Conducting polymer-based peroxidase mimics: synthesis, synergistic enhanced properties and applications

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ABSTRACT The concept of artificial enzymes has been proposed for a long time and a large variety of materials have been exploited in enzyme-like catalytic field for decades. The emergence of nanotechnology provides increasing opportunities for the development of artificial enzymes. Conducting polymer-based nanocomposites are a new type of burgeoning functional materials as enzyme mimics owing to their numerous functional groups, excellent electrical conductivity and redox properties. This review summarizes the recent progress of the synthesis of conducting polymers and their nanocomposites, as well as their applications as efficient peroxidase mimics. After a brief description of the development of conducting polymers, we specifically introduce the fabrication of conducting polymers and their nanocomposites *via* diverse approaches and show the enhanced peroxidase-like catalytic properties. In addition, the mechanism of the enhanced catalytic efficiency of the conducting polymer-based nanocomposites has been proposed. Finally, we highlight the applications of such conducting polymer-based nanocomposites in the sensitive detection of different types of substances. It is anticipated that this review will pave the way for developing more intriguing functional nanomaterials as enzyme mimics, which shows promising applications in a great many technological fields.

Keywords: conducting polymers, artificial enzymes, peroxidase mimics, nanocomposite, synergistic effect

INTRODUCTION

Since the discovery in 1970s, conducting polymers with highly π -conjugated chain structures have been developed rapidly in decades due to their incredible electrical and optical properties [1–5]. Up to now, a large number of conducting polymers have been found and explored in diverse applications, typical species of which include

polyaniline (PANI), polypyrrole (PPy), polyacetylene (PA), poly(phenylenevinylene) (PPV), polythiophene (PTh) and their derivatives. Generally, conducting polymers possess low conductivity in the neutral states, and their intrinsic conductivity is attributed to doped charge carriers. However, conducting polymers are able to exhibit a high conducting ability, whose electrical conductivity depends on the doping levels. In addition, conducting polymers have reversible doping ability, excellent optical activity, ease of synthesis, low cost, as well as outstanding intrinsic flexibility. With these distinctive properties, they have shown broad promising applications in the fields of sensors, actuators and separation membranes [1–5].

Recently, principally impelled by the requirement of improved performance and extended functionality of conducting polymers, nanostructured conducting polymers with a unique morphology have gradually become a research hotspot [6–14]. Compared with conventional bulk conducting polymers, nanostructured ones possess remarkably larger surface area, superior carrier mobility, and favorable processibility owing to their nanosize effects. In the past two decades, many kinds of synthetic approaches including self-assembly polymerization, interfacial polymerization, rapid mixing polymerization, seeding polymerization, and ultrasonication assisted polymerization, etc. have been developed to prepare nanostructured conducting polymers [6–16]. To promote or extend the functionality of conducting polymers, it is an effective way to form composite nanomaterials *via* the combination of other components with conducting polymers [17–20]. Conducting polymer-based nanocomposites not only possess the advantages of each component, but also contribute to the enhanced or new distinct properties originating from the synergistic effect

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between components. For instance, hollow graphene/conducting polymer composite fiber electrode shows outstanding electrochemical performance as well as high flexibility compared to the individual component electrode, offering promising potential applications in wearable electronics [21]. In addition, the conducting polymer-based nanocomposites have shown broad applications in a large variety of fields including nanoelectronics, photoelectronics, sensors, catalysis, energy storage and conversion devices, energy harvesting devices, electromagnetic interference shielding, corrosion protection, environmental science, drug delivery, bioengineering, etc. [9,17–20,22–26].

To date, natural enzymes have been proved to be the earliest and most widely applied biocatalysts in our lives owing to their extraordinarily high catalytic activity and specificity. However, the sensitivity of the catalytic efficiency to environmental conditions, complicated production and purification process, and high output cost has dramatically restricted their broad applications [27–29]. To solve these problems, artificial enzymes which serve as alternative to natural enzymes have aroused increasing attention in recent years [30–35]. Nowadays, by means of the continuous efforts of researchers, the application of enzyme mimics has covered a large variety of fields such as biochemistry, sensors, catalysis, environmental science, biomedicine and energy [36–39]. Among various types of artificial enzymes, nanomaterials including noble metal nanoparticles, carbon nanomaterials, metal oxides, and metal sulfides have attracted more and more attention because of their large surface area, easy synthesis, tunable catalytic activity, and superior stability [32–35]. Such nanomaterials have been widely reported to mimic the catalytic activity of peroxidase, oxidase, catalase, and superoxide dismutase. As a crucial section of artificial enzymes, peroxidase mimics are one type of enzymes that are able to catalyze the oxidation of substrates by H_2O_2 as electron accepters, which have been paid increasing attention owing to their broad applications. Although most of the conducting polymers hardly show peroxidase-like activity, they have been proved to be efficient co-catalyst to enhance the peroxidase-like catalytic performance due to the improved affinity to the peroxidase substrates and excellent electron transfer ability to reduce the recombination of electrons and holes. In addition, the modification of conducting polymers with functional nanomaterials will change the electronic structure and Fermi level of the active nanomaterials, which facilitates the electron transfer from nonbonding orbital of the peroxidase substrate to the

lowest unoccupied molecular orbital (LUMO) of H_2O_2 [40]. Therefore, with the advantage of abundant functional groups, large surface area, and intrinsic electrical and redox property, a synergistic catalytic effect is usually achieved for the conducting polymer-based peroxidase mimics. It is anticipated that such conducting polymer-based nanocomposites will show a bright future in biochemistry, food science, biomedicine, and environmental technology.

In this review, we show an overview of the design, preparation, and the peroxidase-like properties of the conducting polymer-based nanocomposites. This review mainly contains four sections: the first section shows the description of different types of conducting polymer and their nanocomposites as peroxidase mimics and their synergistic catalytic properties. The following section illustrates the possible mechanism for the enhanced peroxidase-like catalytic efficiency of the conducting polymer nanocomposites. The third section highlights a range of sensing applications associated with the conducting polymer-based nanocomposites as peroxidase mimics. Finally, we will give a conclusion on this subject and the promising prospects towards future research in this field.

