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Review

Conducting polymers in industry: A comprehensive review on the characterization, synthesis and application

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ABSTRACT

In recent decades, conducting polymers (CPs) like polyaniline and polypyrrole have attracted the attentions of scientists all over the world due to having important advantages such as simplicity of synthesis, excellent chemical/mechanical stability and good optical properties. Despite the existence of different shortcomings in the pristine form of CPs, hybridization with other substances can be a great solution to decrease these limitations. The synergetic influences of CPs with composites can make them a promising option for industrial-based applications in electronics, medical, biomedical and optoelectronic fields. This paper aims to present a comprehensive review for expert and non-expert readers to be acquainted with the recent advancements in the field of perception, characterization and synthesis of different types of CPs in industries. Additionally, this paper overviews the application of commonly-applied CPs in industrial activities and present the advantages/disadvantages of each of them to provide an opportunity for readers to know the efficiency and feasibility of using each CP based on their conductivity and other related parameters.

1. Introduction

Polymers are known as giant molecules of high molecular weight created from numerous repeated subunits called monomers [1]. Before the origination of conducting polymers (CPs), polymers were contemplated to be electrical insulators. Invention of conducting polymers have revolutionized the attitudes of scientists due to their noteworthy electrical characteristics [2]. CPs are identified as an important classification of organic materials with great electrical/optical features, the same as inorganic semiconductors and metals. This group of organic materials possesses the ability of synthesis applying various approaches such as electro-polymerization [3]. CPs have demonstrated their indisputable positive characteristics as efficient matrices of biomolecules and have been of great interest of application among scientists in disparate industries such as membrane-based separation, biomedicine, nanotechnology, catalysis, electrochemistry, environmental remediation, electronics and so on [4–9]. It is important to note that the most important difference between CPs and non-CPs is the ability of CPs to

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conduct electricity compared to non-CPs. It means that non-CPs belong to a specific class of polymeric materials that are electrically insulating [10,11]. Another parameter, which distinguishes CPs from non-CPs is this reality that the CPs possesses great capability to induce the oxidation of metal surface to create its metal oxide and preserve the metal in its noble form [12]. It is important to note that extensive application of CPs compared to non-CPs is due to the existence of some brilliant characteristics such as cost-effectiveness, tunable electrical property, high physical/chemical stability, ease of synthesis and versatility. Additionally, CPs are existed in disparate morphologies such as sheets, particles and rod-like structure, which facilitates their application in different industrial activities [13,14]. Despite various advantages, the presence of some shortcomings like poor solubility in all commonly-employed organic solvents and non-degradability must be taken into account by the researchers [15,16].

Fig. 1 schematically illustrates disparate applications of CPs and their composites. In recent decades, various methodological approaches have been developed to improve the CPs with the aim of their integration with biomedical utilizations (i.e., biomaterial, bioengineering and regenerative drug). Not only CPs' biocompatibility, but also its indisputable capability to improve cellular activities (i.e., cell adhesion, migration, proliferation) with or without electrical stimulations can provoke the motivation of investigators all over the world to involve CPs in pharmaceutics, tissue engineering and medicine [17–19]. The existence of noteworthy characteristics such as soft interface, CPs have replaced conventional electrodes manufactured from various types of conductors/semiconductors like platinum and gold [20]. Investigations on the effects of CPs on disparate organs of body such as bones, muscle and nerves have been currently an interesting field of study due to their sensitive characteristics with electrical stimulation.

It is important to note that the most important difference between CPs and non-CPs is the ability of CPs to conduct electricity compared to non-CPs. It means that non-CPs belong to a specific class of polymeric materials that are electrically insulating [10,11]. Another parameter, which distinguishes CPs from non-CPs is this reality that the CPs possesses great capability to induce the oxidation of metal surface to create its metal oxide and preserve the metal in its noble form [12].

Polyacetylene (PA), polyaniline (PANI), polypyrrole (PPy), polythiophene (PT), poly (3,4-ethylenedioxythiophene) (PEDOT) and polyazulene (PZ) are considered as the most commonly-applied CPs in industrial activities [21–24]. Table 1 comprehensively presents the most commonly applied CPs, their advantages and applications in various industrial-based activities. Disparate types of CPs possess capability of interaction with biological samples while maintaining their biocompatibility. Therefore, this group of polymers must be considered as a possible candidate for use in various biological and medical applications [25,26].

Despite the existence of noteworthy advancements towards perception, synthesis and manufacturing of CPs, a big number of restrictions and challenges still exist. For instance, some polymers don't have sufficient chemical/thermal/mechanical stability and are vulnerable to some environments. Some factors such as viscosity and surface tension are known as momentous parameters in CPs, which can significantly affect their and processability and stability particularly those polymers applied in drug delivery [50–53]. In current decades, application of nanotechnology to fabricate disparate types of nanomaterials for environmentally-friendly industrial-based purposes has been of paramount attention [54–57]. Due to having brilliant physicochemical properties, the use of nanomaterials in different scientific fields is growing significantly, specifically in bioremediation and engineering [58–62].

Up to the knowledge of the authors, very few papers have systematically reviewed the features, properties and synthesis process of different types of CPs in industries. The main objective of this paper is to comprehensively overview the recent progressions in perception, characterization and synthesis process of different types of CPs in industries.

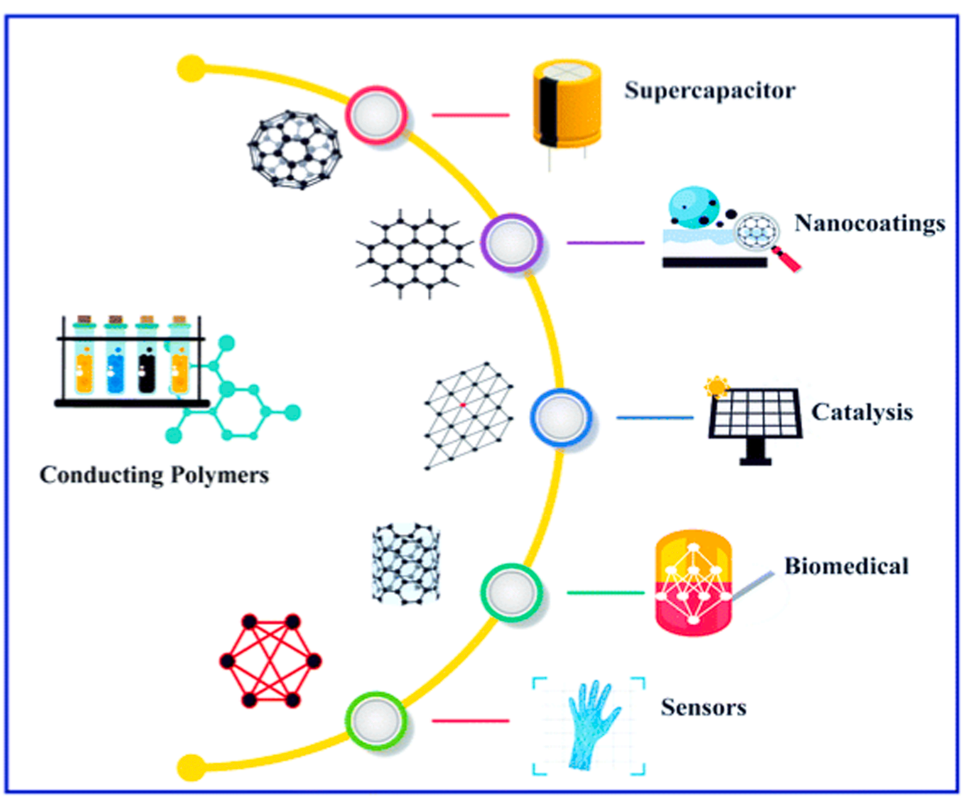

Fig. 1. Schematic demonstration of disparate applications of CPs and their composites in industry. Reprinted from [6] with permission from the Royal Society of Chemistry.

