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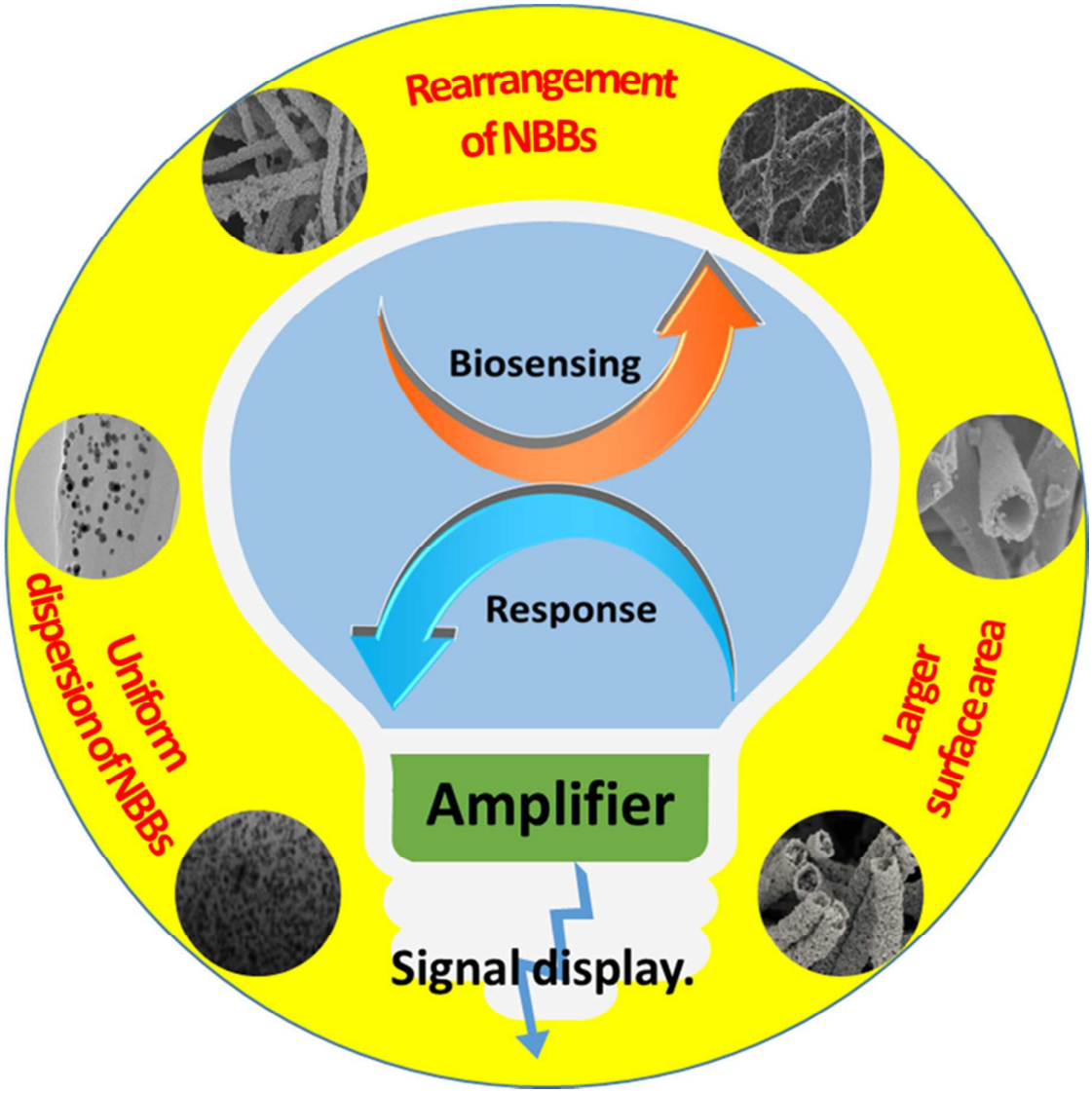

We summarize recent advances in the electrospinning fabrication of hybrid polymer nanofibers decorated with functionalized nanoscale building blocks (NBBs) to obtain biosensors with better performances.

