



# Composite Material–Based Conducting Polymers for Electrochemical Sensor Applications: a Mini Review

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## Abstract

Conducting polymers (CPs) represent a sizeable range of useful organic substances. Their unique electrical, chemical, and physical properties; reasonable price; simple preparation; small dimensions; and large surface area have enabled researchers to discover a wide variety of uses, including sensors, supercapacitors, solar cells, batteries, biochemical applications, and electrochromic devices. To promote the success of CPs, unique composite materials have been prepared with metals or steel oxides. The goal of this overview is to characterize the electrochemical sensor utility of CPs and their composites and to categorize future components of electrochemical sensing materials. CPs have been comprehensively applied over a wide range of variable industrial fields; such CPs have used many new materials with diverse compositions that are utilized as electrochemical sensors and biosensors. These materials have been fabricated inside numerous analytical instruments that are applied in healthcare settings and clinical, environmental, food, and pharmaceutical laboratories. Electrochemical sensors are essentially based on CPs and/or their corresponding composite materials. Therefore, the present work provides a brief illustration of electrochemical sensor and biosensor applications for the most important conducting polymer composite materials. Polyaniline (PANI), poly(o-toluidine) (PoT), and poly(o-anisidine) (PoAN) were considered in this study. Moreover, the most important electrochemical properties of these conducting polymer composite materials are discussed.

**Keywords** Polyaniline · Poly(o-anisidine) · Poly(o-toluidine) · Conducting polymer · Composites · Electrochemical technique · Sensor application

## 1 Introduction

Polymers are molecules composed of many repeated subunits referred to as monomers [1]. Polymers have received considerable interest since the first electrochemical synthesis of polyaniline in acidic media by

Letheby in 1862 [2]. CPs are polymers that exhibit electrical behavior [3]. CPs such as insulating polymers are organic substances. Such CPs can display high electrical conductivity but do not display mechanical properties equal to those of other commercially available polymers [3]. The electrical properties may be optimized via superior dispersion techniques and natural synthesis strategies [4]. The conductivity of CPs was first observed in polyacetylene [5]. Polyacetylene instability in air has led to the discovery of diverse forms of CPs, including polyaniline (PANI), poly(o-toluidine) (PoT), poly(o-anisidine) (PoAN), polypyrrole (PPy), polythiophene (PTh), and polyfluorene (PF). CPs prepared in the form of nanomaterials are of interest because their properties drastically differ from the properties in their bulk counterpart [4]. Natural CPs have low conductivity and are semiconductive. Therefore, it is essential to increase their conductivity, mainly for use in electrochemical sensor programs. To address this problem in CPs, composites and nanocomposites of

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CPs have been thoroughly studied in order that they may be used in various fields [4, 6].

## 2 Electrochemical Properties of Conducting Polymers

The overall chemical properties of CPs are based upon the CP chains, and the physical properties depend upon the dimensions of the CPs [7]. Unlike conventional polymers, CPs have elevated redox properties and electron affinity. CPs are synthesized by applying current through electrodes or oxidizing monomers by using oxidizing agents [8]. The electrochemical synthesis process can determine the properties, conductivity, and morphology [9]. In 1981, Diaz et al. suggested that the principle mechanism of PPy formation [10] was the proliferation of polymerization by the constant development of chains through a combination of monomeric radical cations and oligomer radicals [5].

As an instance displayed in Fig. 1, electrochemical improvement of PANI includes an underlying association of oligomers. The doping of CPs needs to be possible electrochemically, which means that the oxidation and reduction of CPs create a p-doped state and an n-doped state, respectively. The structures of diverse CPs are shown in Fig. 2. Numerous previous reviews have described uses of CPs. CPs and multiple monomers can be functionalized with various substances to change their properties. Increasing the number of material components improves some of the properties of the compound and the principle polymer chain, enhancing the mechanical and electric properties. To improve the properties of CPs, CP composites can be synthesized using highly conductive nanomaterials and catalysis.

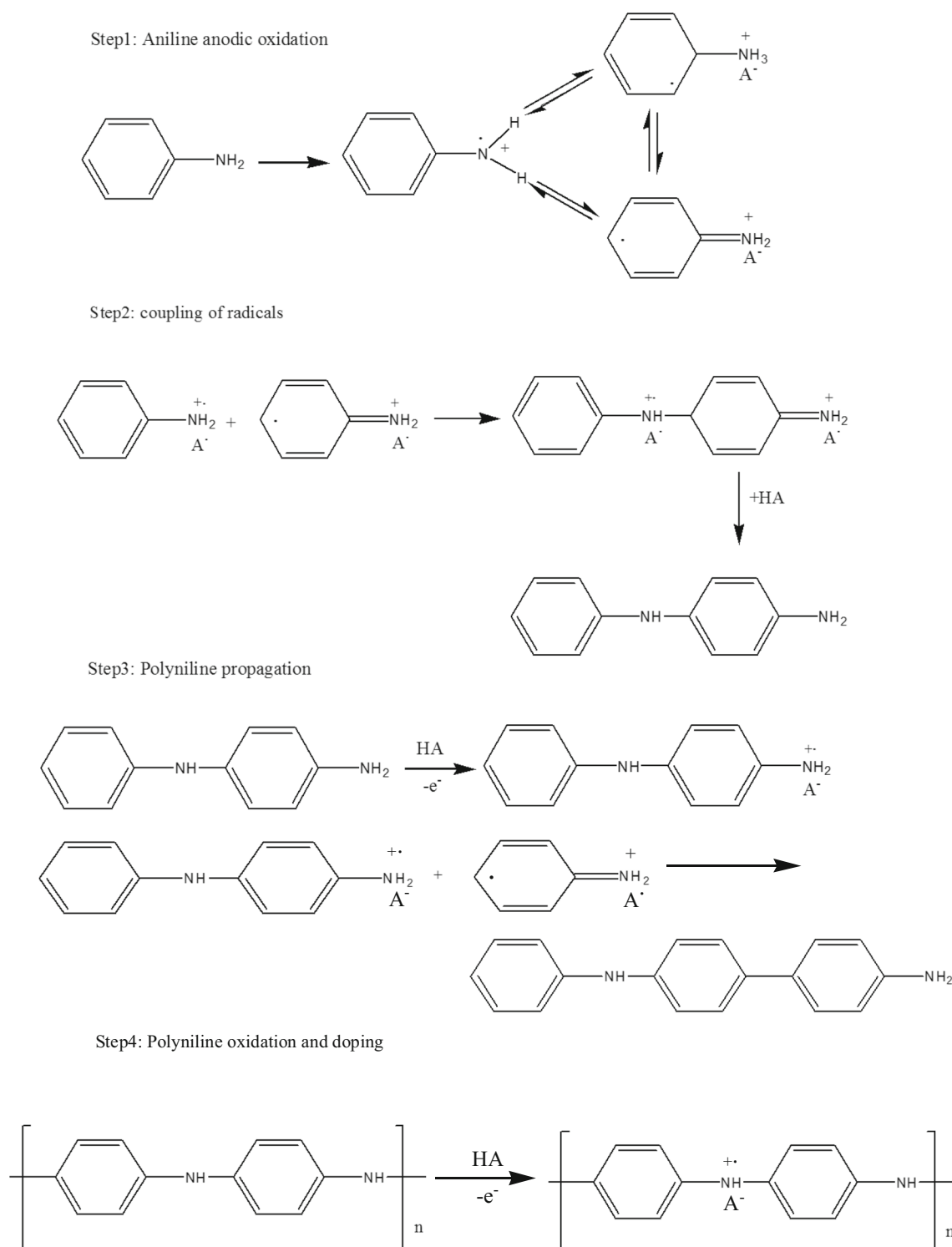
### 2.1 Composite Materials

Carbon-based substances, such as carbon nanotubes, graphene, graphene oxide, carbon specks, and permeable carbon, are ideal substances in many applications [11–13]. The fast improvement of carbon substances has happened in view of their excellent conductivity, outstanding sensitivity, mechanical quality, and large surface area [14, 15]. These properties may be used to develop new kinds of electrochemical sensors. Utilizing carbon substances alone has a noteworthy downside, specifically when applied as part of sensor devices: selectivity for target atoms is required. Therefore, the development of carbon composites and their functionalization is important for new applications. The utilization of carbon composites in sensors mainly requires sensitivity and forming composites with CPs is a highly encouraging approach to enhance their utility. Carbon substances are utilized in composites because