Table 1
Comprehensive data on the advantages and applications of common CPs in industry.

CP type	Advantages	Applications	Ref.
PPy	• High conductivity • Great redox properties • Water solubility • Stabilized oxidized form	• Drug delivery • Bioactuators • Anti-oxidants • Biosensors	[27–31]
PT	• Excellent electrical conductivity • Good optical property	• Biosensors • Food industry • Lithium-sulfur batteries • Antistatic coating	[32–35]
PANI	• Simplicity of preparation • Light weight • Good flexibility • Excellent electrical conductivity	• Cardiovascular application • Biosensors • Oil industry • Antioxidants • Drug delivery • Food industry	[36–40]
PEDOT	• High temperature stability • Good transparency • Proper conductivity	• Microbial fuel cell • Biosensors • Lithium-ion batteries • Drug delivery • Biomedicine • Nanofiber electrode	[41–44]
PA	• High conductivity • Simplicity of synthesis • Good processibility	• Optoelectronics • Gas transport • Cancer treatment • Electronics	[45–49]

Moreover, discussion about the application of commonly-applied CPs in industrial-based activities following with presenting their advantages/ disadvantages is another purpose of this investigation. The authors of this manuscript have made an effort to provide an opportunity for readers to know the efficiency and feasibility of using each CP based on their conductivity and other related parameters.

2. Commonly applied CPs in industrial activities

PA is known as the pioneer of CPs, which was accidentally created by Shirakawa in the 70's decade. This CP was the first polymer that possesses the ability of conducting electricity [63,64]. Generally, PA is an organic polymer, which is formed by the repeating unit $(C_2H_2)n$. Invention of PA as a conductive polymeric material has eventuated in the emergence of significant acceleration towards conducting investigations for the discovery of novel CPs. Excellent electrical conductivity of PA has encouraged the motivation of researchers for the application of organic components in microelectronics [4,48,65,66]. PT is the second leading CP, which has been recently of great interest to fabricate environmentally-friendly and thermally stable substances applied in various apparatuses such as electrical super-capacitor, non-linear optics, antistatic coatings, batteries, solar cells, memory devices and so on [39, 67–70]. The third commonly applied CP is PANI, which belongs to the family of semi-flexible rod polymer. PANI is an old CP invented in the nineteenth century by Letheby who investigated the electrochemical / chemical oxidation products of aniline in acidic media [71]. Among the abovementioned CPs, PANI is of greater global interest due to its noteworthy characteristics including light weight and great thermal stability [37,72–75]. PPy is an important sort of CPs, which is often formed by means of pyrrole polymerization. This CP has illustrated its conductivity in 1968. Among many types of CPs, PPy has allocated a great percentage of investigation due to its simplicity of preparation, great redox characteristics, water solubility and considerable electrical and optical properties [29–31,76–78]. Despite the lack of appropriate characterization, PPy are identified as the polymers of pyrrole where the bonding is generally by α, α' carbons [28,30,79–81]. PEDOT is another CP, which is formed on the basis of 3,4-ethylene dioxyl thiophene monomer. This CP possesses numerous positive points such as optical transparency in oxidized films, good stability and insignificant redox potential. Polymer/glass coating, high conductive shell, nano-fiber electrodes, solar cells and so on [23,44,82]. Polyparaphenylene (PPP) is identified as an important class of CP made of repeating p-phenylene units. Application of an oxidant or a dopant leads to the conversion of this polymer to its conducting form [83–86]. With the aim of increasing its conductivity compared to PA, PPP was doped in 1980 [87]. Ballard et al. applied the derivation process of cis-dihydrocatechol attained from bacterial fermentation to synthesize PPP [88].

3. Synthesis approaches of CPs

The synthesis process of CPs can be implemented by disparate approaches such as chemical synthesis, electrochemical synthesis, photochemical synthesis, metathesis approach, concentrated emulsion method (CEM), inclusion method (IM), solid state polymerization (SEP), plasma polymerization (PP) and Pyrolysis method [26,63,89]. The chemical synthesis of CPs occurs within the oxidation / reduction of monomers following with their polymerization. The prominent advantage of chemical synthesis process is the provision of a good opportunity for mass production at a logical price [90,91]. Many investigations have been implemented to enhance the efficiency of products achieved by oxidative polymerization approach [92–95]. For instance, poly (3-hexylthiophene) is the most commonly investigated CP that is produced chemically. Additionally, PPy and PANI can be chemically manufactured. Apart from conjugation, stability is the most important parameter required during chemical polymerization [63]. A good chemical polymerization requires sufficient reactivity and solubility of oligomers and low molecular weight polymers. The electrochemical synthesis process of CPs takes place via two mechanisms including anodic oxidation of suitable electroactive functional monomers or cathodic reduction [20, 96]. This process has attracted the attentions of many researchers due to having several advantages such as ease of operation, affordability and its brilliant proficiency in a single section glass cell. It is important to note that the potential of monomer oxidation intended to polymerization is significantly more than the oligomeric charging intermediates polymer [63,97]. Fig. 2 schematically demonstrates the electrochemical synthesis of PDA/PPY conductive polymer films applying pyrrole and dopamine on electrodes.

Photochemical method is known as another synthesis process of CPs, which despite noteworthy disadvantages, possesses limited advantages such as cost-effectiveness and low detriment for environment. Moreover, this approach is of great efficiency for the manufacturing of some CPs [20]. For instance, the polymerization process of pyrrole to poly pyrrole can be effectively occurred via irradiation through visible light either as the photosensitizer or an appropriate electron acceptor [99, 100]. This technique has been currently of paramount attention in biomedicine / biotechnology to obtain the binding of RNA molecules to H-terminated a-C/UNCD surfaces [101,102]. This approach includes three steps 1) Photochemical adhesion of amine groups, 2) Reaction of amine groups with a bifunctional cross-linking agent and 3) Adhesion of RNA molecule [2]. Metathesis technique is identified as another approach for the synthesis of CPs. During this process, the occurrence of chemical reaction between two components eventuates in swapping one part of each component to form two disparate components [103,104]. This technique can be divided into three prominent classifications including 1) Ring-opening metathesis of cyclo-olefins, 2) Alkynes metathesis and 3) Diolefins metathesis [105]. CEM is another commonly applied and efficacious procedure for the synthesis of CPs. This hetrophase technique is classified into three parts including the water compartment, the latex particle compartment, and the monomer droplet compartment. Radical polymerization is the initial mechanism in CEM. This technique generally consists of a micelle-forming surfactant, which is defined as a water-soluble initiator inside a water-insoluble monomer. [106,107]. IM is another promising method for the synthesis of CPs, which has great ability to produce composite substances at the atomic or