CLASSIFICATION OF CONDUCTING POLYMER-BASED PEROXIDASE MIMICS

Individual conducting polymers

Generally, most of the conducting polymers possess weak or no peroxidase-like catalytic activity. However, the doping state and the surface charge of conducting polymers are beneficial to improve their catalytic efficiency. For example, Ren, Qu and co-workers [41] have demonstrated that PPy nanoparticles doped with a little content of iron complex exhibited a peroxidase-like activity. The PPy nanoparticles with an average diameter of 58.8 nm were prepared *via* a microemulsion polymerization using FeCl_3 as the oxidant and polyvinyl alcohol (PVA) as a stabilizer. The energy dispersive X-ray (EDX) result demonstrated the presence of Fe element in the PPy nanoparticles, proving the doping state of iron complex. The presence of iron complex contributed a peroxidase-like activity of the as-prepared PPy nanoparticles toward the oxidation of 3,3',5,5'-tetramethylbenzidine (TMB) in the presence of H_2O_2 . This result demonstrated that doping with active components could improve the catalytic efficiency of the conducting polymer peroxidase mimics. In addition, the surface charge of conducting polymers is also an important factor

to improve the peroxidase-like activity. It has been reported that a polythiophene derivative poly(3,4-ethylenedioxythiophene) (PEDOT) possess negligible peroxidase-like activity [42]. However, an anionic polythiophene derivative poly[2-(3-thienyl)ethyloxy-4-butylsulfonate] (PTEBS) showed an intrinsic peroxidase-like activity toward the oxidation of TMB, indicating the key role of the surface charge on the peroxidase-like properties [43]. In fact, PTEBS with negative charge in side chain enhanced the adsorption of peroxidase substrate of TMB with positive charge, which has been proved by the Michaelis Menten constant (K_m) values. The superior affinity of PTEBS to the peroxidase substrate contributed to the good peroxidase-like activity. In addition, a fast electron transfer from PTEBS to H_2O_2 will also increase the reaction rate of the oxidation of TMB. In a word, it is hopeful to construct high-performance conducting polymer-based peroxidase mimics by tuning their chemical structure such as the doping state and the surface charge.

Conducting polymer/noble metal nanocomposites

Up to now, noble metal nanomaterials have been developed rapidly due to their distinctive electronic, optical, magnetic and catalytic properties compared with the bulk materials. In consideration of their reasonable and effective utilization in many fields, the synthesis of noble metal nanomaterials with a controllable size, shape, surface/interface effect, and architecture has become an interesting topic [44–49]. Especially, unique chemical structures and optimal surface compositions endow noble metal nanomaterials with property studies for specific catalytic reactions. Recently, noble metal and their alloy nanoparticles including positively-charged Au nanoparticles, dendrimer-encapsulated Pt nanoparticles, and porous PtPd nanorods have been shown to possess intrinsic peroxidase-like activity [50–52]. To enhance the peroxidase-like activity of noble metal nanoparticles, they are usually deposited on the surface of electronically transmitted supporting materials to maintain their small size and generate a synergistic effect and/or the electronic effect. For example, a synergistic enhanced catalytic activity has been produced by the *in situ* fabrication of naked Au nanoparticles on graphene nanosheets, which could be used as peroxidase mimics for the detection of DNA [53,54].

Conducting polymers are one kind of excellent electronically transmitted supporting materials, which are good candidates to support noble metal nanoparticles for peroxidase mimicking. It has been reported that polyaniline:poly(sodium 4-styrenesulfonate) (PANI:PSS)-sta-

bilized Au nanoparticles with a size of 9.9 ± 0.5 nm showed much better peroxidase-like catalytic activity than PANI/Au nanocomposites and PANI:PSS/mercaptoacetic acid (MAA)-Au composites, due to the higher affinity of PANI:PSS-Au nanoparticles to both H_2O_2 and TMB substrates (Fig. 1a–c) [55]. Recently, our group developed a facile self-assembly polymerization approach to prepare PANI/Au nanorices with a long-axis diameter of about 1 μ m and a width-axis diameter of around 400 nm (Fig. 1d) [56]. The unique nanorice structure with Au nanoparticle encapsulated within PANI matrix provides strong interactions between Au nanoparticles and PANI materials. It was found that the as-prepared PANI/Au nanorices exhibited an excellent peroxidase-like activity (Fig. 1e). Compared with the individual Au nanospheres and PANI nanowires alone, the peroxidase-like catalytic activity of PANI/Au nanorices was much enhanced (Fig. 1f). It is apparent that the higher catalytic activity of Au/PANI nanorices should be attributed to the synergistic effect or electric effect between Au nanoparticles and the PANI matrix. We have also demonstrated a simple two-step approach to prepare coaxial Pd@PEDOT nanocables as efficient peroxidase mimics (Fig. 2a, b) [42]. Firstly, Te@PEDOT nanocables were synthesized *via* a self-assembly redox polymerization between 3,4-ethylenedioxythiophene monomer and sodium tellurite without the addition of any surfactants. Then a galvanic replacement reaction was used to convert Te@PEDOT to Pd@PEDOT nanocables. The core-sheath structure of the Pd@PEDOT offers obvious interface and interactions between Pd nanowires and PEDOT materials. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) images showed homogeneous nanocable-like nanostructures (Fig. 2c, d). Owing to the novel coaxial structure, high crystallinity of Pd core, and synergistic effect between Pd core and PEDOT sheath, the resultant Pd@PEDOT nanocables displayed a superior peroxidase-like catalytic activity toward the oxidation of TMB in the presence of H_2O_2 compared with commercial Pd black (Fig. 2e, f). This result demonstrated that the construction of conducting polymer/noble metal nanocomposites was a good choice to fabricate efficient peroxidase mimics.