they may be handled as chemical reagents, depending upon their inherent carbon shape. Steel and steel oxide nanoparticles (NPs), for example, ZnO, MnO<sub>2</sub>, Cu, Pd, Pt, and Au, are some other substances that display properties distinct from those of their mass counterparts [5]. NPs have been used in numerous fields, as have their mass counterparts. NPs have been utilized in numerous areas and have been incorporated in biomedical studies, prospective energy applications, and electrochemical devices. In particular, the use of metal or metal oxide NPs as electrode substances has produced outstanding success associated with body metal electrodes [16, 17]. For instance, AuNPs (gold nanoparticles) show excellent mobility and have been used as a base substance for sensor detection electrodes [18]. Various methodologies have been utilized to construct NPs, including wet artificial combination, monolayer stacking, dendrimer-driven assembly, and electrochemical precipitation [19, 20]. Metal NPs may be functionalized with auxiliary substances, such as CPs, enzymes, and carbon substances, because they have enhanced mobility and a large biocompatible surface area. The synthesis of CP composites and metallic NPs has been studied [5].

### 2.2 Conducting Polymer Composites

The extraordinary properties of CP composites make them promising competitors, particularly in sensor devices [21]. Many approaches to prepare new CP composite substances have been studied, including utilizing format-organized preparation, chemical functionalization, and in situ polymerization of CP composites. In addition to these techniques, electrochemical processes are a good method to manufacture CP composites. Additionally, electrochemical processes can easily control the conductivity, compound state, morphology, and thickness of the composites. Numerous forms of substances and composites are introduced in Fig. 2. Composites of CPs use CPs as a crucial component and at least one other optional component, which is typically a natural, inorganic or natural species. These substances incorporate metallic particles, nanoparticles, nanostructures, carbon substances, and organically dynamic components, for example, catalysts and antigens. The objective of preparing composite substances is to reveal numerous new properties that are not observed in their constituents [22]. Therefore, utilizing a synergetic technique to create composite substances is important. CP nanocomposites display interfacial cohesion between the auxiliary phase and the CPs, and the properties of the nanocomposites are affected by the proportional composition. CP composites have more advanced properties than CPs [23]. Such composites display



**Fig. 1** Schematic display of mechanism of electrochemical polymerization of aniline

notable performance in, energy storage [23], energy production [24] and numerous other applications including thermoelectric materials and devices [5, 25]. In the previous few years, CP composites have been applied in the construction of biosensors [26].

CPs are a promising essential substance that is affordable for the consolidation and functionalization of biochemical molecules [27]. The capture of compounds by means of sensor strategies has suggested means to improve the coupling effectiveness with biochemical molecules; for instance, to

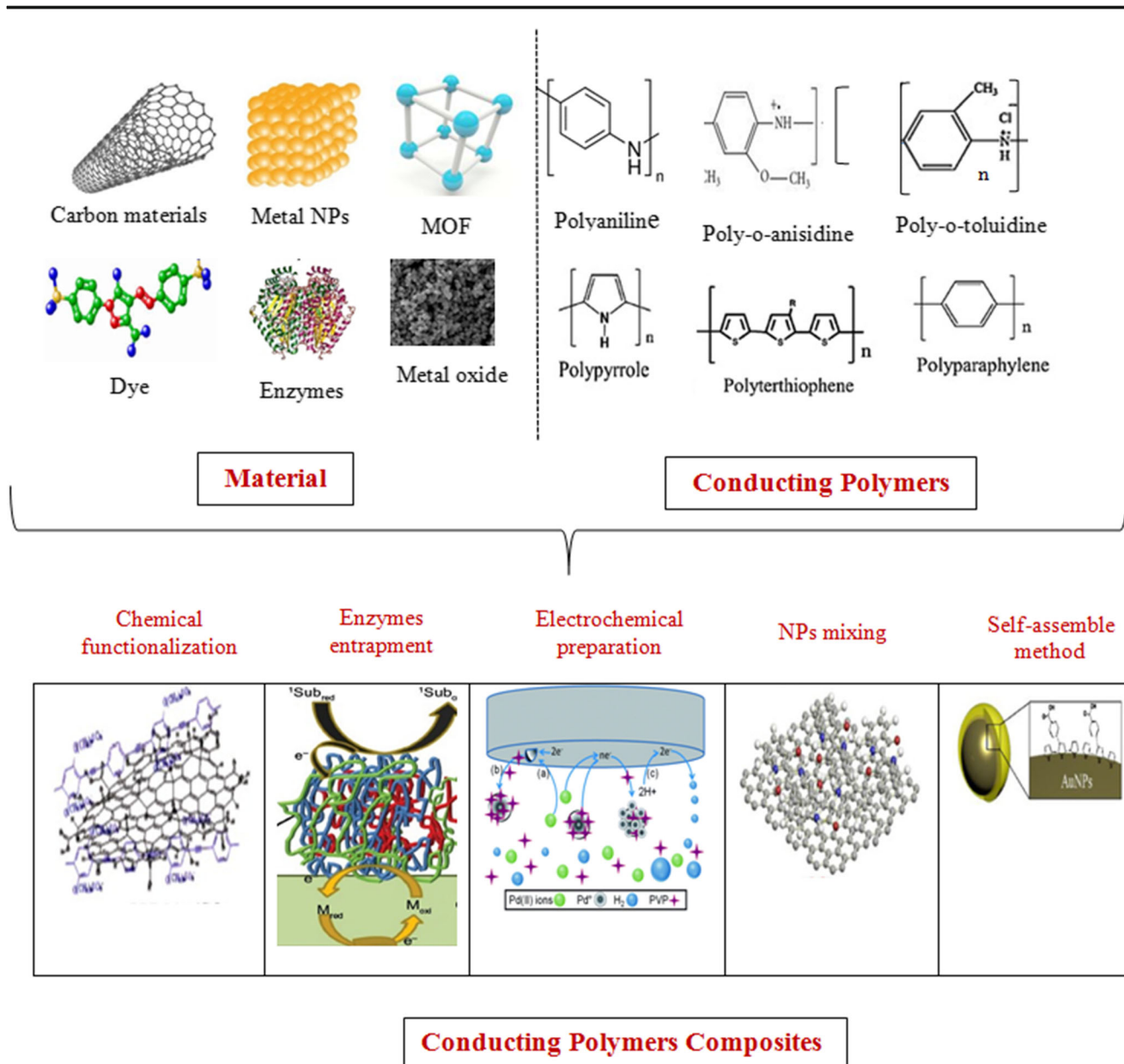


Fig. 2 Conducting polymers and their composites materials

form a matrix of glucose oxidase and PPy, glucose oxidase was trapped in PPy films through an electropolymerization technique [28]. This technique, in contrast to the physical adsorption technique, introduced both immediate and delayed immobilization. Be that as it may, chemicals or biomolecules can be partially uncovered or covered inside polymer films, which can substantially reduce the effective target availability. The principle disadvantage of this approach is that it is more reasonable for simply water-soluble monomers and is not always helpful for monomers that might be soluble in nonaqueous solvents. Therefore, strongly binding enzymes on CPs by covalent binding was suggested [29]. In the previous few years, CPs and their composites have been utilized in the manufacture of biosensors [30]. Furthermore,

functionalization of CPs with biochemical molecules has been utilized to monitor drug transport and bioimaging programs [31].