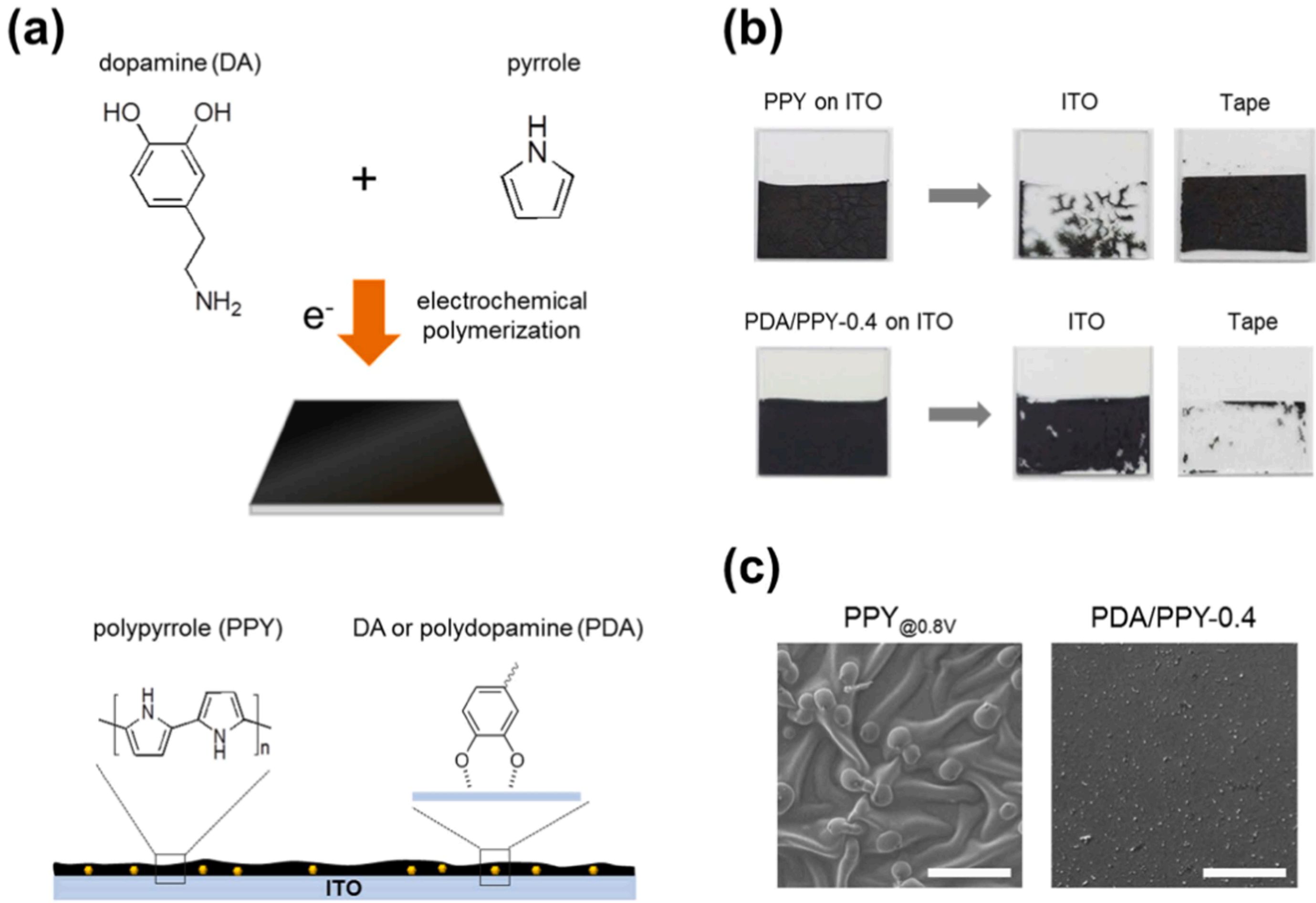

Fig. 2. Demonstration of PDA/PPY conducting polymer film using pyrrole and dopamine on electrode. a) Schematic depiction of PDA/PPY deposition b) Photographs of the PPY- or PDA/PPY-coated ITO electrodes before and after the Scotch tape detachment test. c) SEM of PPY and PDA/PPY. Reprinted from [98].

molecular scale. This kind of polymerization approach possesses significant potential to pave the path to manufacture unique low-dimensionality composite materials with numerous advantages. As an example, application of the IM can lead to the manufacturing of an electroconductive polymer via a molecular wire [108–110]. In an investigation, Miyata et al. corroborated that IM is of great interest as a prevalent space-dependent polymerization and must be obviously regarded from the attitude of stereoregular polymerization [111]. SEP is known as another technique for CP synthesis, which is on the basis of polymer chain lengths enlargement using heat in the non-existence of oxygen and water. This process can be implemented applying either vacuum or inert-gas removal to separate the by-products of reactions

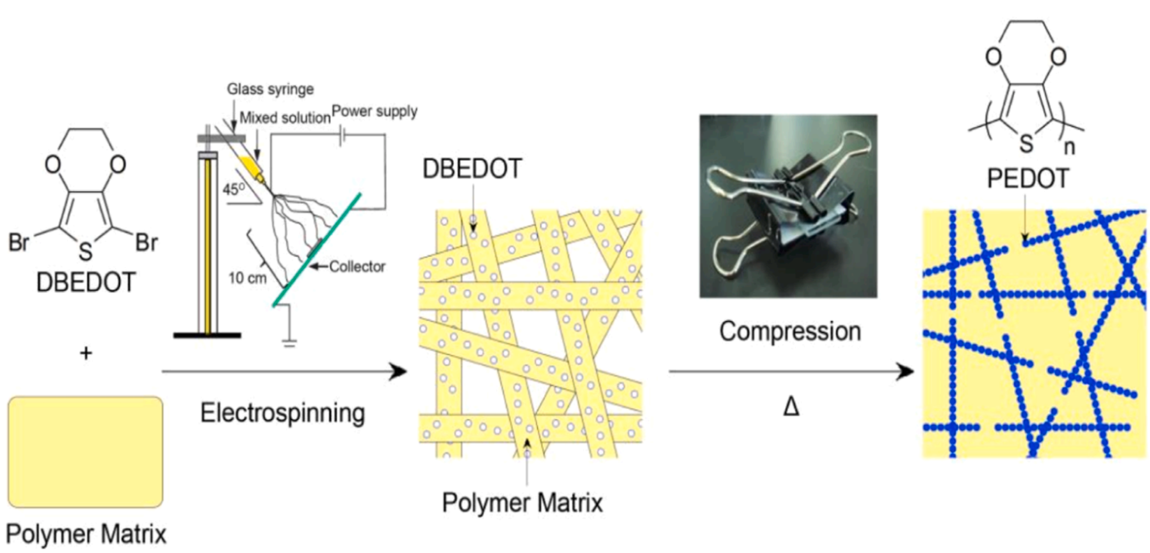

Fig. 3. Schematic demonstration of electrospinning and SEP process to synthesize PEDOT composite films. Reprinted from [117] with permission from Elsevier.

[112–114]. Temperature, pressure, and the by-products diffusion from the pellet core to the shell can be identified as the controlling parameters of the SEP process. This process is usually applied after melt-polymerization to increase the polymers mechanical behavior before injection blow molding [115,116]. The SEP process is significantly beneficial in industrial-based manufacturing of PET-based products, films, and polymeric fibers. The prominent privileges of the SEP process are the possibility of using simple and inexpensive apparatus accompanying with the prevention of some operational challenges appeared in traditional polymerization approaches [117,118]. Fig. 3 presents a schematic illustration of electrospinning and SEP process to synthesize PEDOT composite films.