Conducting polymer/metal oxide nanocomposites

Since Fe_3O_4 nanoparticles were first reported to possess intrinsic peroxidase-like catalytic property [57], a large variety of metal oxide nanomaterials have been developed as peroxidase mimics, such as V_2O_5 nanowires [58], Co_3O_4 nanoparticles [59], CuO nanoparticles [60], CeO_2 nanoparticles [61], TiO_2 nanotube arrays [62], VO_2 na-

Figure 1 (a, b) TEM micrographs of the PANI:PSS-Au nanocomposites. (c) Ultraviolet-visible (UV-vis) absorption spectra of a TMB- H_2O_2 solution in the absence (black curve) and presence of PANI:PSS-Au (red curve), PANI-Au (blue curve), and PANI:PSS/MAA-Au (green curve), respectively. All the solutions were incubated at 45°C for 30 min. The inset shows the color of corresponding solutions after incubation. Reprinted with permission from Ref. [55], Copyright 2014, the Royal Society of Chemistry. (d) SEM image of the prepared Au/PANI nanorices. (e) UV-vis absorption spectra of the systems of TMB + H_2O_2 , the TMB + Au/PANI nanorice catalyst, the H_2O_2 + Au/PANI nanorice catalyst, and the TMB + H_2O_2 + Au/PANI nanorice catalyst in pH 4.0 acetate buffer at room temperature. The inset figure shows the photograph of the above four systems. (f) Comparison of the catalytic activities of PANI nanofibers, Au nanospheres, and Au/PANI nanorices under the same conditions. Reprinted with permission from Ref. [56], Copyright 2017, the Royal Society of Chemistry.

nobeltes [63], etc. However, individual metal oxides as peroxidase mimics usually showed relatively low peroxidase-like activity. Therefore, it is a meaningful object to enhance their peroxidase-like activity by tuning their compositions or chemical structures. In view of the extraordinary electrical conductivity of conducting polymers, the combination of metal oxides with conducting polymers might exhibit an excellent electronic effect, and thus enhance the peroxidase-like catalytic activity [64,65]. Our group developed a two-step approach to prepare $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers. Firstly, $\text{TiO}_2/\text{Fe}_2\text{O}_3$ composite nanofibers were synthesized through an electrospinning followed by calcination process [64]. Then an *in situ* polymerization was used to coat a layer of PPy on the surface of $\text{TiO}_2/\text{Fe}_2\text{O}_3$ composite nanofibers using Fe_2O_3 as an oxidant. The as-prepared $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers exhibited a uniform core-shell structure with a coarse surface (Fig. 3a). Compared with the polymerization of pyrrole by the additional oxidant, this approach demonstrated the preparation of $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers with efficient interactions between PPy and $\text{TiO}_2/\text{Fe}_2\text{O}_3$ nanofibers. The resulting $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ ternary nanocomposites have been verified as efficient artificial enzymes. As shown in Fig. 3b, the prepared $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofi-

bers showed an excellent peroxidase-like activity toward the oxidation of TMB. In addition, the synergistic effect among individual components has been investigated through comparing the peroxidase-like property of the obtained ternary $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers with individual TiO_2 , Fe_2O_3 and $\text{TiO}_2/\text{Fe}_2\text{O}_3$ composite nanofibers (Fig. 3c). This result clearly demonstrated that the modification of PPy strongly enhanced the peroxidase-like catalytic activity of metal oxides. A similar result on the synergistic enhanced peroxidase-like catalytic activity was also observed in a $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ nanofiber system [65]. The ternary $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ nanofibers were prepared *via* electrospinning followed by post-polymerization of EDOT using Co_3O_4 as oxidant, which showed a core-shell structure with the outer size ranging from several nanometers to 30 nm (Fig. 3d). Due to the synergistic effect between CeO_2 , Co_3O_4 and PEDOT, the peroxidase-like catalytic activity of the $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ nanofibers was much better than that of individual CeO_2 , Co_3O_4 and $\text{CeO}_2/\text{Co}_3\text{O}_4$ composite nanofibers (Fig. 3e, f).

Conducting polymer/metal sulfide nanocomposites

It is generally known that metal sulfides are one indispensable branch of artificial enzymes. In the aspect of

Figure 2 (a) The synthetic route of Te@PEDOT coaxial nanocables by one-step self-assembly redox polymerization. (b) Schematic illustration of the fabrication process of Te@PEDOT and Pd@PEDOT coaxial nanocable. (c, d) SEM and TEM images of the synthesized Pd@PEDOT composite nanocables. (e) Typical photographs and UV-vis absorption curves of TMB solutions oxidized by different systems in acetate buffer solution (pH 4.0) recorded at 10 min in the presence of H₂O₂. (f) Time-dependent absorption changes at 651 nm with the addition of different types of catalysts (Pd@PEDOT, Pd black, Te@PEDOT, and pure PEDOT material). Reprinted with permission from Ref. [42], Copyright 2017, American Chemical Society.

peroxidase-like catalysis, metal sulfide nanomaterials have been subjected to intensive study owing to their terrific activities. For example, sheet-like FeS nanomaterials [66], CuS nanoparticles [67], MoS₂ nanosheets [68], and CoS nanospheres [69] have been investigated as efficient peroxidase mimics. In order to further increase the peroxidase-like property and extend their applications, the combination of conducting polymers with metal sulfides has been regarded as an available solution [70,71]. Our group first demonstrated a novel approach to decorate Cu₉S₅ nanocrystals on the surface of PANI nanowires as peroxidase mimics [70]. The synthetic procedure involves three steps (Fig. 4a). Firstly, hydrochloric acid (HCl) doped PANI nanowires were prepared *via* a rapid-mixing approach. Secondly, the HCl doped PANI nanowires were treated with aqueous ammonia and then doped with MAA to form MAA doped PANI nanowires. Thirdly, a hydrothermal reaction was performed between MAA doped PANI nanowires and copper ions to produce PANI/Cu₉S₅ hybrid nanowires. This synthetic strategy provides the well dispersed Cu₉S₅ nanocrystals on

the surface of PANI nanowires and the strong interactions between Cu₉S₅ nanocrystals and PANI matrix (Fig. 4b, c). By ruling out the possibility of the Cu²⁺ leaching for the peroxidase-like activity, we have confirmed the intrinsic peroxidase-like catalytic activity of the prepared PANI/Cu₉S₅ hybrid nanofibers. By comparison, the PANI/Cu₉S₅ hybrid nanofibers showed a factor of around 30 fold higher than that of Cu₉S₅ nanocrystals that were synthesized with a similar procedure and more than 1000 fold higher than that of individual PANI nanofibers (Fig. 4d, e). The superior catalytic performance of the PANI/Cu₉S₅ hybrid nanofibers should be attributed to the synergistic effect between PANI and Cu₉S₅ components due to their strong interactions. Another typical example of conducting polymer/metal sulfide hybrid is algae-like MoS₂/PPy nanocomposite, which was prepared *via* a one-pot redox reaction strategy between ammonium tetrathiomolybdate and pyrrole monomer [71]. The as-prepared MoS₂/PPy nanocomposite exhibited a unique algae-like structure with a few layer of MoS₂ nanosheet coated with PPy. As peroxidase mimics, the as-prepared