### 2.3 Electrochemical Properties of Conducting Polymer Composites

CP nanocomposites containing carbon nanospecies, for example, carbon nanotubes, carbon nanofibers, and graphene, have been produced [23]. These carbon nanospecies enhanced the basic properties of the CP chains and encouraged the delocalization of charge carriers, resulting in upgraded conductivity. A wide range of conductivities was accomplished, ranging from insulating to metallic [32]. The effective synthesis of

CP composites with flexibility, excellent mechanical stability, and conductivity has demonstrated that CPs may be used as key substances in light-emitting diodes [33], transistors [34], electrochromic devices [35], actuators [36], electrochemical capacitors [37], photovoltaic cells [38], and sensors [39]. The critical factor in advances in this area is improving the electrochemical properties of the CPs. Consequently, this review presents a discussion of the electrochemical applications of CPs and CP composites.

## 2.4 Reversible Oxidation/Reduction

Doping generally results in the formation of charge carriers, which are located at transformation sites within the geometric structure of the CP, e.g., from benzenoid to quinoid. The main geometric structure is often restored by reducing the compound back to its original (undoped) state. The reversible doping/dedoping of the compound corresponds to charge/discharge, which forms the premise of the rules governing polymer-based sensors. The electrooxidation or p-doping of conducting polymers can be described mechanistically as electrons within  $\pi$  bonds being extracted and moving across the chemical compound skeleton, while counteranions from the solution are inserted into the chemical compound chain to balance the electronic charge.

The mechanism of n-doping or electroreduction of conducting polymers comprises electron transport to the chemical compound backbone and counteranion intercalation into the chemical compound backbone from the solution to balance the overall charge. The best electrochemical technique used to study oxidoreduction processes in conducting polymers is cyclic voltammetry (CV). CV measures the current produced at a given potential with a fixed scan rate. Throughout oxidoreduction reactions, oxidation leads to positively charged polymer chains, while reduction produces polymer chains that are negatively charged. Ions move in and out of the chemical compound matrix when doping and dedoping are completed [36].

The reaction mechanisms of conducting polymers are reversible and stable in a certain potential range. Moreover, when a conducting polymer electrode is scanned at higher potentials, the conducting polymer undergoes fast structural degradation and electron loss. These phenomena are reportedly attributable to overoxidation [40].

## 3 Application to Electrochemical Sensors

### 3.1 Electrochemical Sensors

Electrochemical sensors change the effect of the electrochemical reaction of target species on electrodes into useful signals that show alterations in potential and conductivity [5]. These

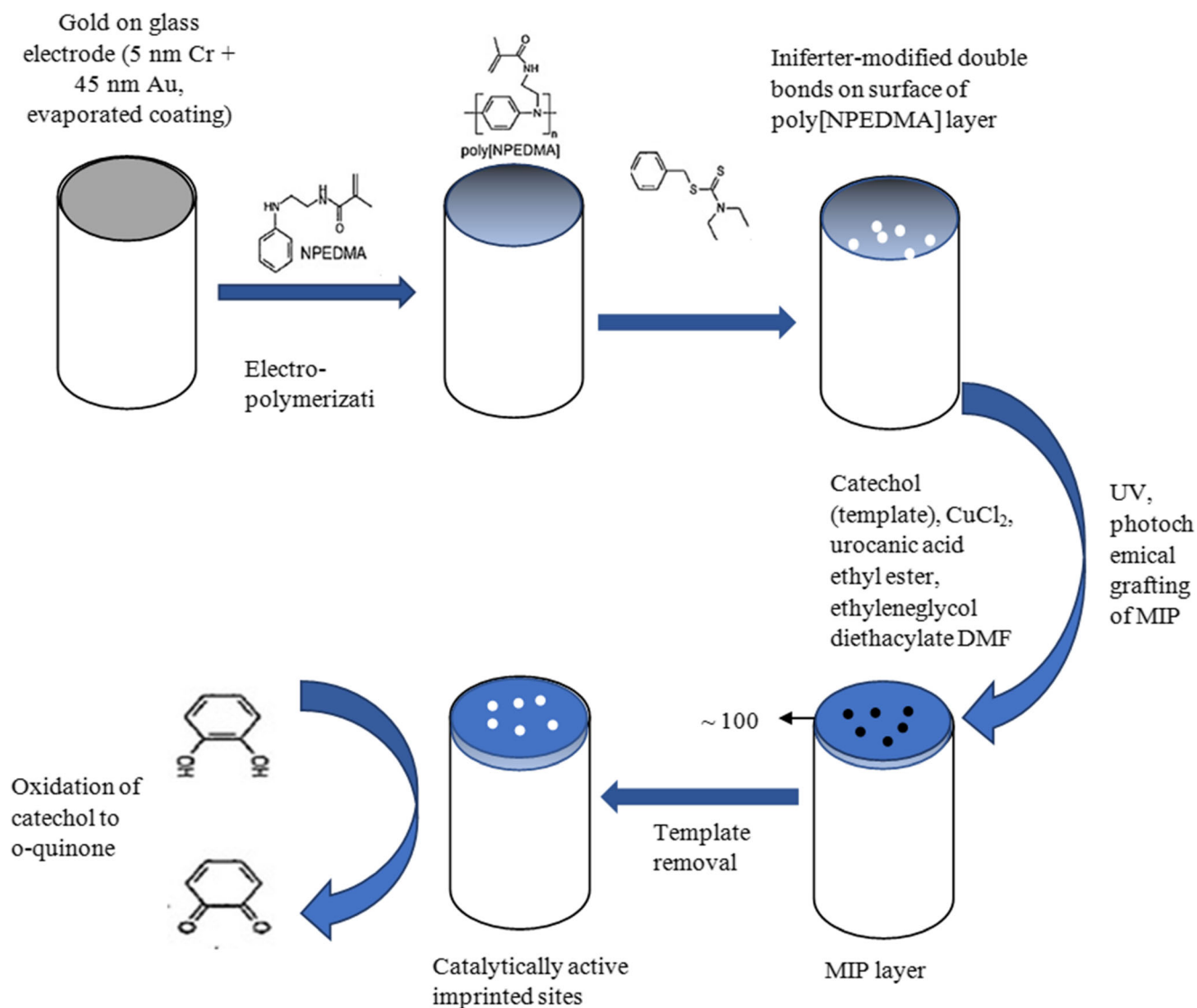
electrochemical sensors can be separated into three types, voltammetric or amperometric, impedimetric, and potentiometric sensors, as delineated by Wang [6]. Sensor strategies offer low limits of detection, high selectivity, and a small needed volume of the indicator species. Estimations in thick substrates such as blood, crimson platelets, and hemoglobin are viable when utilizing sensor strategies, while spectrophotometric measurements of such samples typically suffer from obstruction effects. Electrochemical systems consist of an association of one or a few electrodes. A three-electrode cell can include a gold, platinum, or carbon electrode as a working electrode, and a platinum electrode and Ag/AgCl (saturated KCl) electrode can be employed as the counter and reference electrodes, respectively. In voltammetric sensors, data about an analyte are acquired by measuring the current while applying a potential to the working electrode. The electrochemical reaction that happens on the electrode surface and the electrode/electrolyte interface layer produces the final current [6]. Voltammetric strategies include linear sweep voltammetry (LSV), cyclic voltammetry (CV), differential pulse voltammetry (DPV), and square wave voltammetry (SWV). These systems have an in-depth level of detail, a wide range of effectiveness and a low detection limit. In amperometry, a consistent potential is connected to the working electrode, and the resulting current is measured over time. The difference between amperometry and voltammetry is that amperometry does not have a potential sweep, instead making use of a potential step. Amperometric sensors have more selectivity and sensitivity given that the reduction or oxidation potential utilized in the determination is normal for the analyte sample [41]. In this review, the discussion of the development of electrochemical sensors is restrained to CPs and CP composites.

