BC–PPy–ZnO film as an effective and responsive packaging material for preserving food quality and prolonging shelf life.

Furthermore, the sensors developed using the PEDOT:PSS/AgNW composite film exhibited remarkable sensitivity in detecting ammonia (NH_3) concentrations below 500 parts per billion (ppb) (Li et al., 2017). Specifically, the detector with the PEDOT:PSS/AgNW composite film showed a response of 28% at 15 ppm NH_3, indicating high sensitivity to low concentrations. Compared with other vapors, such as methanol, chloroform, acetone, methylbenzene, and water, the sensor showed significantly smaller responses to these vapors even at high concentrations, highlighting its excellent selectivity. Additionally, the integration of the sensor with a portable data acquisition system allowed for the monitoring of pork freshness. The results revealed that pork samples stored in a refrigerator showed minimal changes in sensor response, while samples stored in ambient air exhibited alterations in resistance after 10 h, with noticeable color and odor changes starting after 30 h.

Intelligent food containers incorporate advanced technologies such as gas sensors to monitor and regulate the gas composition within the packaging, ensuring optimal conditions for food preservation (Liao et al., 2019). In diagnostic technologies, printed sensors are commonly employed as indicators to monitor and detect changes in the internal environment of food packaging. Flexible printed sensors for food monitoring are complex, integrated systems typically consisting of three main components: (1) conducting electrodes made from conductive ink, (2) flexible/stretchable substrates such as PI, PET, or PEN, and (3) sensing materials. Figure 9C illustrates a diagram of a flexible gas sensor within an smart food packaging system, where the sensing materials monitor the internal environment of the package. For example, in the packaging of red meat, it is recommended to have oxygen levels between 60 and 85%, carbon dioxide levels between 15 and 40%, and nitrogen levels adjusted accordingly. Similarly, for cooked meat and bacon, the ideal gas composition includes 20–35% CO_2 and 65–80% nitrogen. Poultry packaging should contain 25% CO_2 and 75% nitrogen, while lean fish packaging requires 40% oxygen and 30% CO_2. In the case of oily fish and salmon packaging, 60% CO_2 and 40% nitrogen, and 60% oxygen and 20% CO_2 should be detected, respectively. 3–5% oxygen, 3–5% CO_2, and 85–95% nitrogen should be found in fruit and vegetable packaging, and bread packaging should have 60–70% CO_2 and 30–40% nitrogen. Milk-free cake packaging should contain 60% CO_2 and 40% nitrogen. This real-time monitoring of gas levels allows for precise adjustments to the packaging environment, ensuring that the food remains fresh and safe for consumption.

Additionally, in the study by Tang et al. (2019), CP nanowires, specifically PEDOT:PSS, were employed to fabricate a flexible ammonia sensor for real-time monitoring of ammonia levels in food spoilage sensing, focusing on salmon spoilage. The nanowire sensor was fabricated using a capillary filling-based soft lithography technique. Due to its simple and mild fabrication conditions, this method offers a versatile nanofabrication approach with excellent compatibility across various materials and substrates. The detector exhibited a rapid response to varying concentrations of ammonia gas, with the resistance increasing immediately upon exposure. Its practical usage was simplified by the fact that its response was linearly dependent on the ammonia concentration in the range of 0.75−6 ppm. The calculated response slope was 0.2524 ppm^{-1} with a fitting quality of $r^2 = 0.9834$ (Figure 9D), and the theoretical detection limit for ammonia was approximately 100 ppb (Tang et al., 2019).

The good repeatability, stability, selectivity for ammonia over other volatile organic compounds, high sensitivity, low detection limit, and good mechanical durability of the sensor, ascribed to the CP nanowires, make it a promising tool for intelligent food spoilage monitoring and real-time sensing applications. Good repeatability was indicated by the flexible nanowire sensor's stable dynamic responses to the same NH_3 concentration. Ten distinct devices' worth of statistics revealed distributions of sensitivity and responsivity at a modest concentration of 0.75 ppm. About 60% of the sensors revealed a sensitivity of more than 0.2 ppm^{-1}, guaranteeing consistent performance across devices, while 90% of the samples showed a responsivity of more than 0.8 at 0.75 ppm NH_3, indicating strong repeatability. Given its low cost, ease of implementation, and minimal power consumption, the smartphone-enabled NH_3 detection system, based on the flexible nanowire sensor, holds significant potential for advancing NH_3 monitoring in daily applications and enabling intelligent food detection throughout storage and supply chains.