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Electrospinning design of functional nanostructures for biosensor applications

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Electrospinning represents a simple and effective strategy for fabricating nanofibrous structures and materials with large surface-to-volume ratio and desirable engineered properties. Thus, incorporating nanoscale building blocks (NBBs) like nanoparticles, graphene quantum dots, carbon nanotubes, and graphene into electrospun fibers has become one of the most attention-getting research topics in the field of biosensing. However, the dispersion behavior of NBBs in the nanofibers, the limited surface area of nanofibers as well as the insufficient immobilization sites for tested biomolecules still restrict the better performances and broader applications of the fabricated biosensors. In this review, we presented a comprehensive survey on strategies that have been utilized to fabricate functional fibrous nanostructures for the amplification of the detection signals of nanostructure-based biosensors. In particular, from the perspective of design configuration, we systematically summarized recent advances in the electrospinning fabrication of hybrid polymer nanofibers decorated with functionalized NBBs. The strategies for promoting better dispersion of NBBs in electrospun nanofibers, including direct blending before electrospinning and in-situ synthesis during electrospinning, are introduced in detail. In addition, some effective processing routes for increasing immobilization sites of tested biomolecules such as arrangement of NBBs and morphological processing of nanofibers, are also presented. In addition, the suitability of electrospun nanostructures for biosensors, the advantages and disadvantages of each method for improving biosensing performance are also discussed.

1. Introduction

During the past few years, polymer nanofiber (PMNF) materials have attracted great interest in many fields such as biosensors, biomedical science, drug delivery, and energy storage due to their large surface area, controllable surface conformation, complex pore structures, suitable surface modification, and superior biocompatibility.[1,2] Among all the utilized techniques, the electrospinning is the most convenient and efficient route to prepare PMNFs.[3-5] It provides a simple and effective way to fabricate functional materials from one-dimension (1D) to three-dimension (3D) with nanoscale to microscale range, in which the physical and chemical properties of the created PMNF materials can be controlled.[6] Although electrospinning was first introduced by Anton Formhals in 1934, it did not receive sufficient attention for several decades.[7] However, in 1996, Reneker *et al.* fabricated ultrafine polymeric fibers with diameters ranging from nanoscale to microscale by a specifically developed electrospinning technique, and proved that it is a very simple and powerful way to produce PMNFs.[8] Thereafter, various applications of electrospinning technique have been widely explored in both academic research and industry fields.[1] An increasing number of natural and synthetic polymers have been fabricated to PMNFs with controlled morphology and desired functionality.[9-11] Meanwhile, many functional additives, such as dyes, biomolecules, and nanoparticles (NPs), have also been incorporated into the electrospun PMNFs to form special functional hybrid nanofibers.[1,9]

Among all the applications of electrospun PMNFs, the biosensor application has always being one of the research hotspots. Generally speaking, a typical biosensor should possess the abilities of precise selectivity, rapid responses, and low detection limit, which means the biosensor system must consist of both biological detection part and signal transduction part.[12] Each part is indispensable and contributes to the final properties as well as applications of a biosensor. The biological detection behavior mainly depends on the electrical activity, stability, and biocompatibility of NBBs like NPs, graphene quantum dots (GQDs) carbon nanotubes (CNTs), and graphene nanosheets (GNs) for the conjugation of PMNFs.[13-15] In addition, the signal transduction performance mainly relies on the distribution behavior of NBBs and the conductivity of electrospun PMNFs.[16]

Many strategies can be used to produce electrospun PMNF-NBB based biosensors, among which the pre-processing and post-processing are the most common ones. In the pre-processing method, NBBs were introduced into the polymer matrix by adding appropriate precursors before the electrospinning processing.[17] It is the most straightforward and effective method with a few obvious advantages. Firstly, NBBs provide an improved electrical conduction

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path between the analytes and electrodes, and then enhance the charge transfer properties, resulting in higher sensitivity and lower detection limit for the fabricated biosensors.[18] Secondly, NBBs have strong adsorption capability for the immobilization of biomolecules, which can provide ideal microenvironments for the immobilization of bio-analytes. Finally, NBBs possess higher isoelectric point, which allows them to easily bind with the bio-analytes with low isoelectric point.[16] Until now, many PMNF-NBB hybrid nanostructures have been successfully fabricated by this means. However, with this method, the huge gap in surface energy between NBBs and spinning solution restricts their uniform dispersion, which may result in strong aggregation of NBBs in the final PMNFs. Hence, suitable modification of NBBs is crucial for improving their distribution in the polymer matrix and enhancing the final properties of a biosensor.

To avoid the harsh problem of the dispersion behavior of NBBs in polymer matrix, another fabrication method, the post-processing technique has also been introduced.[19] In contrast to pre-processing, NBBs were introduced onto the PMNFs after the electrospinning processing by this means. This procedure is quite common and effective for producing PMNFs with good dispersity of NBBs. Firstly, the electrospun PMNFs with or without morphological changes are produced. Then, NBBs can be formed on the PMNF surface directly by various post-treatment techniques, such as self-assembly,[20] in-situ reduction of metallic ions,[21] and hydrothermal synthesis.[22] This method can exploit the maximum capabilities of NBBs on the biological detection due to their exposed surface.