### 3.2 Sensor Applications of Polyaniline and Its Related Composite Materials

PANI has risen as a standout among the most encouraging CP substances in numerous applications. Polymer composites have been utilized in the manufacture of numerous devices for various applications, including supercapacitors, sensors, and batteries [42]. The most encouraging utilization of these composites has been found in electrochemical applications. Specifically, the manufacture of sensors depending upon PANI and PANI composites has become a well-known process in numerous sensor studies, and the sensors show excellent sensitivity and selectivity in the determination of target species. The determination of acid penetration in polymer composites was enabled by the use of composites of PANI and carbon nanotubes (CNTs). This sensor showed high electrocatalytic performance in acid penetration in the analysis of the polymer composite. Conductive PANI with the active catalytic sites in CNTs played an important role in the detection

of acid penetration in polymer composites and displayed high sensitivity [43]. A selective ammonia gas sensor was studied by electrochemical analysis of a polyaniline/ZnO nanocomposite. The nanocomposite films showed good sensitivity and selectivity [44]. An electrochemical sensor for the determination of hydrazine based upon a PANI/graphene nanocomposite-modified electrode was studied. Increased sensitivity and a low limit of detection were observed for the PANI/Gr nanocomposite-modified thin film electrode [45]. A polyaniline-(acrylonitrile-butadiene-styrene) composite sensor was reportedly utilized for the determination of aqueous ammonia. The composite was synthesized by the standard

and high stability, which resulted from the PANI [46]. Xue et al. also developed a phenol electrochemical sensor based upon the immobilization of polyphenol oxidase into a polyaniline-polyacrylonitrile composite matrix. The obtained biosensor displayed high sensitivity and superior stability [47]. As shown in Fig. 3a, a double polymer arrangement of a polyaniline layer with catalytically molecularly imprinted polymers was utilized for the determination of catechol [48]. Recently, an impedimetric immunosensor for 2,4-dichlorophenoxy acetic acid determination based on a AuNP-functionalized PANABA-multiwalled carbon nanotube (MWCNT) nanocomposite was studied. This sensor



**Fig. 3** Graphical representation of the **a** catalytic MIP-hybrid electrodes imprinted with catechol and **b** PtNP-catalyzed sensing method depend upon PANI/PtNPs/ enzyme hybrid films

process of solution casting, in which a common solvent is used for the dissolution of both polymers. This aqueous ammonia sensor probe showed good sensitivity, quick response,

displayed high stability, a wide linearity range, and a limit of detection of 0.0003 ppm [49]. The modification of biosensors based upon metal NP-PANI composites has become a

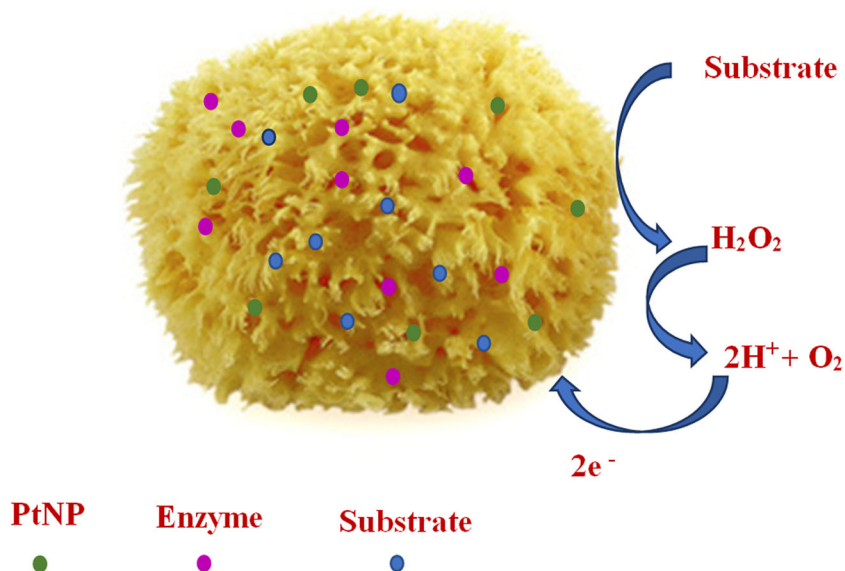


Fig. 3 continued.

promising process in sensor development for different analytical targets using various techniques.

Recently, a combination of Pt nanoparticles (PtNPs) and PANI hydrogel heterostructures was reported to simultaneously detect glucose. This sensor exhibited high sensitivity and a low limit of detection of 0.0007 mM [50]. As shown in Fig. 3b, another PtNP/PANI hydrogel-based electrode was utilized to identify human metabolites, and the performance of the electrochemical sensor test was excellent [51]. An electrochemical sensor consisting of a gold nanoparticle/polyaniline/polydopamine hybrid composite used for the sensitive and selective determination of ascorbic acid (AA) was reported. The sensor showed a low limit of detection of 0.000399 mM [52]. A urinary progesterone sensor was developed by molecularly imprinting poly(aniline-co-metanic acid) on an electrode. The limit of detection for the electrochemical sensing of progesterone was less than  $1.0 \text{ pg mL}^{-1}$  [53].

### 3.3 Sensor Applications of Poly(o-toluidine) and Its Related Composite Materials

PoT is one of the most promising CPs and is prepared via the chemical or electrochemical polymerization of o-toluidine. Many studies have been carried out in which polymer-lined electrodes have been examined. PoT and its composites with metal and metallic oxide MWCNTs, NPs, graphene, graphene oxide, and enzymes have been reported as sensor electrode substances. Due to the useful and unparalleled physical, chemical, and electronic properties of PoT, this polymer has been applied in sensor applications. Poyraz et al. suggested a new system for the sensor determination of glucose using poly(o-toluidine) and gold/copper nanoparticles. The PoT-Au/Cu nanocomposites displayed good biosensitivity and