PP is a modern synthesis approach to produce thin films from some organic-/organometallic-based substances. Plasma polymerized films (PPFs) are of high cross-linking and lack of pinhole. Therefore, they possess brilliant advantage such as thermal stability and mechanical strength [119–123]. Moreover, PPFs are significantly coherent and adherent to a series of substrates including conventional polymer, glass and metal surfaces. Due to this outstanding ability, PPFs have been recently of great attention for an extensive areas of applications like selective membranes, biomedical materials, electronic and so on [124–127]. Pyrolysis technique is defined as the chemical deterioration of organic materials using heating process. This synthesis approach can have great potential of application for detecting organic polymeric materials in rubber production and dentistry. Pyrolysis technique allows the direct investigation of small sample quantity without the importance of prolonged sample preparation [63,128]. Table 2 aims to present information about the synthesis techniques, chemical structure and conductivity amounts of commonly-applied CPs.

4. Important properties of CPs

4.1. Electrical-conducting properties

As demonstrated in Fig. 5, CPs not only illustrate conduction properties, but also possess some unusual electronic, magnetic, optical, mechanical, and wetting features. It is worth mentioning that after doping, the electrical conductivity of CPs is able to attain the metallic conducting regime [144]. In an investigation, Martin proved that the electrical conductivity amount of an individual nanofiber is much bigger than that of in pellet nanotubes or nanowires [145]. Overall, the incorporation of an insulating compound with one dimensional CP nanomaterials significantly reduces the amount of electrical conductivity due to the partial blockage of conductive pathway by the insulating compound [144]. In recent years, it has been understood that the incorporation of a high electrical-conductivity nanocomponent into CP can eventuate in increasing the conductivity of nanocomposites. Long et al. evaluated the electrical conductivities of CNT= PANI composite nanocables. They concluded that increment in the CNT loading considerably improves the conductivity of pure PANI, due to the role of CNT as a conducting bridge between conducting domains [146,147]. Additionally, decrement of temperature can lead to decreasing the conductivity of well-aligned CNT=PANI nanocomposites, which implies an identical semiconductor behavior [148]. Inclusion of metal nanoparticles into CPs is another promising procedure to increase the electrical conductivity of CPs [149].

Table 2
Comprehensive information of synthesis approaches and conductivity amounts of commonly-applied CPs.

CP type	Synthesis approach	Conductivity (s/cm)	Ref.
PA	Chemical polymerization	10,000	[129,130]
PANI	Chemical / Electrochemical polymerization	200	[131–134]
PPy	Chemical / Electrochemical polymerization	500-7500	[135–137]
PT	Chemical polymerization	1000	[138–140]
PZ	Chemical / Electrochemical polymerization	1	[141,142]
PEDOT	Emulsion / Chemical polymerization	0.4-400	[19,143]

4.2. Magnetic properties

Study on the magnetic properties of CPs has been recently an attractive scientific scope among researchers due to their noteworthy capability to provide momentous data on charge-carrying species and unpaired spins [48,150–152]. In an experimental study, Lu et al. evaluated the magnetic characteristics of PANI=Fe_3O_4 composite nanotubes, which were chemically synthesized via an ultrasonic irradiation approach. The conductivity and magnetic properties of the PANI=Fe_3O_4 composite nanotubes demonstrated that this manufactured sample possesses excellent conductivity and a superparamagnetic behavior [153]. In another research, Long et al. investigated the magnetic characteristics of PANI=Fe_3O_4 composites nanorods, which was manufactured using a self-assembly approach. In comparison with the self-assembly technique, the ultrasonic irradiation technique was more successful to synthesize the sample due to facilitating the dispersion of Fe_3O_4 particles. Additionally, the synthesized composite nanotubes via ultrasonic irradiation approach illustrated a superparamagnetic behavior [154].

4.3. Optical characteristics

Optical properties of CPs can be considered as a valuable property, which have been recently of great interest of exploration all over the world due to their feasibility of application in nanophotonic devices [26,155,156]. The one-dimensional semiconductors show their irrefutable potential for the production of disparate apparatuses such as photodetectors and photochemical sensors [157–160]. Xi et al. conducted an experimental investigation to assess the optical characteristics of CdS=PANI composite nanocables. They could find out the similar characteristics of photoluminescence spectrum to CdS nanowires, while enhancement of signal intensities because of the transferring of photo-generated carriers from the PANI layer into CdS nanowires [161]. The synthesis process of a novel PT derivative applying electrochemical oxidative polymerization of 2,5-di(thiophen-2-yl)− 1-(4- (thiophen-3-yl)phenyl)− 1-H-pyrrole (TTPP) was performed by Turac et al. synthesized. Also, they could determine some momentous functional parameters such as the optical contrast, switching time and band gap. They perceived that the fabricated copolymer demonstrated a full switch in 1.8 s with an optical contrast of 26%. [162].

4.4. Wettability

An important property of a solid surface is wettability, which possesses significant effect on the efficiency of some industrial processes like self-cleaning surfaces, microfluidics, and membrane-based separation [163–169]. Collectively, CPs are hydrophilic [170]. In order to specify the wettability of a solid surface, the measurement of the apparent and dynamic contact angle is of great importance. It is worth noting that the contact angle lower than 90° demonstrates the intrinsic hydrophilicity of the surface also the contact angle higher than 90° implies the intrinsic hydrophobicity of the surface the contact angle profoundly relies on some important factors such as surface tension. Surface tension intrinsically depends on solid-vapor, solid-liquid and liquid-vapor surface tensions [164]. Fig. 4 schematically demonstrates a water droplet on various intrinsically hydrophilic and hydrophobic surfaces. Moreover, it is worth pointing out that superhydrophilic surfaces are usually identified by very low apparent contact angles (less than 5–10°), while this amount is higher than 150° superhydrophobic