The biosensor ability of PMNF-NBB hybrid nanomaterials has been attracting remarkable attentions. For example, many articles in this area have been published annually for over a decade. A survey of open publications related with "electrospinning" and "biosensor" in the past 17 years on ***Google Scholar*** was performed and the result is shown in Fig. 1. Taking this fact into consideration, related research on the modification and hybridization of NBBs, as well as the fabrication of nanofibers with controllable morphologies for biosensing should be studied more deeply and presented more clearly.

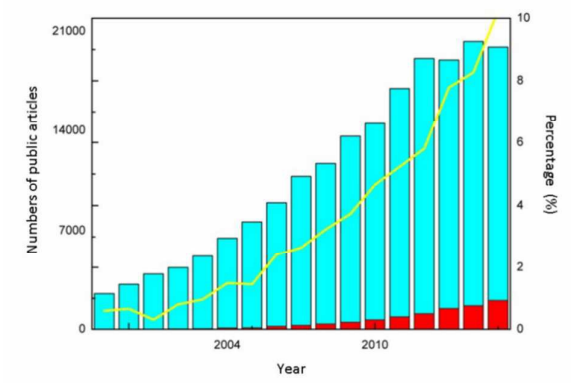

Fig. 1 The number of publications searched by the keywords of "biosensor" (blue histogram) and "biosensor, electrospinning" (red histogram) by using Google Scholar. The yellow line refers to the percentage.

Previously, many reviews on the fabrication and applications of biosensors based on electrospun PMNFs have been published.[23-27] For example, in our previous work, we presented a progress report on applying electrospinning technique to create PMNFs doped with metal NPs and CNTs, as well as the biosensor application of these electrospun hybrid PMNFs.[23] Besides, Torres-Giner *et al.* summarized the potential use of polymer ultrathin and nanoscale structures obtained by electrospinning to design novel engineered materials with bioactive properties.[24] Thavasi and co-workers introduced their work via highlighting the potential and application of electrospun nanofibrous materials for solving critical energy and environmental issues.[25] Similarly, Peng *et al.* presented another review concerning multi-functional electrospun nanofibers, and they emphasized the applications in tissue regeneration, energy conversion and storage, as well as water treatment fields.[26] However, a definitive review about the fabrication of PMNF-NBB nanostructure-based biosensors from the configuration design perspective is still lacking. In this critical review, we highlight the latest literature studies in the fabrication of high performance electrospun PMNF-NBB nanostructure-based biosensors. Firstly, the strategies for modification NBBs and promoting better dispersion of NBBs in electrospun nanofibers are introduced in detail. Secondly, several effective processing routes for increasing surface area of nanofibers as well as immobilization sites for tested biomolecules are presented. Finally, we overview and outlook several key issues on the fabrication of electrospun PMNFs for biosensors.

2. Modification of NBBs for electrospinning design of PMNF/NBB nanostructures in pre-processing

Introducing NBBs into polymer matrix is a traditional and effective way to fabricate nanocomposites for various performance and application. Base on this point, many researchers started exploration about biosensors based on PMNF-NBB nanostructures via electrospinning. In the past years, many kinds of NBBs with different dimensions (0D, 1D, 2D, and 3D) and functions (fluorescence, magnetism, catalysis, adhesion, and immobilization capability, etc.) have been synthesized. Their potential application as the additive phase in an electrospun PMNF for biological detection has been investigated previously.[28] The electrospun PMNF-NBB nanostructures show universality and versatility for the fabrication of biosensors. They possess excellent chemical and thermal stabilities, which make them promising candidates for fabricating biosensors with high performance attributes.[29]

Generally speaking, NBBs play important roles in both sensor and conductor parts. The more content is, the more even distribution is, the better performance of a biosensor. Unfortunately, these two factors are mutually inhibited. To find out a balanced point between content and distribution, some modification methods and auxiliary ways are needed. To include NBBs into PMNFs uniformly, two typical strategies, the direct mixing before electrospinning and in-situ synthesis during electrospinning, have been proven to be very effective. In this section, we would like to present the methods that could promote the better dispersion of NBBs in electrospun PMNFs and improve the detection performance of the fabricated biosensors.

2.1 Blending NPs in PMNFs

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Blending NPs into stocked polymer solution is a traditional and convenient way to fabricate PMNF-NBB hybrids. The ceramic NPs like SiO_2[30], ZnO[31], ZrO_2[32] and TiO_2[33] have been used to adjust the mechanical properties of the final composites in this way. When NBBs are doped into the electrospun PMNFs, the decrease of surface energy of NBBs could result in the local cross-linking of polymers. As a result, the PMNFs with thinner diameter and higher NBB loading can be obtained.[34] For the biosensors based on electrospun PMNF/NBB nanostructures, the dispersion of NBBs in polymer matrix is a vital factor for both the detection limit and the linear detection range. Therefore, better ways to blend NBBs homogeneously into polymer matrix should be studied.