high selectivity for glucose [54]. The modification of biosensors depending completely on titanium dioxide (TiO<sub>2</sub>)-PoT composites has become a favorable method for electroanalytical observation with the aim of obtaining exceptional analytical results and using numerous techniques. Recently, the incorporation of TiO<sub>2</sub> and PoT composites was studied to determine humidity [55]. Pan et al. developed a sensor that utilized a molecularly imprinted poly(o-phenylenediamine-co-o-toluidine)-nitrogen-doped graphene nanoribbons-ionic liquid composite film (MIP/NGNRs-IL/GCE) for the detection of 4-nonyl-phenol (NP). This electrochemical sensor showed excellent performance, high sensitivity, and a limit of detection of  $3.4 \text{ } \mu\text{A}/\mu\text{M}$  [56]. Composites of PoT with graphene oxide and carbon nanotubes have been developed and have displayed noteworthy sensor activity in many applications. For instance, a highly sensitive electrochemical lead sensor was recently developed based on a graphene oxide (GO)/carbon nanotube (CNT)/poly(o-toluidine) (PoT) nanocomposite (GO-CNT-PoT). The GO-CNT-PoT nanocomposite was painted on a GCE layer to give an electrochemical sensor that had a very good selective response to Pb<sup>2+</sup> ions in solution. This sensor displayed high sensitivity, good selectivity, and a detection limit of 89.0 pM [57]. A selective Cd(II) sensor was developed by using a nanocomposite cation-exchange substance, poly(o-toluidine) Ce(IV) phosphate [58]. Reduced graphene oxide (RGO), Prussian blue (PB), and poly(toluidine blue O) (PTBO) sensors have been reportedly utilized for the determination of H<sub>2</sub>O<sub>2</sub>. The results showed that the GC/RGO/PB/PTBO-modified electrode provided good sensitivity and high stability for the analysis of H<sub>2</sub>O<sub>2</sub> in phosphate buffer solution (pH 7.4) [59]. Some other hydrogen peroxide sensors were developed by Change et al. In 2013, an electrochemical biosensor was prepared for the

determination of  $\text{H}_2\text{O}_2$  by integrating graphene with gold nanoparticles and poly(toluidine blue O) films. The modified electrode showed exceptional selectivity and excellent stability for  $\text{H}_2\text{O}_2$  [60]. A NADH sensor was improved by utilizing a poly(toluidine blue O) (PTBO)-ordered mesoporous carbon (OMC)-ionic liquid (IL) gel/GC electrode, wherein the polymerization of a composite containing TBO-functionalized OMC was achieved by  $\pi$ - $\pi$  stacking interactions with the IL.

The modified electrode showed a low limit of detection of 0.004 mg/dL and high conductivity, as determined by electrochemical methods [61]. As shown in Fig. 4, a selective Pb(II) electrode was developed by a solution casting process utilizing polystyrene as a binder of poly(*o*-toluidine (POT)/multiwalled carbon nanotubes (MWCNTs)/Sn(IV) tungstate (ST) thin films (PoT/MWCNTs/ST thin films) [62].

### 3.4 Poly(*o*-anisidine) and Its Related Composite Material Sensor Applications

Orthoanisidine polymer is one of the most favorable CPs, and its unrivaled properties have allowed it to be used in many

applications. Orthoanisidine-based CP composites have been utilized in the manufacture of memory devices, electrochromic devices, semiconductors, and thin-film transistors. Notwithstanding these applications, polyorthoanisidine-based composite substances have been utilized in the creation of numerous sensors, including those used for the determination of neurotransmitters, gases, glucose, and numerous different analytes [63]. Various mixtures of substances with orthoanisidine-based polymers have been analyzed for use as glucose biosensors. For example, polyorthoanisidine films doped with perchlorate and paratoluene sulfonate anions were synthesized electrochemically. The films were observed to be appropriate for the immobilization of glucose oxidase protein and were observed to be an effective detection matrix for glucose. The films additionally showed reactant movement towards the oxidation of NADH [63]. Sangamithirai et al. synthesized poly(*o*-anisidine) (PoA)/graphene (GR) nanocomposites via chemical oxidative polymerization. The prepared nanocomposites were utilized to modify glassy carbon electrodes (GCEs), and the modified electrodes were found to show electrocatalytic activity for the oxidation of NADH

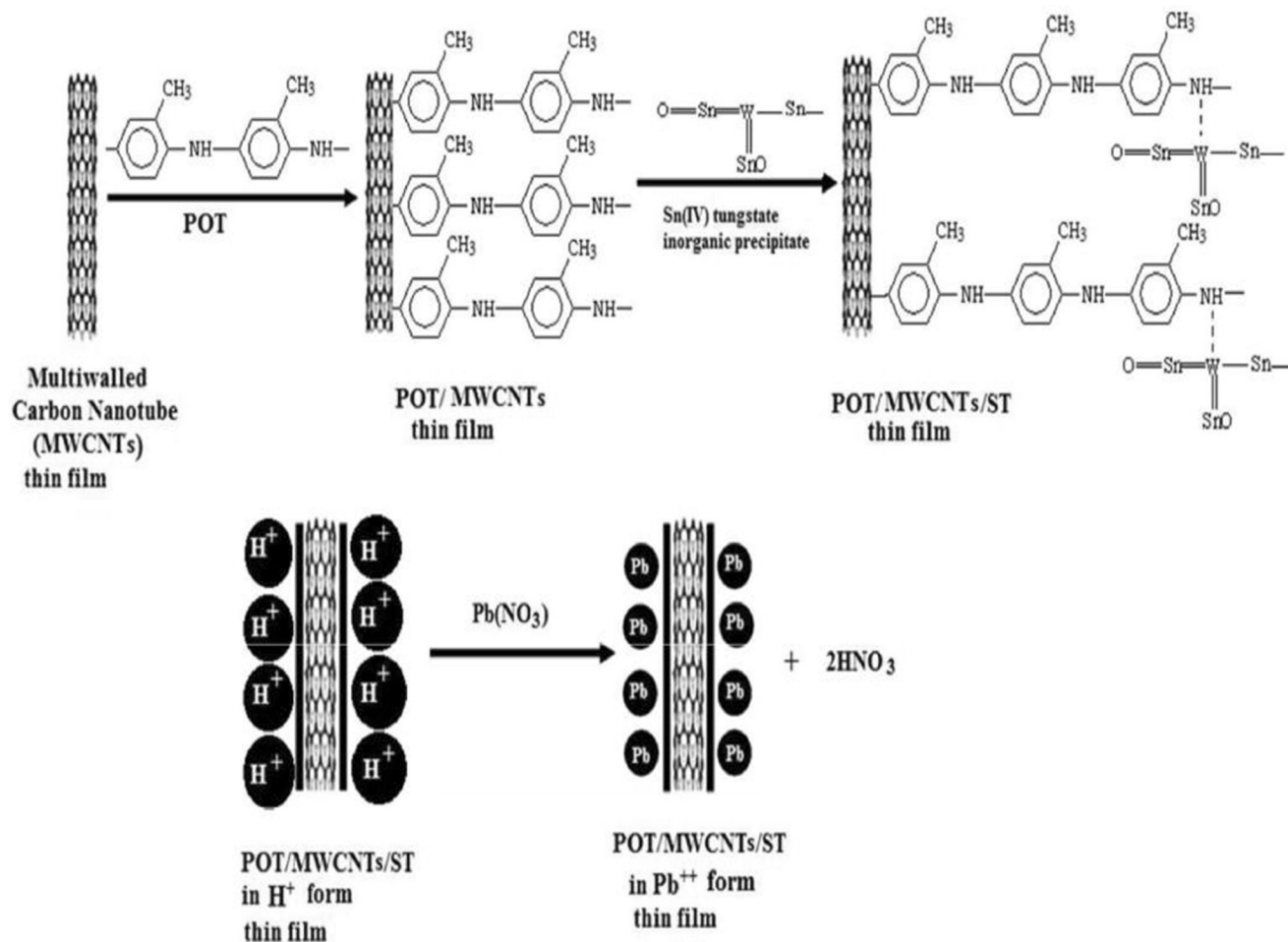


Fig. 4 The graphical impersonation of the structure of PoT, PoT/ MWCNTs, and PoT/MWCNTs/ST ion exchange thin films [62]



(Fig. 5). This fabricated sensor showed a current response with excellent sensitivity, good stability, and high selectivity for the detection of NADH [64]. On the other hand, poly(o-anisidine)-silver nanocomposites were prepared and used as sensors for the detection of NADH and dopamine. The detection limits were 6 nM and 52 nM for NADH and DA, respectively. The modified electrodes displayed high sensitivity, good stability, excellent selectivity, and high reproducibility [65]. Aussawasathien et al. prepared poly(o-anisidine)-polystyrene composite fibers and utilized them for chemical vapor sensing [66]. A sensitive electrochemical assay was developed to detect 3-methoxy phenol by a poly(o-anisidine)/silverized multiwalled carbon nanotube (PoAS-Ag/MWCNT) nanocomposite [67]. The PoAS-Ag/MWCNT nanocomposite was prepared by adsorption between PoAS and MWCNTs using a solution technique (Fig. 6).