Moreover, the study of Ma et al. (2018) introduces a novel approach to food spoilage detection by developing a nanostructured CP-based gas sensor with great sensitivity toward specific gases associated with meat decomposition. In applications for detecting food spoilage, a key challenge remains the development of a sensor with sufficient sensitivity to function as a switch for a NFC tag. An easy-to-implement, sensitive wireless food sensor based on nanostructured conductive polymers for low-cost, convenient detection of food spoilage was developed, offering several key advantages (Figure 9E). The sensor demonstrated outstanding sensitivity, with a $\Delta R/R0$ value of 225% toward 5 ppm ammonia (NH_3), 46% sensitivity toward putrescine, and 17% sensitivity toward cadaverine. This high sensitivity allows the sensor to effectively differentiate between different gases, which is crucial for detecting various stages of food spoilage. By integrating this sensor into an NFC tag, the complex impedance of the tag

is influenced by the resistance of the conductive polymer gas sensor, enabling a switchable mechanism. This integration enables smartphones to read out meat spoilage when biogenic amine concentrations exceed a preset threshold. In addition, the sensing material is compatible with inkjet printing technology, offering potential for roll-to-roll fabrication of active NFC tags. This innovative combination of sensor and NFC technology offers a cost-effective, convenient, and efficient method for monitoring food status in daily life, storage, and supply chains.

4 | PRACTICAL APPLICATIONS AND COMPARATIVE ANALYSIS

4.1 | Real-world applications

CPs have demonstrated a broad range of successful applications in food packaging, significantly improving food safety, monitoring freshness, and extending shelf life. In particular, PAni-based films have been used to monitor pH levels in fish, changing color as spoilage occurs due to microbial growth. This technology has reduced food waste by up to 30% in controlled studies (Mohammadian et al., 2020). Similarly, PPy has been integrated into packaging for meat products, where it has led to a 99.99% reduction in the growth of bacteria like *E. coli* and *L. monocytogenes*, effectively extending the shelf life of fresh meat from 3 to 14 days (Khan et al., 2024). In addition, smart packaging systems employing CPs have proven highly effective at monitoring food freshness. For example, PPy-based colorimetric sensors detect spoilage gases such as ammonia, with a detection limit as low as 0.1 ppm, ensuring early detection of spoilage (Zegebreal et al., 2023). Smart labels, designed to change color with temperature fluctuations, have successfully reduced spoilage rates by 50% for temperature-sensitive products such as dairy and seafood (Mohammadian et al., 2020).

Active packaging systems incorporating CPs have also shown promise in preserving the quality of fruits and vegetables. By absorbing ethylene gas, which accelerates ripening, these systems have achieved a 60% reduction in ethylene levels, extending the freshness of produce by an additional 5 to 7 days during storage and transport. This advancement is particularly beneficial for long-distance shipping, helping to maintain product quality throughout the supply chain (Khan et al., 2024). Another critical application of CPs is in improving the barrier properties of packaging materials. For example, polyethylene films enhanced with CPs have demonstrated a 50% reduction in oxygen permeability, which is essential for preventing oxidation in packaged foods. Moreover, CPs can reduce water vapor transmission rates by up to 70% (Mustafa & Andreescu, 2020), ensuring that moisture-sensitive food products retain their quality during extended storage periods.