Figure 3 (a) SEM and TEM image (inset) of the synthesized TiO₂/Fe₂O₃/PPy composite nanofibers. (b) UV-vis absorption curves of TMB solutions oxidized by different systems in acetate buffer solution (pH 4.0) recorded at 750 s in the presence of H₂O₂. The inset shows a typical photograph of TMB solution oxidized by TiO₂/Fe₂O₃/PPy composite nanofibers in the presence of H₂O₂. (c) Time-dependent absorbance changes at 651 nm with the addition of different kinds of catalysts (20 μg mL⁻¹) in the presence of 0.1 mmol L⁻¹ TMB and 65 mmol L⁻¹ H₂O₂. Reproduced with permission from Ref. [64] Copyright 2016, the Royal Society of Chemistry. (d) SEM and TEM image (inset) of the prepared CeO₂/Co₃O₄/PEDOT composite nanofibers. (e) Typical photographs and UV-vis absorption curves of TMB solutions oxidized by different systems in acetate buffer solution (pH 4.0) recorded at 10 min in the presence of H₂O₂. (f) Comparison of the catalytic activities of CeO₂, Co₃O₄, CeO₂/Co₃O₄, and CeO₂/Co₃O₄/PEDOT composite nanofibers under the same conditions. Reprinted with permission from Ref. [65], Copyright 2017, IOP Publishing Ltd.

MoS₂/PPy nanocomposites showed an enhanced catalytic activity compared with individual MoS₂ flowers, pure PPy, and their physical mixtures. In addition, the content of PPy in MoS₂/PPy nanocomposite has a large influence on their peroxidase-like activity. A double content of PPy resulted in a reduced peroxidase-like catalytic activity. Recently, ternary CuFe₂O₄/Cu₉S₈/PPy hybrid nanotubes were synthesized as efficient peroxidase-mimics through a three-step way [72]. During the synthetic process, CuFe₂O₄/CuO hybrid nanofibers were firstly prepared *via* an electrospinning followed by a calcination process. Then CuO in the hybrid nanofibers could be used as the oxidant for the polymerization of pyrrole, resulting in the formation of PPy within the hybrid nanofibers accompanied by partial reduction of Cu(II). Meanwhile, a sulfuration process took place between the copper source and thioacetamide to generate Cu₉S₈ in the hybrid nanofibers (Fig. 5a–g). Similarly, a synergistic catalytic effect has been investigated for the peroxidase-like catalytic reaction. The as-prepared ternary CuFe₂O₄/Cu₉S₈/PPy hybrid nanotubes showed a better peroxidase-like catalytic activity than individual CuFe₂O₄ nanofibers, CuFe₂O₄/CuO hybrid nanofibers, CuFe₂O₄/CuS hybrid nanofibers, and PPy materials (Fig. 5h, i), which should be attributed to the strong interactions and synergistic

effect among CuFe₂O₄, Cu₉S₈ and PPy components. This work demonstrated that an improved peroxidase-like catalytic activity could be achieved by the introduction of conducting polymers with metal sulfides.

Conducting polymer/hemin nanocomposites

Apart from the inorganic nanomaterials mentioned above, conducting polymers can be combined with other functional materials to form functional nanocomposites as efficient peroxidase mimics. For instance, Dong and co-workers [73] developed a one-pot chemical oxidative polymerization to synthesize PPy/hemin nanocomposites, among which hemin molecule was entrapped in the PPy nanocomposite as a dopant. By using Pluronic123 as a template kit and steric stabilizer, the as-synthesized PPy/hemin nanocomposite exhibited an approximate spherical morphology with a diameter of around 60 nm. The Fourier transform infrared (FTIR) and UV-vis spectra confirmed the formation of the PPy/hemin nanocomposites. It was hypothesized that an improved intrinsic peroxidase-like activity of hemin had been achieved due to its hydrophobic protein microenvironment. Herein, the modification of water-insoluble PPy with hemin can provide a hydrophobic external environment for hemin, which is in favor of the peroxidase-like activity. As a

Figure 4 (a) Schematic illustration of the fabrication process to synthesize PANI/Cu₉S₈ composite nanowires. (b, c) TEM and high-resolution TEM (HRTEM) images of the as-prepared PANI/Cu₉S₈ composite nanowires. (d) The time-dependent absorbance changes at 652 nm in the presence of pristine Cu₉S₈ nanocrystals, PANI nanowires, the physical mixture of PANI nanowires and Cu₉S₈ nanocrystals, and the as-prepared PANI/Cu₉S₈ composite nanowires in pH 4.0 acetate buffer (0.1 mol L⁻¹ NaAc-HAc) at room temperature. (e) Comparison of the catalytic activities of PANI nanowires, pristine Cu₉S₈ nanocrystals, the physical mixture of PANI nanowires and Cu₉S₈ nanocrystals, and PANI/Cu₉S₈ composite nanowires under the same conditions. The difference in the absorbance between 10 and 0 min stands for the activity and the maximum point was set as 100%. Reprinted with permission from Ref. [70], Copyright 2017, Nature Publishing Group.

Figure 5 (a, b) TEM and HRTEM images of the as-prepared CuFe₂O₄/Cu₉S₈/PPy ternary nanotubes. (c–g) EDX element mapping images of Cu-K, Fe-K, N-K, O-K and S-K in the as-prepared CuFe₂O₄/Cu₉S₈/PPy ternary nanotubes. (h) UV-vis spectra of different systems under the condition of pH 4 acetate buffer solution which was recorded for 10 min of the absorption mode. The inset displays the corresponding photographs. (i) Time-dependent absorbance changes of TMB solution in the time course at 650 nm with diverse catalysts and fixed TMB (0.15 mmol L⁻¹) as well as H₂O₂ (97.5 mmol L⁻¹). Reprinted with permission from Ref. [72], Copyright 2017, the Royal Society of Chemistry.