The fabricated electrochemical sensor also showed excellent sensitivity, high dynamic concentration ranges, good stability, and enhanced electrochemical performance towards 3-methoxy phenol [68]. Moreover, a rapid process to determine dopamine (DA) was developed, and a sensor modified with poly(o-anisidine) (PoA) and a silver nanoparticle (AgNP)-based nanocomposite was applied [69] to poly(o-anisidine)/CNT nanocomposite [70]. Recently, Ag was electrodeposited on a polyorthoanisidine CP. As explained in Fig. 7, this nanocomposite displayed high stability and an electrochemically active area and was utilized for the selective determination of

paracetamol (PCM) [71]. The same group synthesized a new functionalized poly(o-anisidine)/GO nanocomposite and used it for the analysis of benzaldehyde [72]. A poly(o-anisidine)/carbon nanotube (PoAS/CNT) nanocomposite sensor was utilized for the determination of inorganic vapor [73]. The modification of sensors with poly(o-anisidine) (PoA)-tin oxide ( $\text{SnO}_2$ ) nanocomposites has become a favored process in sensor research aiming to reach different analytical objectives and utilizing various processes. Recently, a combination of poly(o-anisidine) and tin oxide was studied to determine humidity. The sensor was prepared by in situ chemical polymerization of o-anisidine in the presence of  $\text{SnO}_2$  nanoparticles. The PoA- $\text{SnO}_2$  nanocomposite sensor was used to quantify humidity and showed better humidity sensing properties than pure PoA, including high sensitivity, rapid response, fast recovery, and good repeatability [74]. Khan et al. developed a sensor that utilized a poly-o-anisidine Sn(IV) tungstate composite. A nanocomposite electrochemical sensor showed the selective and sensitive determination of Hg(II) ions [75].

### 3.5 Sensor Applications of Other Conducting Polymers and Their Related Composite Materials

Although traditional polymers and their composites have been widely utilized, other polymers, such as poly(diaminonaphthalene), polypyrrole, polyterthiophene, polyindole, and polyazulene, have been used in various

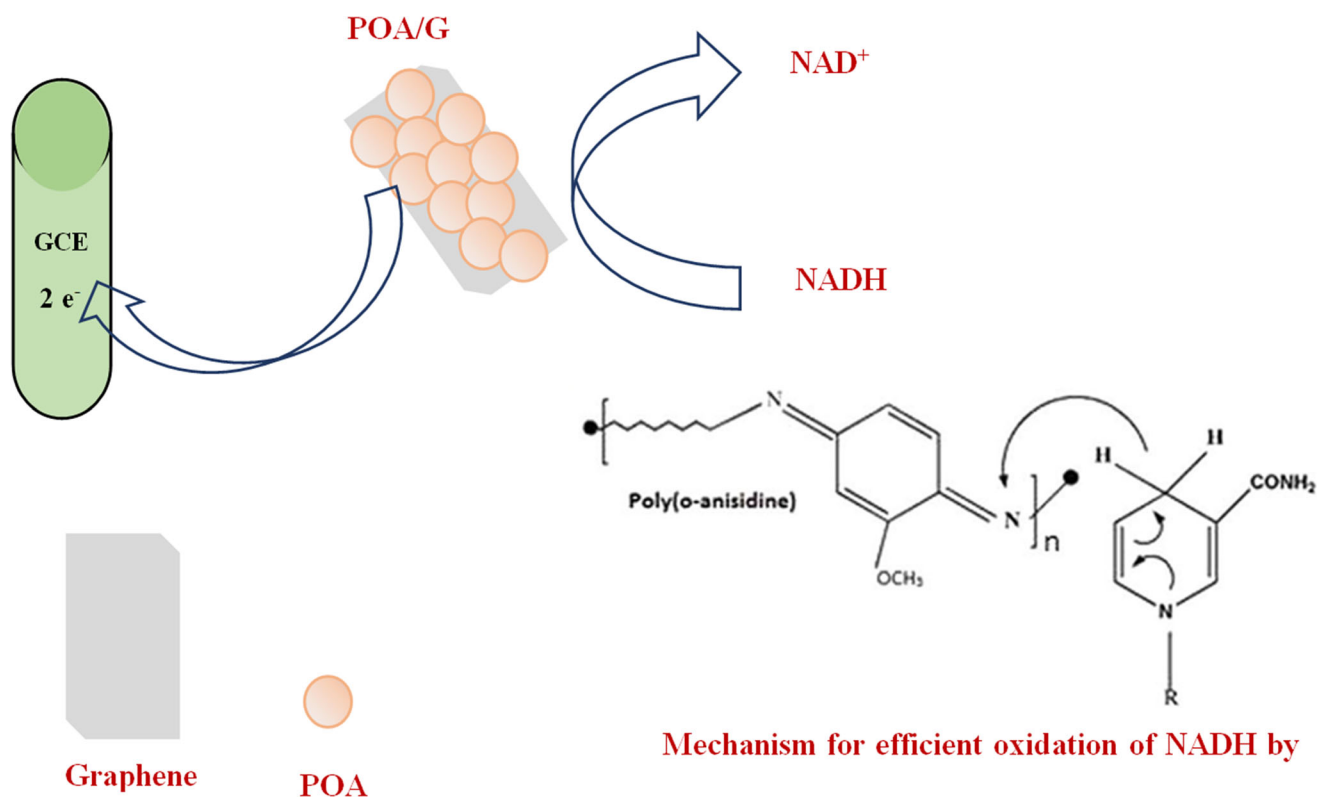
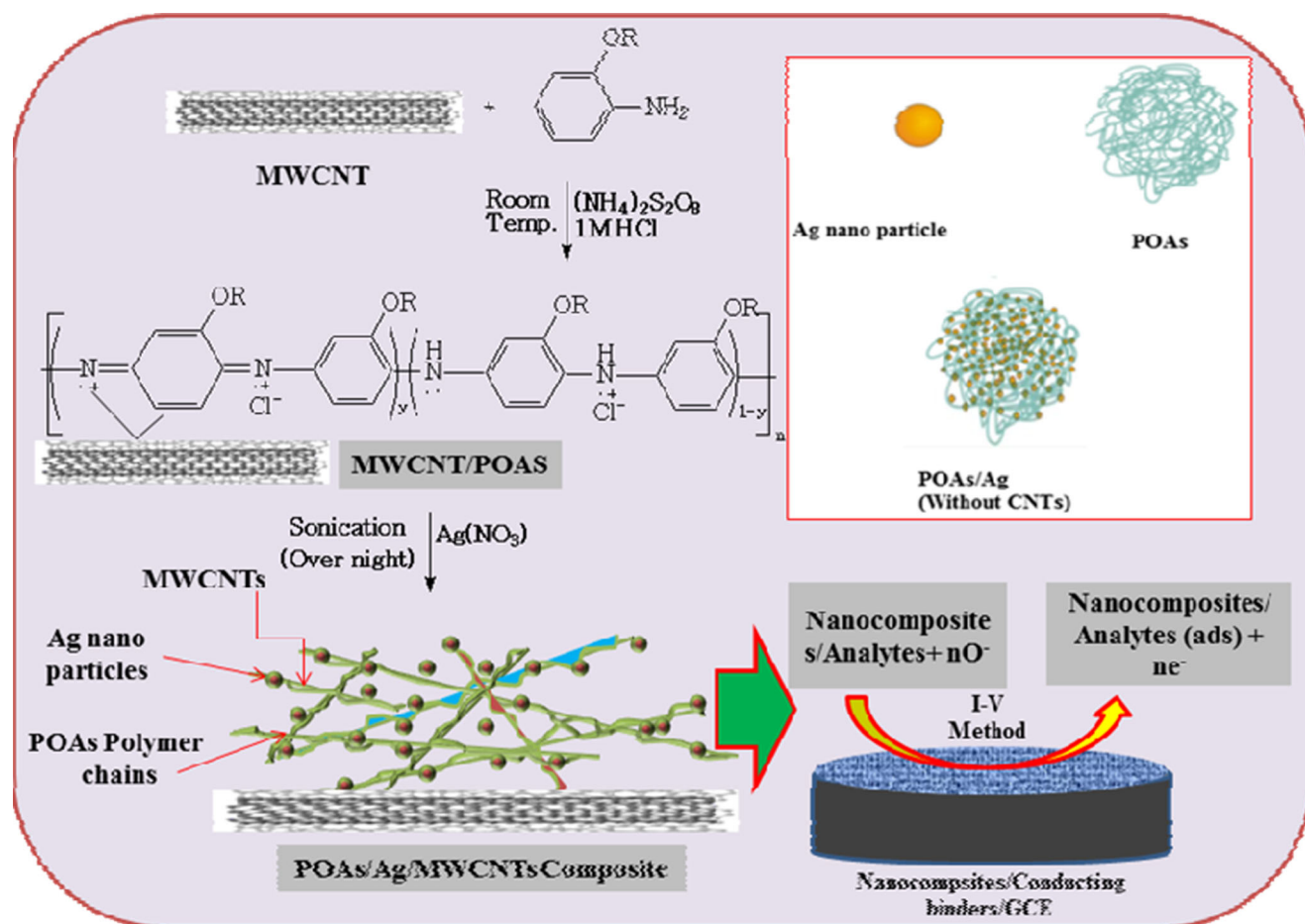