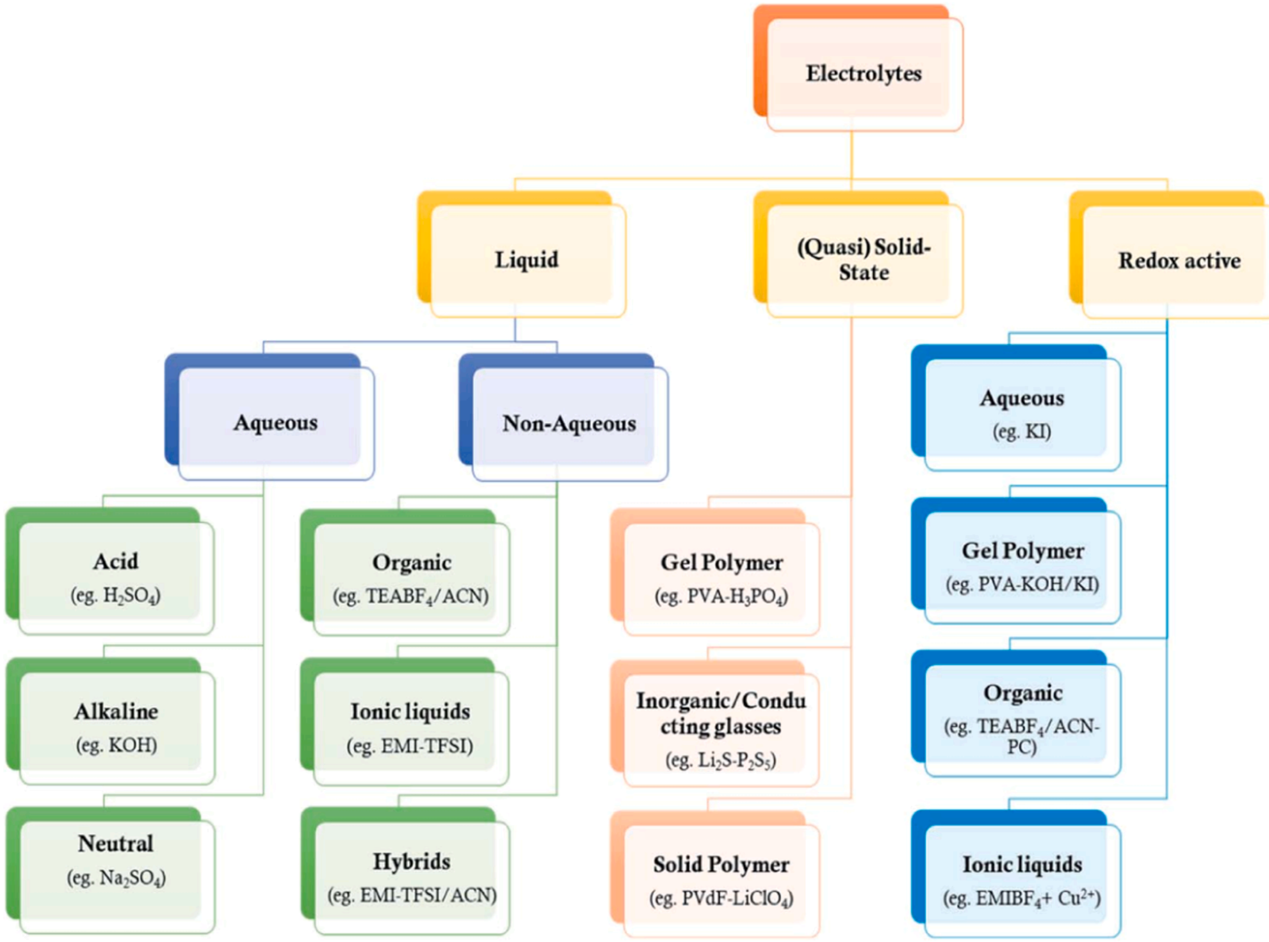

Fig. 5. Schematic demonstration of different classifications of electrolytes for electrochemical supercapacitors. Reprinted from [185] with permission from the Royal Society of Chemistry.

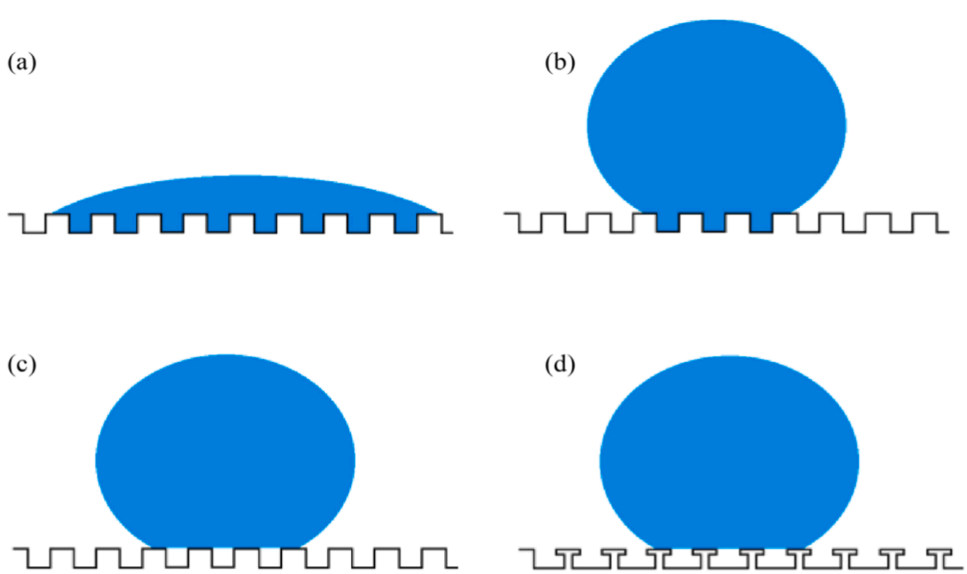

Fig. 4. Schematic representation a water droplet on various intrinsically hydrophilic and hydrophobic surfaces. a) Rough intrinsically hydrophilic surface (Wenzel/Cassie–Baxter state), b) Rough intrinsically hydrophobic surface (Wenzel state) (c) Rough intrinsically hydrophobic surface (Cassie–Baxter state) and (d) rough intrinsically hydrophobic surface with re-entrant structures (Cassie–Baxter state). Reprinted from [164] with permission from Elsevier.

surfaces [171–173].

4.5. Mechanical features

In current years, the mechanical and microwave-absorbing properties of CPs have attracted the attention of numerous investigators all over the world [174]. The mechanical features of polymeric substances considerably rely on the monomer arrangement and crystallinity. In comparison with amorphous semi-crystalline polymers, crystalline polymers possess superior mechanical properties. The mechanical properties of CPs in the macroscopic scale profoundly rely on the alteration of macromolecules' molecular mobility. Molecular mobility of macromolecules is an important factor, which depends on some microscopic parameters such as the structure of branching polymer conformations and macroscopic parameters such as pressure and temperature [6,57,175,176]. Cuenot et al. conducted an experimental investigation to evaluate the force-curve / resonance-frequency measurements and presented the elastic tensile modulus of PP nanotube. They proved that the decrement of the PP nanotube thickness significantly enhanced the elastic modulus [177].

5. Prevalent applications of CPs

5.1. Supercapacitors

Nowadays, increasing utilization of fossil fuels has eventuated in the emergence of disparate socioenvironmental concerns such as climate change, acid rain, global warming, and health problems [178–181]. Hence, the scientists have been encouraged to find novel environmentally-friendly and renewable energy resources to substitute the traditional energy sources. In recent decades, promising technologies such as supercapacitors have been of significant commercial interest due to their great impact on the future markets of some industrial-based apparatuses such as wearable devices [182–184]. According to the charge storage mechanism, supercapacitors can be divided into three major types including electric double-layer capacitors (EDLC), pseudocapacitors and asymmetric supercapacitors (ASCs) [185]. EDLC is one of the most important types of supercapacitors, which works based on a non-faradic process. In this supercapacitor, the charge accumulation takes place in the electrode- electrolyte interface. Carbon-based substances with high surface area (i.e., carbon nanotubes and graphene) are usually applied as electrode materials of EDLC supercapacitors [62,182,186,187]. Pseudocapacitors are known as the second common type of supercapacitors, which work by means of a faradic process. In this type of supercapacitors, the charge storage takes place based on a redox reaction or intercalation process. In comparison with EDLCs, pseudocapacitors have shown their great potential to improve power / energy density [188–190]. CPs and transition metal oxides like Mn_3O_4 are known as the most prevalent electrode materials applied for pseudocapacitors because of their excellent redox activity [191,192]. Hybrid supercapacitors are defined as the mixture of both EDLCs and pseudocapacitors, which demonstrate suitable specific capacitance and excellent cycle stability of EDLCs and appropriate energy and power density of pseudocapacitors [193]. ASCs can be presented as the third common supercapacitors, which have been of paramount attention all over the world due to their wider voltage window in comparison with symmetric supercapacitors [194]. In comparison with conventional types of symmetric supercapacitors, ASCs have demonstrated both superior energy/power density. According to the charge storage mechanism of two electrodes, the ASCs are divided into two groups including EDLC/pseudocapacitive-type ASCs and EDLC/battery-type hybrid SCs [195,196]. One of the prominent segments of the electrochemical supercapacitors is electrolyte. Commonly, the dissolution process of the salt into the solvent/solute is the main mechanism for electrolytes preparation. This prepared solution keeps the charge neutrality and prepares vital ionic transfer during the charge– discharge processes. Disparate types of electrolytes such as aqueous, organic, and solid-state ceramic electrolytes have shown their great potential of application in supercapacitors [197,198]. Among the abovementioned electrolytes, organic ones (i.e., (ACN)-based solutions) can be applied in industrial-based supercapacitors due to their wider operating potential. Despite the lower voltage of the aqueous electrolytes compared to organic electrolytes, they have brilliant advantages such as low toxicity, cost-effectiveness and better safety than the organic electrolytes. One of the most important shortcomings in the application of the aqueous solution is its confined working potential, due to their lower energy density compared to the organic solution [199,200]. Fig. 5 schematically demonstrates different classifications of electrolytes for electrochemical supercapacitors.