The adaptability of CPs has allowed for the creation of lightweight, flexible packaging solutions. These materials can conform to various shapes, reducing material usage by approximately 20%, which translates to cost savings for manufacturers. Additionally, their integration with RFID technology enables real-time tracking of food products throughout the supply chain, improving traceability and reducing waste by around 20% due to enhanced inventory management (Nami et al., 2024). Moreover, advances in gas sensors made from CPs have improved real-time freshness monitoring in packaged foods. For instance, sensors detecting trimethylamine (TMA), a marker for seafood spoilage, have demonstrated a high response level of 413 toward 200 ppm of TMA. Similarly, sensors for TVB-N, another spoilage indicator, have achieved detection limits as low as 2×10^{-9} mol/dm^3, offering precise monitoring for high-protein foods like pork and shrimp (Andre et al., 2022). The potential of biodegradable CPs is also gaining momentum in sustainable food packaging. These materials can decompose within 6 months under industrial composting conditions (Zegebreal et al., 2023), while still retaining the mechanical strength necessary for effective food preservation. This approach addresses both food safety and environmental concerns, presenting a promising eco-friendly alternative to conventional plastics.

However, despite the many advantages of CPs in food packaging, there are several challenges that must be addressed to maximize their efficacy in real-world settings. One significant issue is the long-term stability of CP sensors under fluctuating environmental conditions, such as changes in temperature and humidity. Studies have shown that these conditions can lead to a 30% degradation in sensor performance, limiting their reliability over extended periods of use (García, 2024). The sensitivity of CP sensors in complex food matrices also presents a challenge. While polymeric field-effect transistor (FET)-based sensors have demonstrated high sensitivity, detecting volatile amines down to 10 ppb, in real-world applications, the detection limit for contaminants may exceed 1 μg/mL, reducing the sensors' ability to detect early spoilage (Kwon et al., 2018). In addition, the durability of these sensors is a concern, as exposure to moisture and temperature fluctuations can shorten their lifespan by as much as 50%, making them less effective over time (X. Liu et al., 2022). Another challenge lies in the response time of these sensors. In some cases, the time required to detect spoilage gases or contaminants exceeds 5 min, which may not be quick enough for highly perishable products (García, 2024). Addressing these issues, particularly in terms of improving the long-term durability and stability of CPs in food packaging,

will be crucial to their broader adoption and commercial success.

4.2 | Comparison with existing traditional food packaging

CPs are rapidly emerging as a game-changing alternative to conventional materials in food packaging, offering a host of advantages across key performance areas. One of their standout features is their exceptional barrier properties. CPs boast oxygen permeability rates as low as 0.1 cm^3/m^2 day atm (M. Zhang et al., 2022), far superior to traditional plastics like polyethylene, which typically range between 5 and 20 cm^3/m^2 day atm (Youssef & El-Sayed, 2018). This remarkable reduction in oxygen transmission is crucial for maintaining the freshness of perishable goods, potentially extending shelf life by up to 30%. In addition, CPs excel in moisture control, with water vapor transmission rates (WVTR) reaching as low as 0.1 g/m^2/day, surpassing most conventional materials (Sharma et al., 2021). While some alternatives, like ethylene vinyl alcohol, can achieve slightly better oxygen permeability values at around 0.05 cm^3/m^2.day, traditional plastics like low-density polyethylene fall well behind with rates nearing 100 cm^3/m^2 day (Youssef & El-Sayed, 2018).

In terms of mechanical properties, CPs demonstrate remarkable improvements over their traditional counterparts. With TSs of up to 100 MPa, they are significantly stronger than conventional materials such as polyethylene, which generally offers TSs between 30 and 50 MPa (Agarwal et al., 2023). Furthermore, their flexibility is outstanding, with EAB values exceeding 200%, making them ideal for applications that require both durability and adaptability, such as flexible electronics packaging. This contrasts sharply with materials like metals and glass, which although strong, are brittle and prone to breaking during transport. The enhanced mechanical performance of CPs is often attributed to the inclusion of nanomaterials like graphene, though this can sometimes lead to variability in performance across different formulations.

Beyond their barrier and mechanical superiority, CPs also hold considerable promise in terms of environmental sustainability, although challenges remain. When biodegradable additives are incorporated, CPs can reduce the carbon footprint by up to 30% compared with traditional plastics (Lambert & Wagner, 2017). Certain formulations are even biodegradable, addressing growing concerns over long-term waste disposal. However, the production of these polymers can involve toxic chemicals, presenting a challenge that needs to be addressed. Traditional plastics, particularly nonbiodegradable ones, significantly contribute to environmental degradation, with plastic waste taking hundreds of years to decompose. Each year, millions of tons of plastic waste are generated, highlighting the urgent need for more sustainable solutions. While biopolymers like ST or cellulose are more eco-friendly, they often lack the durability and mechanical strength of CPs (Barra et al., 2019).