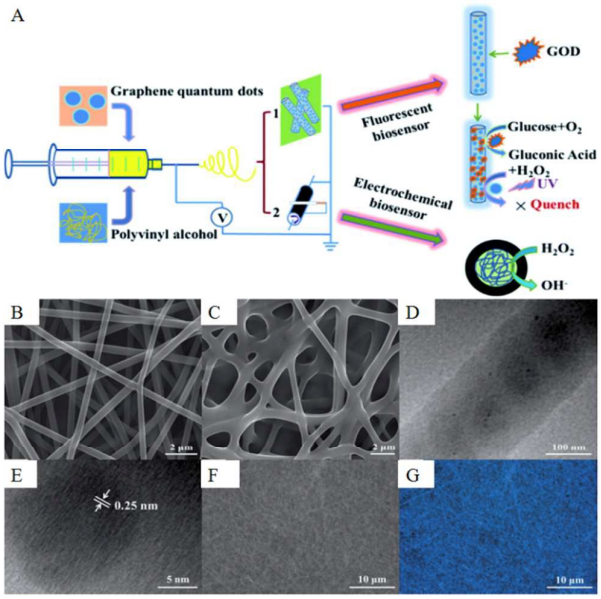

Fig. 2 (A) Schematic diagram illustrating the production of the PVA/GQD nanofibrous membrane and the subsequent fabrication of dual purpose fluorescent and electrochemical biosensors. (B) and (C) SEM images of PVA and PVA/GQD membranes. (D) and (E) HRTEM images, (F) and (G) optical and fluorescence images under sunlight and UV light (365 nm). Reproduced with permission from ref. 17, Copyright 2015, Royal Society of Chemistry.

2.1.1 External force-assist dispersity of NBBs

If the doping NBBs have high affinity with the polymer matrix, they can be well distributed into the polymer to form homogeneous solution by exerting ultrasonic treatment or adding a surface active agent. For instance, SiO_2 is known as an attractive material for preparing polymer electrolytes. The distribution of SiO_2 in polymer matrix is crucial to form robust shape and disturb the order packing tendency of the host polymer chains.[35] GQDs have also been utilized as common additive to fabricate well-dispersed nanofibrous materials due to their good dispersity. Besides, the good electron transport and acceptance capacity of GQDs make them optimal candidate for producing chemical active electrode or biosensing materials.[36,37] In our previous work, we utilized water-soluble GQDs to fabricate dual-purpose nanofibrous polyvinyl alcohol (PVA)/GQD membrane for both fluorescent and electrochemical biosensors (Fig. 2A).[17] In this study, GODs were dispersed in PVA aqueous solution by ultrasonication for 2h and incubation for 10h. The corresponding TEM, optical, and fluorescence images proved that the distribution of GQDs is uniform throughout the entire membrane (Fig. 2B-G). The good distribution of GQDs in PVA nanofibers contributes to the fabrication of biosensors with high performances. The fluorescence detection shows linear detection ranges of 0.05–35 and 0.25–24mM with corresponding detection limits of approximately 1.0 and 10.0μM toward the hydrogen peroxide (H_2O_2) and glucose biosensors, respectively. In addition, the electrochemical H_2O_2 biosensor shows a linear detection range of 0.1–200mM and a detection limit of 0.53μM.

It should be noted that it is not easy to find suitable solvent for doping NBBs into the hydrophobic polymers. In that case, using "assisted polymer" could be an alternative way. For example, polyvinylpyrrolidone (PVP), a promising polymer additive for electrospinning, has been used widely to disperse some NBBs into the spinning solution.[38] It possesses good solubility in many organic solvents like alcohol, acid, amine, and halogenated hydrocarbons due to its hydrogen bond acceptor from both carbonyl group and nitrogen sites.

2.1.2 Anisotropic additives-promoted disperse of NBBs

Generally speaking, the anisotropic materials or their hybridizations with other 0D NBBs have higher dispersity in polymer matrix due to the self-assembly effect that is driven by the reduce of Gibbs Free Energy.[39,40] When it comes to biological applications, both the dispersion of the NBBs and conductivity of the electrospun PMNFs should be considered, especially for those non-conductive polymers. Hence, to facilitate the dispersion of NBBs and improve the conductivity of electrospun hybrid nanofibers, it is necessary to adopt some NBB additives both anisotropic and conductive. For example, the 1D nanostructures like CNTs[41] or TiO_2 nanotubes[42] and 2D structures like graphene[17,43] or MoS_2[44] nanosheets show higher orientation after electrospinning and the created nanostructures display enhanced electrochemical biosensing response.