Figure 6 Steady-state kinetic assay of $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ composite nanofibers. The $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ composite nanofibers concentration was fixed at $10 \mu\text{g mL}^{-1}$ in 3 mL of acetate buffer solution (pH 4.0). (a) TMB concentration was kept constant at $100 \mu\text{mol L}^{-1}$. (b) H_2O_2 concentration was maintained at 5 mmol L^{-1} . (c, d) Double reciprocal plots of catalytic activities for H_2O_2 and TMB substrates. Reprinted with permission from Ref. [65], Copyright 2017, IOP Publishing Ltd.

result, the as-prepared PPy/hemin nanocomposite showed an enhanced peroxidase-like catalytic activity toward the oxidation of TMB and *o*-phenylenediamine over individual hemin and PPy materials. This study demonstrates that the modification of conducting polymers may change the external environment of the catalyst, which enhances their peroxidase-like catalytic activity.

POSSIBLE MECHANISM OF THE ENHANCED PEROXIDASE-LIKE ACTIVITY OF CONDUCTING POLYMER-BASED NANOCOMPOSITES

As mentioned, conducting polymer-based nanocomposites have been verified as excellent peroxidase mimics. Generally, the individual conducting polymers possess weak or no peroxidase-like activity. However, the catalytic activity of the nanomaterials based peroxidase mimics is much improved by the combination of conducting polymers. A possible reason for the enhanced peroxidase-like activity might be due to the increased affinity between the catalysts and substrates after the modification of conducting polymers. Kinetic experiments are usually carried out to explore the catalytic ef-

iciency of the peroxidase mimics. The kinetic parameters including the K_m and the maximal reaction velocity ($V_{\max}$) can be obtained on the basis of the Michaelis-Menten equation. The K_m value is closely related to the affinity between the catalyst and the substrate. The smaller the K_m value, the stronger affinity of the catalyst to the substrates. A smaller K_m value is usually achieved by the introduction of conducting polymers, indicating a stronger affinity between the conducting polymer-based nanocomposite and the peroxidase substrates. For example, the K_m value of $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ composite nanofibers for H_2O_2 substrate (0.12 mmol L^{-1}) is much lower than not only that of individual Co_3O_4 nanoparticles ($140.37 \text{ mmol L}^{-1}$) and CeO_2 nanoparticles (64.6 mmol L^{-1}), but also that of the reported HRP (3.7 mmol L^{-1}) [65] (Fig. 6a, c). The similar result was also observed for the TMB substrate with the K_m value of $1.26 \times 10^{-3} \text{ mmol L}^{-1}$, which is much lower than those of Co_3O_4 nanoparticles ($0.037 \text{ mmol L}^{-1}$), CeO_2 nanoparticles ($0.046 \text{ mmol L}^{-1}$), and HRP (0.43 mmol L^{-1}) (Fig. 6b, d). The results indicate the high affinity of the conducting polymer-based nanocomposites to the H_2O_2 and TMB substrates contributes to the superior peroxidase-like activity.

Another possible mechanism for the enhanced perox-

idase-like activity of the conducting polymer-based nanocomposites is their excellent electron transfer properties. It is well known that the oxidation of the substrate by H_2O_2 is mainly due to the formation of $\cdot\text{OH}$ radical during the peroxidase-like catalytic reaction. For example, when Fe_3O_4 nanoparticles are used as peroxidase mimics, H_2O_2 molecules are adsorbed on their surface and then activated by the bound Fe^{2+} and Fe^{3+} to produce $\cdot\text{OH}$ radical, which is similar with a Fenton reagent. After that, the generated $\cdot\text{OH}$ radical will oxidize the TMB molecules to the oxidation state. During this catalytic reaction, it seems that Fe^{2+} plays a dominant role in the excellent peroxidase-like activity of Fe_3O_4 nanoparticles [5]. It has been reported that the visible light irradiation can excite electrons from the valence band to the conduction band of the semiconductors, and thus the excited electrons may transfer to H_2O_2 to form $\cdot\text{OH}$ radicals or photoexcited holes which can also decompose H_2O_2 into $\cdot\text{OH}$ radicals [74]. However, the photoexcited electrons are easily recombined with the holes in a single semiconductor. In a peroxidase-like conducting polymer-based nanocomposite catalyst such as PANI/ Cu_9S_5 under visible light irradiation, the photoexcited electrons from Cu_9S_5 will transfer to PANI due to the different energy level, which can reduce the recombination of electron-hole pairs and increase the number of the formed $\cdot\text{OH}$ radicals [70]. Therefore, the oxidation ability toward the peroxidase substrate will be largely enhanced.

On the other hand, density functional theory has also been used to evaluate the mechanism of the hybrid nanomaterials-based peroxidase mimics. For example, Zhao and co-workers [40] studied the mechanism of the peroxidase-like activity of the graphene/ Fe_3O_4 -Au nanoparticles for the oxidation of TMB. As the work functions of graphene, metals and Fe_3O_4 are 4.50, 5.52 and 5.54 eV, the electronic structure and Fermi level of graphene will change after the combination with Au and Fe_3O_4 components, which facilitate doping with electrons or holes. The modification of Fe_3O_4 and Au nanoparticles decreases the Fermi level of graphene. The graphene/ Fe_3O_4 -Au hybrids with reduced Fermi level can receive the lone pair electrons from the nonbonding orbital of TMB, exhibiting a higher Fermi level than the LUMO of H_2O_2 and possessing an oxidation of TMB. Similarly, for the conducting polymer-based nanocomposites, the difference of the work functions between conducting polymers and the peroxidase-like nanocatalyst will change the Fermi level of the nanocatalyst, resulting in an electron transfer from the nonbonding orbital of TMB to conducting polymer-based nanocomposites and subsequent to the LUMO of

H_2O_2 . Thus the oxidation of TMB is successfully achieved.

APPLICATIONS OF CONDUCTING POLYMER-BASED NANOCOMPOSITE PEROXIDASE MIMICS

As demonstrated in the above section, several representative species of conducting polymer-based nanocomposite peroxidase mimics have been prepared as efficient peroxidase mimics. Enhanced peroxidase-like catalytic activities have been achieved in those catalytic systems. In the following section, we will illustrate the promising applications of these conducting polymer-based nanocomposites in sensitive detection assays.