5.2. Corrosion inhibition applications

Generally, metals have shown their brilliant potential of applications in disparate types of industry such as automobiles, electronics, energy and aerospace and therefore, possess a desirable global market [201]. It is clear that the exposure of metals with moisture or acidic/basic environment can cause their quick degradation. Corrosion is an important unfavorable phenomenon in industry, which possesses unbelievable economic aspect. As an example, 300 billion dollars are spent to develop novel techniques to prevent corrosion in various industries [202]. Due to this fact, paramount attention has been recently made by researchers on corrosion–resistant coatings. In the past, chromate-based primers demonstrated their brilliant capability of utilization due to their significant corrosion–resistant property. Chromate coatings could be applied as both anodic and cathodic inhibitors due to having valuable advantages such as excellent adhesion with the metal surface and topcoats and excellent cost-effectiveness [6,203,204]. Despite noteworthy advantages, the emergence of important shortcoming such as detrimental effects for the environment and human well-being have limited the extensive application of chromates and chromium-containing coatings [205]. In recent years, the substitution of organic coatings (i.e., acrylic and polyvinyl butyral) with chromate conversion coatings has been of great interest among researchers to overcome their detrimental environmental disadvantages [206,207]. CPs have recently been interesting as feasible components of corrosion–resistant coating systems because of retaining the consistent passivity of a metal via an anodization process accompanied with O_2 reduction on the film surface. The combination of anodization process with O_2 reduction results in the creation of a metal-oxide interface layer [208]. Recently, epoxy-based coatings have illustrate their capability to be a promising alternative for carcinogenic chromate coatings [209,210]. Graphene-incorporated coatings is another pigment, which has been recently investigated due to their brilliant properties such as hydrophobicity and sheet-like morphology [211,212]. Moreover, zinc phosphates are identified as another commonly-applied anticorrosion pigment, which has been of great attention due to its negligible toxicity compared to chromates [213]. Sathyanarayanan et al. experimentally synthesized PANI pigmented epoxy and vinyl acrylic organic coating and evaluated their efficiency on stainless steel. They concluded that initial decrement of the value of electrochemical impedance spectroscopy along with its enhancement by increasing the exposure time. This phenomenon can be justified owing to the creation of pinholes on the metal surface. Additionally, they perceived from their evaluation that PANI pigmented organic coatings possess significant efficiency as corrosion inhibition coatings [214]. Various researchers have currently investigated the anticorrosion manner of carbonaceous substances such as carbon dots, carbon nanotubes, graphene, and graphene oxide. They corroborated that these substances enjoy excellent rate of corrosion inhibition [215–217]. In a research, Jafari et al. found out that that the corrosion inhibition value of the PA graphene composite is approximately 97% [218]. Due to the imposition of strict laws for the application of corrosion inhibitors, this scientific field there have been of substantial

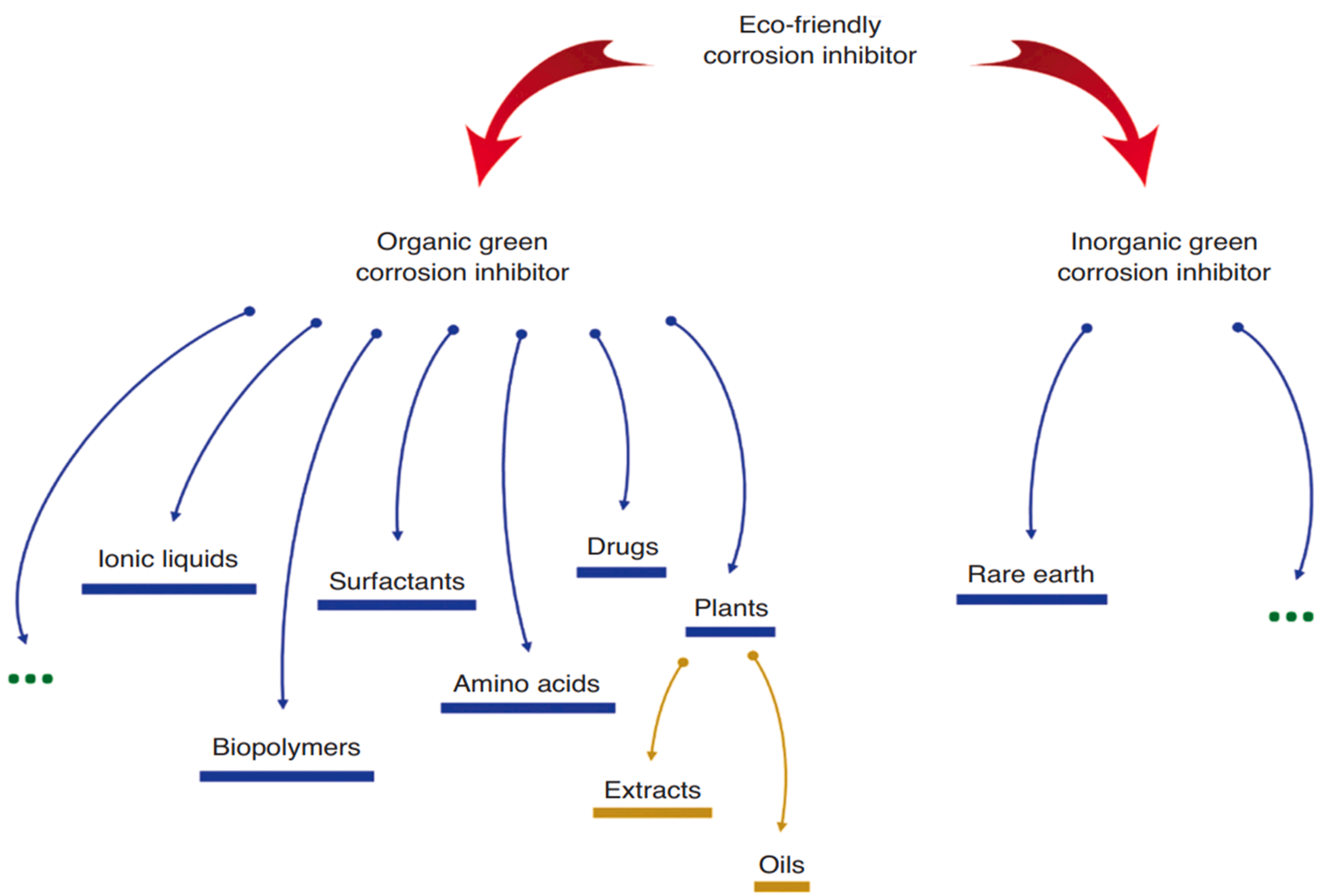

Fig. 6. Schematic presentation of disparate sources of organic green corrosion inhibitors. Reprinted from [219] with permission from Elsevier.

alterations from disparate key-points such as environmental compatibility, toxicity and biodegradability [219,220]. Therefore, the development of new corrosion inhibitors with minimum or zero detrimental environmental-associated impacts has been considered as a vital scientific challenge [221]. Fig. 6 schematically demonstrates disparate sources of organic green corrosion inhibitors.