When some nonconducting polymer matrixes are utilized for electrospinning, the modified carbon NBBs could be considered as connectors due to their good dispersibility in some solvents and polymer matrix.[45,46] In addition, their large surface area, excess holes, and defective sites could lead to the fast electron transfer process and high electrocatalytic activity.[47] Previously, we fabricated a H_2O_2 biosensor based on polyurethane (PU) nanofibers filled with multi-walled carbon nanotubes (MWCNTs) and silver nanoparticles (AgNPs) by electrospinning, as shown in Fig. 3A-C.[48] In this study, both electrospun PU/AgNPs (Fig. 3A) and PU/MWCNT/AgNPs (Fig. 3B) nanofibers-modified electrode were prepared. TEM test showed that when AgNPs were added separately, they agglomerated into clusters and distribute discretely along the nanofibers due to their preference to interact with the soft phase of PU. However, when the MWCNTs were added into the PU nanofibers together with AgNPs, they were highly stretched and oriented in the poly matrix, and prefer to interact with the hard segments of PU. We attributed this effect to MWCNTs, which act as bridges for connecting discrete AgNPs (Fig. 3 C). Moreover, due to the notable synergistic effect, the PU/MWCNT/AgNPs composites

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were endowed with better performance sensing H_2O_2. Performance tests showed that the linear detection range from 0.5 to 30 mM (R = 0.9999), and the detection limit (LOD) is 18.6 μM and sensitivity is 160.6 μA $mM^{-1}cm^{-2}$.

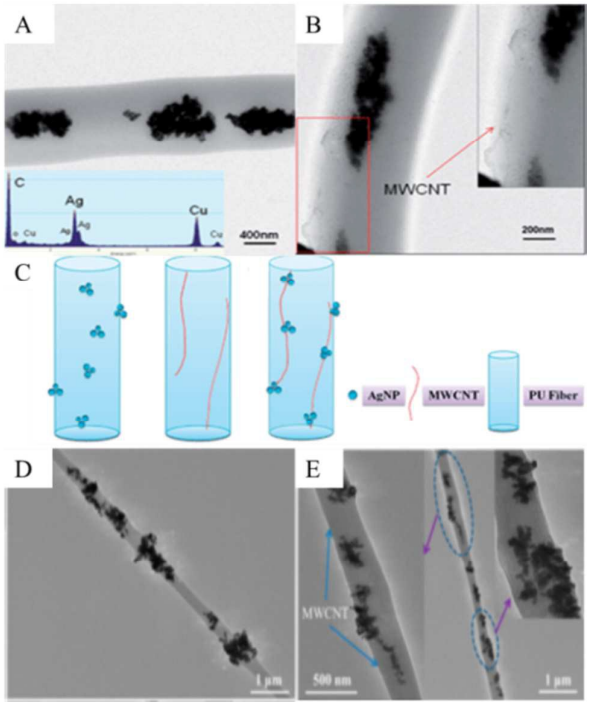

Fig. 3 (A,B) TEM photographs of (A) PU/AgNPs and (B) PU/MWCNT/AgNPs hybrid nanofibers, the inset in (A) is the EDX spectrum of PU–AgNPs nanofibers. (C) A proposed model for the dispersion of AgNPs and MWCNTs in PU nanofibers, respectively. Reproduced with permission from ref. 48, Copyright 2013, Royal Society of Chemistry. (D,E) Electrospun (D) PVDF/PtNP and (E) PVDF/MWCNT/PtNP nanostructures for H_2O_2 and glucose biosensors. Reproduced with permission from ref. 49, Copyright 2014, American Chemical Society.

In another study, we utilized electrospinning to fabricate a piezoelectric β-phase polyvinylidene difluoride (PVDF) hybrid nanofibrous membrane decorated with MWCNTs and platinum nanoparticles (PtNPs), which serve as the functional materials for non-enzymatic H_2O_2 biosensors.[49] With the help of ultrasonication and electrospinning, MWCNTs were well-dispersed and aligned in the created PVDF nanofibers, which can facilitate both the electron transfer and the uniform dispersion of PtNPs along the PVDF nanofibers, as shown in Fig. 3D and E. When MWCNTs were added, the synergistic effect makes them show neat arrangement. The fabricated PVDF/MWCNT/PtNP nanostructure based electrochemical H_2O_2 biosensor performed wide linear range (0.1-75 mM), relatively low detection limit (about 0.61 μM), good reusability, and long-term stability.