Detection of H_2O_2

It has been commonly acknowledged that H_2O_2 is closely related to our production and life. H_2O_2 not only makes significant contributions to biological processes of human, but is involved in variety of fields such as industrial manufacture, food processing, bleach and biomedicine. It is the universal by-product of numerous oxidases as well. In addition, the abnormal concentration level of H_2O_2 may induce various damages to our health [75]. Consequently, the sensitive and selective detection of H_2O_2 is a meaningful object. To date, with the development of varied analytical methods, diverse techniques have been explored for the detection of H_2O_2 , such as spectrophotometry [76,77], electrochemical method [78–80], chemiluminescence [81–83], fluorescence [84–86], etc. Among them, colorimetric assay is a conventional, facile and convenient approach to precisely determine H_2O_2 content, which has been widely developed for decades [59,87]. Considering the remarkable peroxidase-like catalytic performance of conductive polymer-based nanocomposites, a colorimetric method for detection of H_2O_2 has been established and extensively studied. For example, on the basis of the fantastic activity of the $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers as peroxidase mimics, we have developed a colorimetric approach for the sensitive detection of H_2O_2 . As the absorbance of the oxidized TMB is proportional to the H_2O_2 concentration, one can quantitatively detect H_2O_2 by monitoring the absorbance at 651 nm in UV-vis spectrum. From Fig. 7a and b, the detection limit based on the $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ -TMB- H_2O_2 system is calculated to be $2.4 \mu\text{mol L}^{-1}$ with a wide linear range of $2.0\text{--}50 \mu\text{mol L}^{-1}$. Similarly, $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ hybrid nanofibers as peroxidase mimics have also provided a sensitive detection of H_2O_2 with a detection limit of $1.7 \mu\text{mol L}^{-1}$ (Fig. 7c, d).

The colorimetric approach offers a simple detection of

Figure 7 (a) Time-dependent absorbance changes of TMB solution at 651 nm catalyzed by $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers in the absence and presence of H_2O_2 with varied concentrations in acetate buffer solution (pH 4.0). (b) A dose-response curve for the detection of H_2O_2 using $\text{TiO}_2/\text{Fe}_2\text{O}_3/\text{PPy}$ composite nanofibers as an artificial peroxidase. The inset in (b) is the linear calibration plot for H_2O_2 . Reprinted with permission from Ref. [64], Copyright 2016, the Royal Society of Chemistry. (c) Time-dependent absorbance changes of TMB solution at 651 nm catalyzed by $\text{CeO}_2/\text{Co}_3\text{O}_4/\text{PEDOT}$ composite nanofibers in the absence or presence of H_2O_2 with varying concentrations in the acetate buffer solution (pH 4.0). (d) Dose-response curve for the detection of H_2O_2 . The inset shows the linear calibration plot for H_2O_2 . Reprinted with permission from Ref. [65], Copyright 2017, IOP Publishing Ltd.

H_2O_2 based on the conducting polymer-based nanocomposites with a favorable detection limit. However, it is still a great challenge to enhance its sensitivity by introduction of the new detection techniques. Surface enhanced Raman scattering (SERS) is a powerful analytical technology with a remarkably high sensitivity. Compared with traditional FTIR, UV-vis, and Raman spectroscopy, SERS technique could show the structural information of the target molecules with an extensively large enhancement [88,89]. To detect H_2O_2 using SERS technique in a peroxidase-like catalytic reaction system, it is necessary to fabricate bifunctional SERS substrate with a peroxidase-like activity. As mentioned in the section “Conducting polymer/noble metal nanocomposites”, we have prepared PANI/Au nanorices *via* a facile self-assembly method. The as-prepared PANI/Au nanorices showed both good SERS properties and unique peroxidase-like activity. In view of the high accuracy of SERS technique, a high sensitivity approach for the detection of H_2O_2 has been developed. It can be observed that H_2O_2 can be detected as low as 10 nmol L^{-1} by using SERS (Fig. 8a, b). This

work offers a novel pathway for the determination of H_2O_2 with an ultrahigh sensitivity.

Detection of glucose

The determination of glucose is of great significance in plenty of scientific research areas, such as blood glucose monitoring, clinical diagnostics, food and medicine analysis [90–93]. Among them, the well-known diabetes have threatened more than millions of people worldwide in recent years. Therefore, it is urgent to develop sensitive glucose sensors. On the basis of the demand of accurate detection toward glucose, numerous analytical methods have been established [90–93]. Especially, Pan, Yu and co-workers [94] developed a glucose enzyme biosensor based on Pt nanoparticles/PANI hydrogel *via* an electrochemical detection approach. The three-dimensional (3D) porous microstructure provides the well dispersion of Pt nanoparticles and immobilization of glucose oxidase (GOx) (Fig. 9a, b). Another advantage of the 3D microstructure of Pt nanoparticles/PANI hydrogel is the efficient collection of the transferred charges from the

Figure 8 (a) The SERS spectra of TMB molecules at different time intervals during the peroxidase-like catalytic reaction process on the surface of the Au/PANI nanorice substrate in the presence of H_2O_2 . (b) SERS spectra of oxidized TMB molecules on the surface of the Au/PANI nanorice substrate in the absence and presence of H_2O_2 with different concentrations from 10^{-1} to 10^{-8} mol L^{-1} . The right figure shows an enlarged spectra in the absence and presence of H_2O_2 with different concentrations from 10^{-5} to 10^{-8} mol L^{-1} . Reprinted with permission from Ref. [56], Copyright 2017, the Royal Society of Chemistry.