Fig. 5 Intermediate electron transfer on a PoA/GR-modified electrode through NADH oxidation



**Fig. 6** Graphical impersonation of the synthesis of PoAS-Ag/MWCNTs, polymer composite fabrication onto glassy carbon electrode, and electrochemical sensor applications [67]

electrochemical sensors. In 2009, poly(1,5-polydiaminonaphthalene) was combined with Cibacron blue to create a composite film used for dopamine detection [76]. Shim et al. prepared a composite film from blue 4 dye in poly(1,5-DAN) for acetaminophen and dopamine detection [77]. To assist this approach, in 2015, Mir et al. synthesized a composite layer on an electrode surface from GO combined with poly(1,5-polydiaminonaphthalene). This electrode surface exhibited a high response increase and displayed the lowest limit of detection for dopamine ( $0.005 \mu\text{M}$ ) [78]. The modification of biosensors based primarily upon graphene and PPy composites has become a favorable approach in electrochemical analysis to achieve specific analytical goals by utilizing numerous techniques. Recently, the combination of graphene with overoxidized PPy composites was studied to determine guanine [79]. Mao et al. developed an electrochemical sensor probe that utilized poly(ionic liquids) (PILs) with a PPy cross composite. Electrochemical sensor probes containing PILs/PPy/GO nanocomposites achieved the regular and selective determination of dopamine [80]. Tiwari et al. improved a

biosensor by utilizing a mixture of graphene substances, AuNP, and PPy. This sensor indicated excellent sensitivity ( $1 \times 10^{-9} \mu\text{M}$ ) [80]. Early research into the enhancement of sensors by terthiophene polymers was performed by Shim et al. The aim was to improve electrocatalytic composite materials and electrochemical sensors [81]. For instance, Shim et al. developed an electrochemical sensor with the aid of 5,2:5,2-terthiophene-3-carboxylic acid (TTCA) monomers on a glassy carbon electrode to detect DNA hybridization [82]. Moreover, poly(indole-6-carboxylic acid) was further utilized for the determination of DNA hybridization [83]. Together with polyazulene, polyindole and its composites have also been examined for diverse applications [84]. Recently, thiophene acetic acid and azulene copolymer were modified on an electrode surface to produce an electrochemical sensor for the determination of  $\text{H}_2\text{O}_2$  [85]. In another study, n-type polybenzimidazobenophenethroline-poly(ethylene oxide) (BBL-PEO) was blended with p-type polyazulene to create a composite layer. This layer was applied in sensor studies [86]. Table 1 summarizes CP detect, linear range, and LoD.