Graphene, the typical 2D material, has attracted increasing attentions in biological field for its large specific surface area and 2D electron conduction path. What's more, under the influence of interstitial defect and electrostatic interaction, the surface of nanoscale GNs can be modified.[42,43,50,51] Recently, we employed electrospinning technique to directly fabricate PVA and GN-based hybrid membrane doped with highly dispersed AgNPs, as shown in Fig. 4A.[52] AgNPs were successfully conjugated onto GNs by self-assembly (Fig. 4B-D). Thereafter, the created GN-AgNPs nanohybrids were electrospun with PVA solution together. Compared to the PVA/AgNPs nanofibers, the introduction of GNs promoted the dispersion of AgNPs in the electrospun PVA nanofibers. No clear aggregation was observed (Fig. 4E-G). Due to the high-loading amounts and uniform dispersity of AgNPs, PVA/GN/AgNPs nanostructure showed significantly improved catalytic properties toward H_2O_2. The detection limit is lower (about 0.56 μM), and the linear detection range is 5μM to 47mM (R =0.9991).

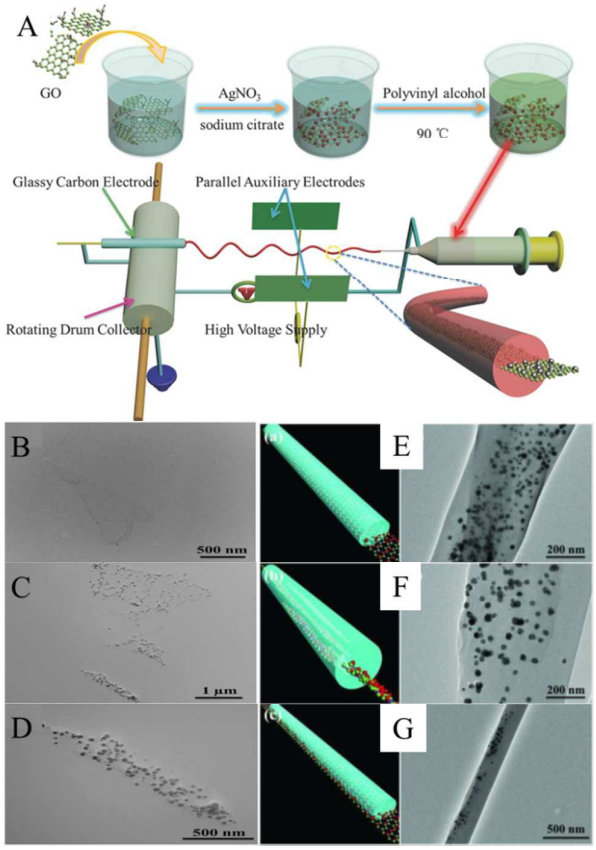

Fig. 4 Electrospun PVA/GN/AgNP hybrid nanostructures for H_2O_2 biosensing. (A) Schematic presentation for the fabrication of PVA/GN/AgNP hybrid membrane. (B-D) TEM images of (B) GN sheet and (C,D) GN/AgNP nanohybrids. (E-G) Orientations of GN/AgNP nanohybrids in PVA nanofibers: simulation images and typical TEM images. Reproduced with permission from ref. 52, Copyright 2015, Wiley-VCH Verlag GmbH & Co.

2.2. In-situ synthesis of NPs in PMNFs

Similar with blending, in-situ synthesis is another effective way to incorporate NPs into polymer matrix with the pre-processing method. Previously, several in-situ synthesis methods like sol-gel synthesis,[53] hydrothermal reaction,[54] oxidation-reduction reaction,[55] and hydrolysis [56] have been utilized to prepare PMNF-NP nanostructures. In this process, metallic ions are first dispersed into

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spinning solution before electrospinning. Then, the reactions triggered by heat, light, electrochemistry, and reactive additives are used to reduce the uniformly distributed metallic ions to metallic NPs inside or on the surface of the PMNFs. Considering that the additives are dispersed in ionic form, the local aggregation of NPs can be avoided, which is a huge benefit of this approach. However, this kind of strategy can only be used for the creation of metallic NPs in PMNFs.