electrochemical process. Thus the enzyme sensor based on the Pt nanoparticles/PANI hydrogel heterostructure displays an excellent sensitivity of $96.1 \mu\text{A} (\text{mmol L}^{-1})^{-1} \text{cm}^{-2}$, a fast response time of about 3 s, a low detection limit of $0.7 \mu\text{mol L}^{-1}$ with a linear range of 0.01 to 8 mmol L^{-1} (Fig. 9c, d). Recently, the Pt nanoparticles/PANI hydrogel has also been used to immobilize different types of enzymes as biosensors for the detection of a series of metabolites [95]. As mentioned, colorimetric assay is a simple and common approach for the rapid and effective detection of H_2O_2 . On the other hand, H_2O_2 is the by-product of enzymatic reactions by glucose oxidase with glucose. Consequently, a simple colorimetric route could be developed for the detection of glucose by in-

tegrating glucose oxide and peroxidase-like nanocatalyst [96–101]. Recently, researchers have shown the potential applications of conducting polymer-based nanocomposites as peroxidase mimics for the detection of glucose. For instance, the PANI:PSS-Au nanocomposites have been used as efficient peroxidase mimics to detect glucose in the presence of glucose oxide and TMB substrate. A detection limit of $4.0 \mu\text{mol L}^{-1}$ was estimated with a linear range of 8.0 – $1,000 \mu\text{mol L}^{-1}$ and excellent selectivity [55]. Similarly, PPy/hemin nanocomposites have also been used as peroxidase mimics for the detection of glucose, which provides a detection limit of $50 \mu\text{mol L}^{-1}$ (Fig. 10a–c) [73]. In addition, the detection assay also showed a high selectivity for the glucose determination (Fig. 10d). These results offer possibility of conducting polymer-based nanocomposites in the area of sensitive and selective detection of glucose.

Detection of dopamine

Dopamine has been commonly defined as a type of typical and significant neurotransmitter in human brain, which influences affections of human beings *via* information transfer. However, the anomalous levels of dopamine in brain can cause various diseases. Therefore, the precise determination of dopamine is of critical importance in our life [102–106]. Owing to the inhibition effect of dopamine toward the catalytic oxidation of TMB, colorimetric assays can be developed for the detection of dopamine. Considering this in mind, conducting polymer-based nanocomposites have also been used as peroxidase mimics for the sensitive detection of dopamine. We have demonstrated that $\text{CuFe}_2\text{O}_4/\text{Cu}_9\text{S}_8/\text{PPy}$ ternary nanocomposites exhibited excellent peroxidase-like catalytic reaction toward the oxidation of TMB [72]. However, after the addition of dopamine, the blue color faded, which can be monitored by the change of absorbance at 650 nm. Fig. 11a shows the intensity of the absorption peak at 650 nm in response to varied concentrations of dopamine ranging from 0– $1,000 \mu\text{mol L}^{-1}$. It is found that the detection limit is about $1.0 \mu\text{mol L}^{-1}$ with a linear range of 2 – $20 \mu\text{mol L}^{-1}$ (Fig. 11b). The $\text{CuFe}_2\text{O}_4/\text{Cu}_9\text{S}_8/\text{PPy}$ ternary nanocomposites as peroxidase mimics showed a better sensitivity for the detection of dopamine than previous reported colorimetric approaches. The determination of dopamine can be used in a real sample, extending their practical applications. In addition, this detection system also exhibits an excellent selectivity toward the detection of dopamine (Fig. 11c, d). It is anticipated that the obtained $\text{CuFe}_2\text{O}_4/\text{Cu}_9\text{S}_8/\text{PPy}$ ternary nanocomposites possess promising potential applications

Figure 9 (a) Schematic representation of 3D Pt nanoparticles/PANI hydrogel heterostructure for immobilization of GOx and the reaction mechanism of a typical glucose sensor based on the heterostructure. (b) SEM image of Pt nanoparticles/PANI hydrogel heterostructure. (c) Amperometric response of the Pt nanoparticles/PANI hydrogel electrode after successive additions of glucose at an applied potential of 0.56 V. Inset: the magnified portion of the curve marked with red square. (d) The calibration curve for glucose concentrations from 1 to 80 mmol L⁻¹. Reprinted with permission from Ref. [94], Copyright 2013, American Chemical Society.

Figure 10 (a) The absorption spectra and digital photos of colorimetric reaction of TMB and H₂O₂ in NaAc buffer solution in the absence and presence of PPy/hemin, hemin and PPy. (b) UV-vis absorption of the TMB + H₂O₂ + PPy/hemin system with different concentrations of glucose ranging from 0 to 10.00 mmol L⁻¹. The photograph above b shows the color change of the detecting system under different glucose concentrations. (c) Dose dependency curve of absorption intensity versus the target concentration. The inset shows the calibration curve for target molecule concentration ranging from 0.05 to 8.00 mmol L⁻¹. (d) Selective determination in the presence of different interferences. The final concentrations of the relative species were as follows: fructose, 25 mmol L⁻¹; maltose, 25 mmol L⁻¹; sucrose, 25 mmol L⁻¹; lactose, 25 mmol L⁻¹; glucose, 5 mmol L⁻¹. The error bars are the standard deviation (SD) across three repetitive experiments. Reproduced with permission from Ref. [73], Copyright 2014, American Chemical Society.

Figure 11 (a) UV-vis absorption curves of the system recorded for 10 min involving constant TMB (0.15 mmol L^{-1}), H_2O_2 (97.5 mmol L^{-1}) and $\text{CuFe}_2\text{O}_4/\text{Cu}_9\text{S}_8/\text{PPy}$ ternary nanotubes catalyst solution ($20 \mu\text{g mL}^{-1}$) as well as dopamine with varied concentrations under the optimal conditions (pH 4); (b) the related absorbance changes at 650 nm and the inset presents the linear calibration plot for detection of dopamine. (c) The absorbance difference between 0 and 10 min at 650 nm of diverse systems involving constant concentrations of TMB (0.15 mmol L^{-1}), H_2O_2 (97.5 mmol L^{-1}), catalyst suspension ($20 \mu\text{g mL}^{-1}$) with dopamine (1 mmol L^{-1}) or other different interferents (1 mmol L^{-1}). (d) The photographs corresponding to the above systems on 10 min. Reproduced with permission from Ref. [72], Copyright 2017, the Royal Society of Chemistry.

in dopamine sensing and other fields.