5.3. Photocatalytic applications

CPs and their nanocomposites have demonstrated noteworthy photocatalytic efficacy for removing organic pollutants such as dyes and personal care products [222]. Those CPs having been recently used for various photocatalytic applications were initially synthesized by some synthesis mechanisms like chemical oxidative polymerization, electrochemical polymerization or vapor phase polymerization [7,223–226]. In current decades, development of various types of CPs for photocatalytic applications has been an interesting topics among scientists [227]. TiO_2 has shown superior photocatalytic efficiency compared to other photocatalysts due to possessing some important advantages such as novelty of bandgap, ease of synthesis, cost-effectiveness and resistance against photocorrosion. Usually, TiO_2 shows three disparate phases including anatase, rutile, and brookite that among them, anatase shows better photochemical manner because of its high bandgap (around 3.2 eV) [228]. Despite the wide application of TiO_2 photocatalysts, investigation and development of new photocatalysts have been of great interest owing to the appearance of momentous functional/operational challenges towards the application of TiO_2 nanoparticles in the large-scale industrial activities such as water treatment. For instance, the existence of wide bandgap in TiO_2 significantly increases the demand of high-energy UV radiation for photocatalytic applications. Additionally, confined photoresponse and difficulties in post-treatment recovery of nanoparticles can be identified as other major limitations towards the large-scale application of TiO_2 [222,229]. To enhance the removal efficiency of micropollutants from water sources, different types of inorganic photocatalysts such as ZnO, Fe_2O_3, V_2O_5, WO_3 and graphene have been under comprehensive study [228,230]. In current years, organic photocatalysts such as linear poly(p-phenylene)s, conjugated polymers, conjugated triazine frameworks and covalent organic frameworks have shown their potential of application for photocatalytic water decontamination owing to having valuable properties such as excellent tenability and ease of application [231]. PANI with organic semiconductors has been an outstanding research outlook due to its excellent electron–hole charge separation, simple synthesis process, great cost-effusiveness and suitable mobility of charge carriers. Reddy et al. developed an in-situ polymerization process to synthesize a TiO_2/PANI hybrid system to evaluate the photocatalytic activity of this hybrid system for the degradation of rhodamine and methylene blue. Based on their investigations, the degradation percentage of rhodamine and methylene blue under continuous 3 h UV irradiation and in 200 min of irradiation time was obtained 80% and 67%, respectively [232]. Jiang et al. manufactured PANI/TiO_2 hydrogel. In this sample, uniform dispersion of TiO_2 nanoparticles was performed on the three-dimensional matrix of PANI hydrogel. They perceived from their investigation that 3D-structured PANI/TiO_2, demonstrated excellent reactivity in nano-sized powder substances and has separation-free features in bulk materials implying the simplicity of recycling the composite hydrogel [233]. Fig. 7 shows the synergistic removal mechanism of PANI/TiO_2 composite hydrogel based on UV light irradiation.

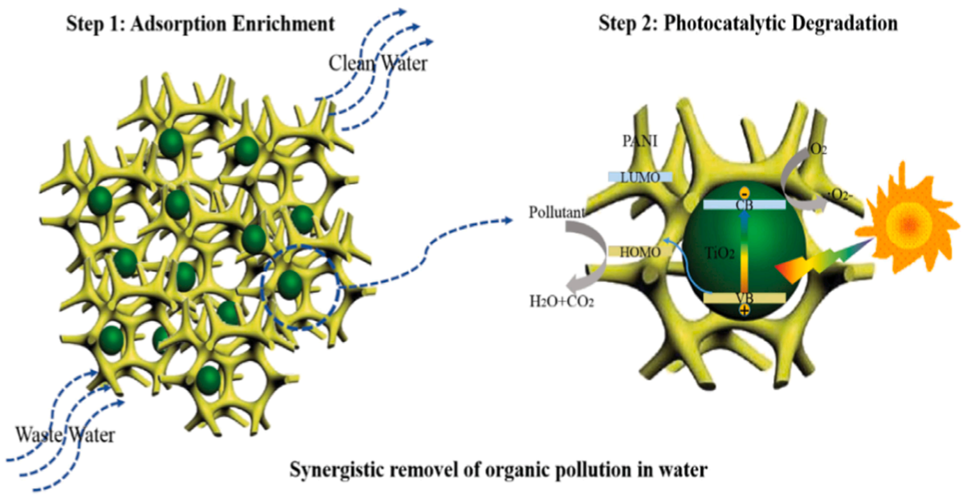

Fig. 7. Schematic demonstration of the synergistic removal mechanism of PANI/TiO_2 composite hydrogel based on UV light irradiation. Reprinted from [233] with permission from John Wiley and Sons.

5.4. Biomedical and antimicrobial application

CPs have been recently proposed as a promising class of biomaterials for extensive biomedical applications [234]. This class of polymers have shown its significant potential of application in disparate medical/-biomedical approaches like tissue engineering during the 1990 s [235, 236]. The existence of encouraging advantages such as excellent electrical/optical properties, appropriate biodegradability/biocompatibility and soft interface have motivated the scientists to substitute CPs with conventional electrodes formed by conductors/semiconductors like platinum and glassy carbon [20]. Fig. 8 schematically depicts the creation of biodegradable CPs with conducting oligomers of pyrrole-thiophene-pyrrole (PTP) and degradable ester linkage and aliphatic linker. There are various promising procedures (i.e., blending and composite formation) for the synthesis of biodegradable CPs applying conducting and degradable substances.

One of the most important challenges in the medical/biomedical industries is the packaging waste due to the application of insufficient biodegradable materials, which results in occurring some dangers for environment and human/animal health. To solve this important problem, biodegradable CPs from renewable sources have gained numerous attentions [238]. CPs have been recently considered as a promising option for antibacterial/antimicrobial application owing to having advantages such as good cellular response [239]. Nanocomposites of PANI, cellulose and cobalt ferrite have demonstrated brilliant antimicrobial performance against pathogenic agents such as Bacillus subtilis, E-coli and Candida albicans [240,241]. The abovementioned nanocomposites possess great conductivity (3.5×10^{-3} s/cm) and biodegradability in nature. In an experimental investigation, Abou Hammad et al. corroborated that increment of the content of cobalt ferrite in nanocomposites significantly reduced the biodegradability of sample while increased the antimicrobial nature [242]. In another scientific investigation, the chemical synthesis and characterization process of a copolymer of PPy and chitosan was performed by Cabuk et al. using spectral, thermal and morphological analysis. Based on their research, a strong interaction between PPY and CS existed in the copolymer chains and the electrical conductivity of CS enhanced substantially because of grafting. Additionally, they showed that the antibacterial activity of PPY-co-CS increased considerably compared with PPY and C. Moreover, they corroborated that the antibacterial activity of PPY-co-CS superior than Trimethoprim (25 mg), Rifampicin (5 mg), and penicillin (10 mg) [243]. In the current twenty years, CPs have been under extensive application targeted drug delivery processes. The electroactive substances recommend a promising technology stage by combining the electrical property with other processing techniques. CPs demonstrated their great potential to move charged molecules to their backbone. Therefore, according to electrical/electrochemical stimuli, the aforementioned mechanism can be helpful to effectively control drug release [244].