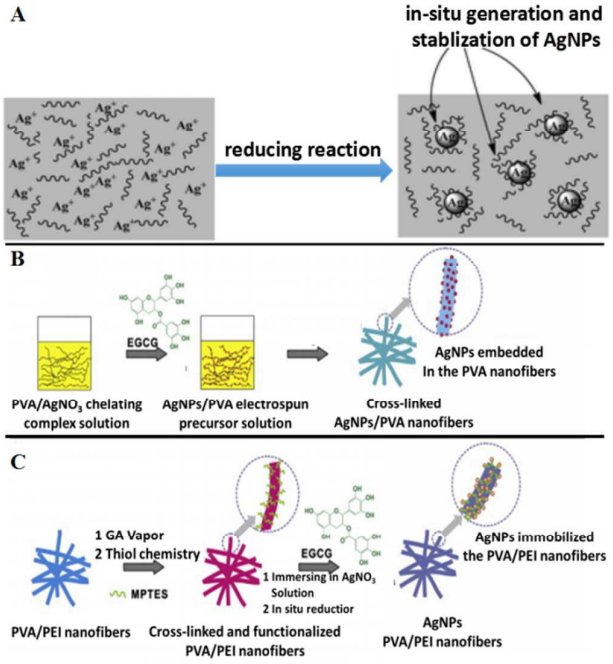

Fig. 5 (A) In-situ generation and stabilization of AgNPs in polymer matrix. Reproduced with permission from ref. 58, Copyright 2011, Royal Society of Chemistry. (B, C) Schematic models of the fabrication process of (B) PVA/AgNP and (C) PVA/PEI/AgNP nanofibers. Reprinted with permission from ref. 59, Copyright 2013, Elsevier.

Previously, Yang *et al.* reported the synthesis of AgNPs in PVP/ polymethyl methacrylate (PMMA) matrix by the in-situ photo reduction of silver ions.[57] They used polymethacrylic acid (PMAA) to improve the absorbing amounts of silver ions in the polymer matrix due to its linear structure with abundant carboxyl groups, which makes the content and size of formed AgNPs in the polymer matrix easily controllable. In another case, Shi and co-workers employed a facile approach to in-situ synthesize AgNPs-filled nylon 6 nanofibers by electrospinning.[58] The method they adopted is a typical one-pot process, which needs no post-treatments and can be carried out at ambient conditions without using additional chemicals. They used the electrospinning solvent as a reducing agent for the in-situ conversion of Ag^+ to AgNPs during the solution preparation, as shown in Fig. 5A. The resultant AgNPs-filled nylon 6 hybrid nanofibers show an excellent fibrous structure (diameter at 50–150 nm) with uniform dispersity of AgNPs (2–4 nm). In a similar work, Zhu *et al.* demonstrated a facile and green approach for the synthesis of PVA/polyetherimide (PEI)/AgNPs hybrid fibrous nanostructure and further utilized the created nanostructure to fabricate H_2O_2 biosensor.[59] In their work, PVA/AgNPs nanostructure was created by reducing the mixed $AgNO_3$ and PVA solution with epigallocatechin gallate (EGCG), and the PVA/PEI/AgNPs nanostructure was created by in-situ synthesis of AgNPs on the electrospun PVA/PEI nanofibers, as shown in Fig. 5B and C. The corresponding electrochemical tests indicated that the fabricated biosensor shows highly sensitive detection of H_2O_2 with a detection limit of 5 μM and it exhibits a fast response, broad linear range (0.6-5 mM), as well as excellent stability and reusability.

2.3. Summary on the modification of NBBs

Pre-processing is the way to mix NBBs into polymers matrix before electrospinning, which is the most common method for fabricating biosensor. In principle, this is the way to fabricate nanocomposites, particle size distribution, and particle interface interactions should be highly considered. These are key issues for desired properties and targeted applications of nanocomposites as well as NBBs-PMNFs based biosensor. With this method, NBBs are encapsulated within PMNFs, the NPs can be more stable, which ensure the excellent reusability and the long-term storage stability. Ideally, NBBs act like electron connector, while polymer serve as selective adsorptive on electrode for bio-tests, working as efficient device for electrochemical biosensor electrode.

NBBs play the dominant roles in biosensing system, they serve as a bridge between tested biomolecules and the signal transduction system. Theoretically, as for a biosensor based on electrospun PMNF, the more NBBs content is, the better biosensing performance. However, on the other hand, the high surface energy of NBBs with diameters in the low nanometer range often leads to aggregation. It means that the more NBBs contents lead the worse dispersion, which could reduce not only the physical properties of nanofibers but also the effective immobilization sites for analytes.

To solve this paradox, it is necessary to introduce some strategies for NBBs modification and dispersion, whose ultimate destination is to promote the more uniform dispersibility of NBBs, and further increase the biosensing performance. As we discussed above, blending is the most convenient and universal method. By the help of external force, such as ultrasonic processing or violent stirring, some NBBs with high affinity like water-soluble GQDs can achieve better dispersion to some extent. Whereas, this kind of filler is few, most NBBs possess high cohesion energy density and have limited resolvability in polymers. Hence, to obtain micro- or nano- scaled distribution, some suitable solution or amphipathic assisted polymer, or we can call them NBB-carriers, are indispensible. Their worth of existence is to mitigate the huge gap in surface energy between NBBs and PMNF matrix and contribute to the final goal: homodisperse of NBBs. In comparison, anisotropic additives have more superiority for being NBB-carriers than isotropous ones due to their self-assembly effect. Besides, anisotropic electric structures have more advantages over the 0D NBBs in electron transfer due to their perfect network and high surface-to-volume ratio.