Detection of phenol

Phenols are derived from multitudinous industrial manufactures such as oil refining, metallurgy, plastics, drugs, pesticides, etc. Nevertheless, their high toxicity and unpleasant organoleptic characteristics lead to various diseases. Consequently, researchers focus on the urgent requirement of sensitive determination of phenols [107–111]. Among the variety of detection methods, colorimetric assay has occupied a vital position due to its convenience and effectiveness [112]. With regard to conducting polymer-based nanocomposites as peroxidase mimics, a colorimetric determination of phenol can be developed based on the formation of quinone imine complex. For instance, we have prepared $\text{rGO}/\text{Cu}_8\text{S}_5/\text{PPy}$ nanocomposites through a two-step approach [113]. Firstly, GO/CuO composite nanosheets were prepared *via* a wet-chemical approach. Then the prepared GO/CuO composite nanosheets could be used as templates and oxidant to polymerize pyrrole to form PPy, accompanied with the reduction of GO and Cu(II) as well as the sulfuration of copper source, resulting in the formation of $\text{rGO}/\text{Cu}_8\text{S}_5/\text{PPy}$ composite nanosheets. The as-prepared $\text{rGO}/\text{Cu}_8\text{S}_5/\text{PPy}$ composite nanosheets showed an excellent peroxidase-like activity toward the oxidation of

TMB. As phenol can be reacted with 4-aminoantipyrine (4AAP) in the presence of H_2O_2 to form quinone imine complex, which showed a typical characteristic absorbance at 500 nm, a colorimetric approach for the accurate determination of phenol has been developed (Fig. 12a). As shown in Fig. 12b and c, a detection limit for the phenol was estimated to be about $1.78 \mu\text{mol L}^{-1}$ with a linear range of $0\text{--}20 \mu\text{mol L}^{-1}$. This work provides the possibility of conducting polymer-based nanocomposites as peroxidase mimics for the sensitive detection of phenol.

CONCLUSIONS AND OUTLOOK

Artificial enzymes, which are defined as candidates to natural enzymes, have been developed rapidly in decades. Peroxidase mimics are indispensable part of artificial enzymes and have caused widespread interest recently. Conducting polymers are species of electron transport medium, especially when their sizes are reduced to nanoscale. It is anticipated that the incorporation of conducting polymers with other nanomaterials can remarkably promote peroxidase-like catalytic activities. In this article, we summarize several typical kinds of conducting polymer-based peroxidase mimics. In addition, by comparing the catalytic activity of conducting polymer-based nanocomposite with individual components,

Figure 12 (a) Schematic illustration of the peroxidase-like activity of the rGO/Cu₃S₂/PPy composite nanosheets. (b) UV-vis absorption curves in the absence and presence of phenol with varied concentrations in PBS solution. (c) Plot of the absorbance at 500 nm versus phenol concentration. Reprinted with permission from Ref. [113], Copyright 2017, WILEY-VCH Verlag GmbH & Co.

the possible catalytic mechanism has been proposed. Furthermore, on the basis of their excellent performance, we discuss the potential applications of these materials for the sensitive detection of H₂O₂, glucose, dopamine and phenol.

Despite great advances toward the development of conducting polymer-based peroxidase mimics, several challenges still remain to be addressed. The first problem is related to the synthetic strategy for conducting polymer-based peroxidase mimics. It has been deduced from the above mentioned discussions that the morphology, size and composition of the conducting polymers and their nanocomposites have much influence on their peroxidase-like activity. Therefore, the precise synthesis of conducting polymer nanomaterials and their composites with controllable morphology, size and composition is a substantial challenge. Especially, for the conducting polymer nanocomposites, the synergistic effect is much related to the interactions among the components. It is necessary to develop new synthetic protocols to prepare conducting polymer-based nanocomposites with strong interactions and smart interfaces.

Another open question is the mechanism for the enhanced peroxidase-like catalytic activity. Although we have mentioned that the improved peroxidase-like activity is related to the higher affinity of the conducting polymer-based nanocomposites to the peroxidase substrates and the excellent electron transfer properties of conducting polymers, the detailed mechanism of the sy-

nergistic effect between conducting polymers and other active components still needs to be exploited. It is also a challenge to find out the catalytic mechanism on the molecular scales, which could give a much deeper understanding about the nature of the artificial enzyme-like catalysis.

Therefore, for future development, the theoretical calculation and simulation studies should be adopted to reveal the deeper understanding of the peroxidase-like activity of conducting polymer-based nanocomposites. Especially for the individual conducting polymers, the relationship between the oxidation state, aggregation state, doping state, and surface chemistry of conducting polymers and their peroxidase-like activity should be further investigated. In addition, the simulation of the interactions between conducting polymers and functional nanomaterials should also be emphasized, which can give a direction for the fabrication of peroxidase mimics based on the conducting polymer nanocomposites with a tunable Fermi level. It is necessary to achieve novel peroxidase mimics with much enhanced catalytic efficiency by tuning molecular and micro-scale structures of conducting polymer-based nanocomposites. Furthermore, a major challenge for the enzyme mimetic research based on the conducting polymer nanocomposites is developing simple and efficient methods to fabricate multiple-enzyme mimics or biomimetic catalysts for cascade reactions. This article reviews the promising applications of the conducting polymer-based nanocomposites as per-

oxidase mimics for the sensing applications. It is expected that the research on the conducting polymer-based nanocomposites as peroxidase mimics could show more extensive applications in biocatalysis, environmental monitoring, and medical diagnosis in the near future. These pioneering studies are hopeful to open new pathways to develop new novel conducting polymer-based nanocomposites with unique morphology, size, surface and interfacial structure as efficient enzyme mimics for a broader range of properties and applications.

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导电高分子基类过氧化物酶: 制备、协同增强性质及其应用

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摘要 人工模拟酶的概念已经提出了很长时间. 近几十年来, 许多材料已经被应用于模拟酶催化领域. 纳米技术的出现给模拟酶的发展提供了越来越多的机会. 由于其众多的官能团、优异的导电性和氧化还原性质, 导电高分子基纳米复合材料逐渐成为一类新兴的模拟酶功能材料. 本综述介绍了导电高分子及其纳米复合材料的合成以及作为高效类过氧化物酶的应用进展. 在简要介绍导电高分子的发展之后, 我们特别讨论了通过不同方法制备导电高分子及其纳米复合材料, 并且展示了它们增强的类过氧化物酶催化性能. 此外, 我们还提出了导电高分子基纳米复合材料催化效率增强的机理. 最后, 我们强调了这种导电高分子基纳米复合材料在高灵敏检测领域的应用. 本综述为发展更有趣的功能模拟酶纳米材料提供了参考, 这类材料在很多技术领域具有广阔的应用前景.