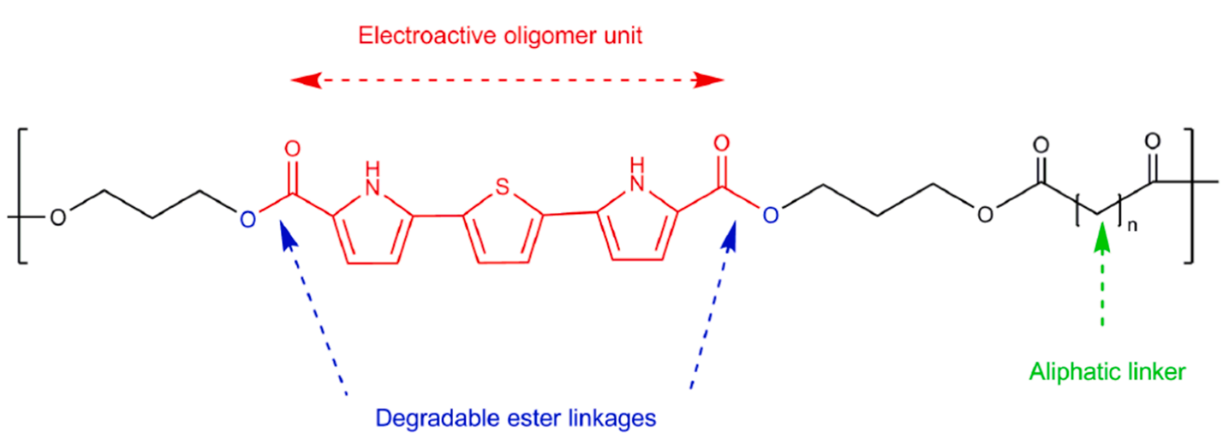

Fig. 8. Schematic demonstration of creation of biodegradable CPs with conducting oligomers of PTP and degradable ester linkage and aliphatic linker. Reprinted from [237].

5.5. Electrochemical gas sensors (EGSs)

In the 50th decade, oxygen monitoring was a successful example for the application of old version of EGSs [6,245]. In recent decades, the development of novel EGSs has been of paramount attention for the monitoring of combustible/poisonous gases in various applications. Despite similar structures of disparate EGSs for gas detection, their functions are significantly different. Momentous operational/functional factors such as specificity, sensitivity, and operational life may significantly affects efficiency of EGSs [246–248]. For instance, a low-concentration sensitive EGSs applies a hydrophobic porous membrane (HPM). In these apparatuses, superior sensitivity may be obtained by adequate signal production because of decreasing the limitation of capillary movement, which permits the of more gaseous molecules It is important to note that a highly-sensitive EGSs must possess a relatively low operating life due to the evaporation of water molecules inside HPM [6]. The selectivity value of an EGSs for gas detection is in direct relationship with several parameters including type of sensor, gaseous flow type and concentration. Moreover, the chemical reactivity of a determined target gas through the sensing process profoundly relies on the electrolyte compounds and electrode material [249]. True action of EGSs is on the basis of the reaction with the target gas. An EGSs contains a sensing electrode and a counter electrode. The two electrodes are separated from each other via a thin electrolyte layer. At first, the gaseous flow moves inside a small capillary-type opening. Then after, the gaseous flow diffuses through the hydrophobic barrier and ultimately, enters the electrode surface. The diffused gas through the porous barrier experiences an oxidation or a reduction mechanism on the surface of the sensor electrode [250,251].

5.6. Batteries and solar cells

In recent decades, CPs have illustrated their irrefutable place in the fabrication of new batteries [252–255]. The most commonly-employed CPs to fabricate batteries are polyheterocycles (i.e., PPy, PANI, PEDOT and their derivatives) owing to exhibiting high electrical conductivity (0.01 to 500 s/cm) [256,257]. The application of CPs in lithium batteries would be traced back to the late 1980 s [258]. Indeed, Fabrication of various types of batteries can be considered as the first scientific field where CPs have shown their indisputable impact. Excellent conductivity and electroactivity of CPs have made their application possible for rechargeable batteries [89]. Each battery comprises of some parts as follows [89]:

1) Electrodes, which are employed for current compilation and power diffusion
2) Cathode and anode materials for reduction and oxidation
3) The electrolyte for the supplement of cations and anions to balance the redox reactions. Moreover, the electrolyte causes the creation of a physical partition between the cathode and the anode

Energy storage (ES) techniques have recently experienced significant evolution for ever-increasing demands. Lithium-ion batteries (LIBs) can be regarded as the most commonly-applied battery, which occupy a high percentage of the global ES market [254]. Despite great efficiency, the emergence of important challenges like the high cost of raw materials and the electrolyte flammability avoids their further development in industrial applications. A promising alternative for LIBs, which has recently been of paramount attention is rechargeable aqueous Zn-ion batteries (AZIBs) [259]. In current decades, numerous scientists have conducted their investigations on improving the efficiency of batteries using CPs. For instance, Samsudina et al. found a promising biopolymer material on the basis of carboxymethyl cellulose for use in rechargeable proton battery. The results have demonstrated that the developed biopolymer electrolytes (BPE) is electrochemically stable and appropriate for use in proton battery [260]. Guerfi et al. studied the stability of Zn-anode/CP rechargeable battery with non-aqueous electrolyte. This investigation illustrated that the battery experienced a strict self-discharge of 48% per day [162].

CPs have shown their brilliant ability of application for fabricating polymeric solar cells (PSCs), which is known as a promising alternative for silicon-based solar cells. Disparate advantages of PSCs like negligible production cost, simplicity of process and flexibility of chemical structure has made them promising for industrial-based applications [261–264]. Over the last decades, various investigations have been done to fabricate flexible equipment applying a plastic film substrate. With the aim of synthesizing the fully-plastic PSCs, application of transparent anode via organic-based materials is of great importance [89,265]. For example, Heo et al. evaluated the patternable solution of changeable PSCs applying polydimethylsiloxane. They corroborated that the prepared PSCs illustrated short-circuit current density, open-circuit voltage and power conversion values of 4.2 mA/cm^2, 0.878 V and 0.98%, respectively, which showed a 38% enhancement over those PSCs prepared via the spin coating technique [265].

6. Conclusion and future outlook

In recent decades, substantial advancements have occurred in the perception, synthesis, and characterization of CPs. CPs and their composites have been recently of paramount attentions by scientists all over the world due to their noteworthy advantages such as great metallic conductivity and very good physical properties. Based on various conducted investigations, it can be perceived that CPs behave as an insulator or a semiconductor in their pristine form but when doped with an appropriate dopant illustrate considerable metallic conductivity. True perception of the fundamental characteristics of CPs is of great importance for their design in various applications. Disparate parameters such as temperature, dopants, and structural features may be effective on transport properties. CPs have extensive use in different industrial-based applications like supercapacitors electrode materials, corrosion inhibition, photocatalytic and biomedical/ antimicrobial applications due to their suitable conductivity, great flexibility/processability and simplicity of fabrication. Overall, physical characteristics and biocompatibility are the most prominent issues for CPs, which must be considered in each related study. Various techniques such as chemical oxidation, electrochemical polymerization, hydrothermal, electrospinning and photochemical can be defined as the most prevalent approaches for the synthesis of CPs. The main objective of this paper is to review the current progressions in perception, characterization and synthesis process of different types of CPs in industries. Moreover, discussion about the application of commonly-applied CPs in industrial-based activities following with presenting their advantages/disadvantages is another purpose of this investigation. The authors of this manuscript have made an effort to provide an opportunity for readers to know the efficiency and feasibility of using each CP based on their conductivity and other related parameters. As a future perspective, endeavors must be made towards improving synthetic techniques and developing new assembly processes with the aim of more appropriate control of the size, composition, and structure CP nanocomposites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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