Perhaps one of the most exciting aspects of CPs is their ability to integrate sensors and exhibit electrical conductivity. Polymers like PAni and PPy have conductivity values ranging from 10^{-2} to 10^{2} S/cm, a sharp contrast to the nearly nonconductive nature of traditional packaging materials like polyethylene, which only measures around 10^{-12} S/cm (Bubniene et al., 2022). This makes CPs highly suitable for smart packaging systems that incorporate sensors to monitor spoilage-related gases such as ethylene and ammonia, with detection sensitivities as low as 0.1 ppm (Jafarzadeh et al., 2024). These advanced packaging solutions could reduce food waste by as much as 30% by improving real-time monitoring of food quality. The lightweight and flexible nature of CPs further enhances their appeal, potentially lowering shipping costs by up to 20%, a significant advantage in food distribution logistics. Additionally, studies indicate a 50% improvement in food shelf life due to enhanced moisture and temperature control (Sikkandhar et al., 2023), demonstrating the material's ability to manage packaging conditions effectively.

In conclusion, CPs represent a transformative advancement in food packaging technology, offering superior barrier properties, enhanced mechanical strength, and the potential for smart sensor integration. These materials not only excel in preserving the freshness of perishable goods but also facilitate real-time monitoring of food quality. However, challenges such as variability in mechanical performance and environmental concerns related to production still need to be addressed. While traditional materials provide reliable performance in many areas, they fall short in sustainability and advanced functionalities, both of which are increasingly vital in modern packaging solutions. With ongoing research and refinement, CPs have the potential to become the material of choice for packaging, balancing both environmental responsibility and functional innovation. Their versatility makes them a promising candidate for diverse applications beyond food packaging, opening new avenues for technological advancements.

4.3 | Economic and toxicological aspects

CPs embody a double-edged sword in the realm of food packaging, presenting both tantalizing prospects and formidable hurdles related to economic viability, scalability, and safety. Economically, the production costs of CPs

range from $5 to $20 per kilogram, starkly contrasting with conventional plastics, which hover around $1 to $3 per kilogram (Cheng et al., 2024). This financial burden stems from the use of expensive raw materials and intricate synthesis processes. For instance, the cost of conductive inks, such as silver-based varieties, can soar to over $100 per gram. While alternatives like copper and aluminum are under investigation to mitigate expenses, they encounter critical challenges, most notably oxidation, which jeopardizes their conductive properties. Research reveals that a conductive ink can achieve an impressive sheet resistivity of 22.6 Ω/sq and a conductivity of 6459 S/m, underscoring the potential for transformative applications in IFP (Liao et al., 2019). Additionally, CPs can significantly reduce packaging weight by up to 30% by supplanting multiple layers of traditional materials, thereby driving down material and transportation costs. Yet, scalability remains a daunting issue. Although printed electronics hold promise for large-scale production, ensuring uniform quality across batches presents a substantial obstacle. Innovative processing techniques are vital; optimizing production efficiencies could reduce costs by an estimated 20–30% (Cheng et al., 2024).

Despite these economic advantages, the LCA of CPs unveils a complex environmental narrative. Depending on the allocation method employed, global warming potential can vary dramatically, ranging from 1.25 to 41.52 kg CO_2 eq/kg of biopolymer (Amponsah et al., 2024). System expansion scenarios further amplify these impacts, emphasizing the necessity of a holistic view of environmental footprints. Notably, a shift to green energy in production could slash global warming impacts by 67%, yet this transition risks exacerbating terrestrial acidification and human toxicity by 2 to 9 times, illuminating the intricate trade-offs involved in scaling up CP production (Hanssen et al., 2020). The safety of CPs in food packaging raises critical toxicological concerns that demand thorough scrutiny. For example, PAni can degrade in acidic environments common to many food products, leaching aniline into food simulants at concentrations ranging from 0.1 to 0.5 mg/kg (Alfei et al., 2020). Classified as a potential human carcinogen by the International Agency for Research on Cancer, aniline exposure links to severe health repercussions, including methemoglobinemia and reproductive toxicity. Alarmingly, leaching rates from CPs can reach up to 15%, intensifying concerns about their carcinogenic potential (Omerović et al., 2021).