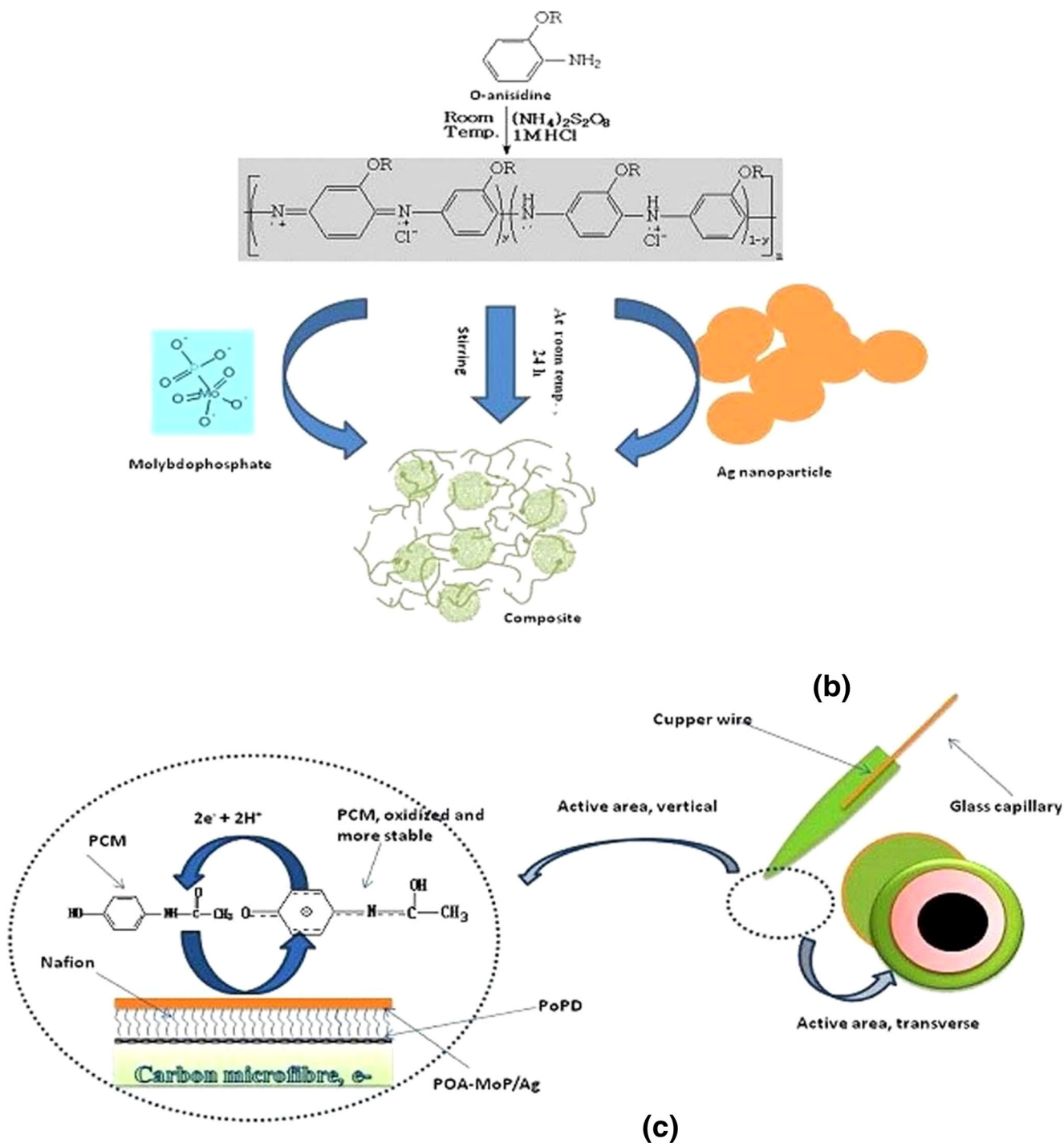


Fig. 7 Graphical impersation for the synthesis of PoA-MoP/Ag nanocomposite and modification of carbon fiber microelectrode displaying active sensing area vertical and transverse (A) to (C) [71]

### 4 Conclusions

Conducting polymers, such as polyaniline, polyorthoanisidine, polyorthotoluidine, and polypyrrole, have appeared as key new advanced materials for the development of new devices and the structure-dependent characterization of different properties required in developed applications.

Chemical sensors and biosensors are analytical devices that change chemical and biological responses, respectively, into an electrical signal. We have summarized the new improvements in the applications of conducting polymers in chemical sensors. Previous studies have proposed that among conducting polymers, those including polyorthoanisidine, polyaniline, polyorthotoluidine, and polypyrrole display

**Table 1** Types of polymers, electrochemical sensors, detection, the linear range, and the limit of detection

Material	Electrochemical sensors	Detection	The linear range	The limit of detection	Ref.
Polyaniline (PANI)	PANI and carbon nanotube (CNT).	Acid penetration	—	—	[43]
	Polyaniline/ZnO	Ammonia gas	—	—	[44]
	PANI/graphene nanocomposite	Hydrazine	0.01 $\mu$ M–0.01 M	15.38 mM	[45]
	Polyaniline-(acrylonitrile-butadiene-styrene) composite	Aqueous ammonia	$10^{-4}$ – $10^{-5}$ N	—	[46]
	PAN-PAN/PPO	Phenols	—	—	[47]
	AuNPs-PANABA-(MWCNTs) nanocomposite	2,4-Dichlorophenoxy acetic acid	—	0.0003 ppm	[49]
	AuNPs-PANI	Glucose	0.01–8 mM	0.0007 mM	[50]
	PtNP/PANI hydrogel	Uric acid	0.07–1 mM	0.001 mM	[51]
	AuNPs/PANI/PDA hybrid composite	Ascorbic acid (AA)	$1.0 \times 10^{-6}$ – $1.9 \times 10^{-3}$ M	0.000399 mM	[52]
	Molecularly imprinted poly (aniline-co-metanicilic acid)	Progesterone	0.64–5.27 ng mL <sup>-1</sup>	1.0 pg mL <sup>-1</sup>	[53]
Poly(o-toluidine) (PoT)	PoT-Au/Cu	Glucose	1–30 mM	0.027 $\mu$ M	[54]
	(TiO <sub>2</sub> ) -PoT	Humidity	—	—	[55]
	(MIP/NGNRs-IL/GCE)	4-Nonyl-phenol (NP)	0.1–120 $\mu$ M	3.4 $\mu$ A	[56]
	(GO-CNT-PoT)	Pb <sup>2+</sup> ions	0.1 nM–1.0 mM	89.0 pM	[57]
	Poly(o-toluidine) Ce(IV) phosphate	Cd(II)	—	—	[58]
	GC/RGO/PB/PTBO	H <sub>2</sub> O <sub>2</sub>	—	—	[59]
	GO/AuNPs/PoT	H <sub>2</sub> O <sub>2</sub>	—	—	[60]
	PTBO/OMC/IL gel/GC	NADH	—	0.004 mg/dL	[61]
	POA/GR	NADH	0.166–1.77 $\mu$ M	47.1 $\mu$ A	[64]
	Poly(o-anisidine)-silver nanocomposites	NADH	0.03–900 $\mu$ M	0.006 $\mu$ M	[65]
Poly(o-anisidine) (PoAN)	Poly(o-anisidine)-silver nanocomposites	Dopamine	5–270 $\mu$ M	0.052 $\mu$ M	[65]
	POAS-Ag/MWCNT	3-Methoxyphenol	0.4 nM–40.0 mM	$0.36 \pm 0.05$ nM	[67]
	POA-AgNP nanocomposite	Dopamine	10.0–140.0 $\mu$ M	0.2 $\mu$ M	[69]
	DPOMA/GO	Benzaldehyde	0.1 nM–0.1 mM	0.03 nM	[72]
	POA-SnO <sub>2</sub>	Humidity	—	—	[74]
	F3GA/PDAN	Dopamine	5–100 $\mu$ M	$0.1 \pm 0.01$ $\mu$ M	[76]
	Blue 4 dye in poly(1,5-DAN)	Acetaminophen and dopamine	—	—	[77]
	Poly(1,5-polydiaminonaphthalene)/GO	Dopamine	—	0.005 $\mu$ M	[78]
	Poly(1,5-polydiaminonaphthalene)/GO	Dopamine	10 nM–1 $\mu$ M	5.0 nM ( $\pm 0.01$ )	[78]
	PPy <sub>ox</sub> /GR	Adenine	0.06–100 $\mu$ M	0.02 $\mu$ M	[79]
5,2:5,2-Terthiophene-3-carboxylic acid	PPy <sub>ox</sub> /GR	Guanine	0.04–100 $\mu$ M	0.01 $\mu$ M	[79]
	PPy/G	Guanine	—	—	[79]
	PILs/PPy/GO	Dopamine	4–18 $\mu$ M	73.3 nM	[80]
	TTCA/GC	DNA	—	—	[82]
	Poly(indole-6-carboxylic acid)	DNA	—	—	[83]

favorable advantages for future applications. Moreover, these polymer composites have shown suitably high selectivity, excellent stability, and good conductivity. Numerous researchers are presently combining nanomaterials with at least two polymers to create very sensitive and selective conjugated substances that generate highly sensitive responses when utilized for detection applications.

## Compliance with Ethical Statements

**Conflict of Interest** The authors declare that they have no conflict of interest.

**Ethical Approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed Consent** Informed consent was obtained from all individual participants included in the study.

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