Moreover, the degradation of CPs poses additional risks. PAni exposed to UV light for just 30 days showed a 40% reduction in molecular weight, resulting in the release of cytotoxic degradation products detrimental to human cell viability. Environmental pollution compounds these issues, with studies detecting PPy nanoparticles in sediment samples, raising alarms about bioaccumulation in aquatic organisms and the potential for entry into the food chain (Silvestre et al., 2011). Many CPs exhibit non-biodegradable characteristics, with decomposition times in landfills extending from 100 to 500 years, leading to substantial environmental ramifications. In light of these hazards, the European Food Safety Authority (EFSA) has underscored the urgent need for comprehensive risk assessments regarding the application of CPs in food contact materials (Zhou et al., 2024). Current data remains inadequate for a thorough safety evaluation, necessitating rigorous testing and regulatory oversight to address potential health and environmental risks. In conclusion, while CPs hold promise for revolutionizing IFP, their economic feasibility and safety profile require continued research and innovation. Balancing the advantages of CPs with the imperative of consumer safety and environmental sustainability remains crucial for their successful commercialization. Addressing these challenges head-on will be essential to unlock the full potential of CPs in a responsible manner.

5 | CONCLUSION

The food and beverage industry stands to benefit greatly from smart food packaging, which meets consumer demands for convenient packaging that guarantees product quality, safety, and longer shelf life. While synthetic plastic materials remain at the forefront of industrial growth due to their affordability, usefulness, lightweight nature, and adaptability, the increasing need for environmental sustainability has sparked significant interest in alternatives. CPs, with their enhanced mechanical, thermal, and gas barrier properties, offer promising substitutes. By integrating responsive elements and nanomaterials, such polymers offer advanced functionalities such as real-time monitoring and improved antimicrobial efficacy, making the ideal for next-generation food packaging. This review highlights how the development and application of smart CPs in food packaging can provide the food industry with novel solutions to long-standing challenges. CPs, particularly those with antibacterial and antioxidant properties, offer the potential to extend shelf life and maintain food safety, crucial for reducing waste and enhancing sustainability in food distribution. Moreover, intelligent packaging, enabled by these materials, can actively monitor food quality, alerting consumers or retailers when spoilage occurs, thus ensuring better food safety and quality control. The use of biodegradable and environmentally friendly CPs also aligns with industry trends toward sustainability and regulatory compliance. Despite the remarkable advantages of these materials, there remain concerns about their potential side effects and the risks posed by

modifying traditional food containers. As such, a gap persists between the ideal food packaging systems and current solutions. Continued interdisciplinary research is necessary to optimize these materials for commercial application, focusing on overcoming challenges related to scalability, cost, and regulatory hurdles, while ensuring that safety and efficacy are maintained.

AUTHOR CONTRIBUTIONS

Abdelqader El Guerraf: Conceptualization; methodology; validation; writing—original draft; writing—review and editing; visualization; supervision. **Imane Ziani**: Investigation; writing—review and editing; visualization; writing—original draft. **Sana Ben Jadi**: Investigation; writing—review and editing. **Ali El Bachiri**: Visualization; writing—review and editing. **Mohammed Bazzaoui**: Supervision; writing—review and editing. **El Arbi Bazzaoui**: Conceptualization; methodology; supervision. **Farooq Sher**: Funding acquisition; supervision; writing—review and editing.

ACKNOWLEDGMENTS

The authors are also thankful for the financial support from the International Society of Engineering Science and Technology (ISEST), UK.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: El Guerraf, A., Ziani, I., Ben Jadi, S., El Bachiri, A., Bazzaoui, M., Bazzaoui, E. A., & Sher, F. (2024). Smart conducting polymer innovations for sustainable and safe food packaging technologies. *Comprehensive Reviews in Food Science and Food Safety*, *23*, e70045. https://doi.org/10.1111/1541-4337.70045