Besides blending, in-situ synthesis is another available way. As we mentioned, NPs in ionic form can be easier mixed equably into the PMNFs matrix, after reactions initiated by heat or other conditions, the uniformly distributed metallic ions are reduced to metallic NPs which are simultaniously stuck inside or on the surface of the

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PMNFs. With this method, all the dramas in part 2.1, like dispersion and assisting-dispersion, can be omitted.

3. Modification of PMNFs for electrospinning design of PMNF/NBB nanostructures in post-processing

In principle, only the NBBs bound onto the exterior electrospun PMNFs are available for interacting with the tested biomolecules, which means the interior ones possess limited role for biological detection.[60-62] Some rational methods are still needed to remove the outer shell and yet not disturb the dispersed state of NBBs at the same time. In this part, we will discuss the recent studies on the arrangement of NBBs and the morphological processing of electrospun PMNFs to enhance the sensing performance of PMNF/NBB based biosensors.

3.1 Arrangement of NBBs without changing PMNF morphology

The aim of arrangement of NPs is to transfer more NBBs to the PMNF surface. This process can increase the chances of the interaction between NBBs and bio-analyses, which is of great significance to biosensors.[63] For instance, Wang *et al*. fabricated water-stable PVA-gold nanoparticles (PVA/AuNPs) hybrid nanofibrous mats and further demonstrated their potential application as H_2O_2 biosensor.[64] In their study, the water-stable and robust PVA nanofibrous mat was first prepared via electrospinning and subsequent cross-linking with glutaraldehyde (GA). Thereafter, AuNPs were homogeneously decorated on the PVA/GA nanofibrous mat through covalent interaction. Finally, the PVA/GA/AuNPs nanofibrous mats embedded with horseradish peroxidase were used as biosensor materials for H_2O_2 detection, as shown in Fig. 6A. The electrochemical test indicated that the fabricated biosensor possesses high performance for sensing H_2O_2, which exhibits fast response (1s), broad linear range (1-500μM), and low detection limit (0.5μM).

Beside the metallic NPs, CNTs can also be used for the modification of PMNFs. For example, Mercante *et al.* presented a novel nanostructure comprising electrospun polyamide 6/poly-(allylamine hydrochloride) (PA6/PAH) nanofibers functionalized with MWCNTs to detect the neurotransmitter dopamine (DA).[65] In their study, MWCNTs solution was first ultrasonicated at 20 kHz for 2h. Thereafter, the electrospun nanofibers were immersed into the MWCNTs solution, and then rinsed with distilled water and dried under ambient conditions. The scanning electron microscope (SEM) test indicated that MWCNTs were adsorbed onto the nanofibers' surface uniformly, as shown in Fig. 6B. Due to their large surface-to-volume ratio and ability to promote electron transfer reactions, the response was linear for a DA concentration range from 1 to 70μM with a detection limit of 0.15μM. In another study, Uzun and co-workers presented an efficient design of nanofibrous substrate by modifying a graphite rod electrode surface with the one-step electrospun nylon 6,6 nanofibers and 4% (w/w) MWCNTs (nylon 6,6/4MWCNT).[66] The modified substrate was further coated with a conducting polymer, (poly-4-(4,7-di(thiophen-2-yl)-1H-benzo[d]imidazol-2-yl) benzaldehyde) (PBIBA) to obtain a high electroactive surface area. Due to the robust covalent bonding between glucose oxidase (GOx) and the nanofibrous structure, the GOx-modified electrode was utilized for the electrochemical sensing of glucose. The corresponding results showed the fabricated glucose biosensor exhibits quick sensing response, low detection limit (9μM), and long-term stability (44 days).

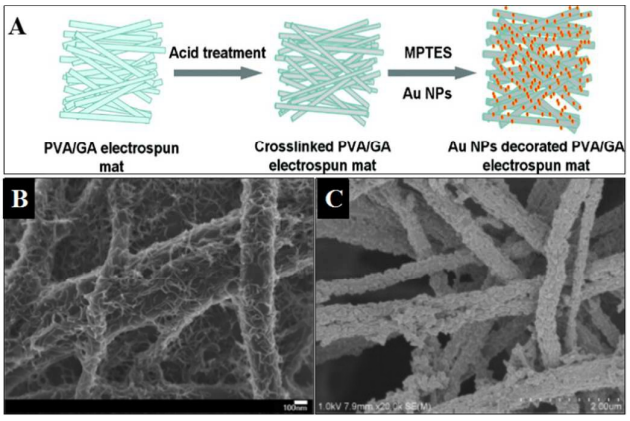

Fig. 6 (A) Schematic fabrication of water-stable functional PVA/GA/AuNP nanostructure. Reproduced with permission from ref. 64, Copyright 2012, American Chemical Society. (B) FEG-SEM image of PA6/PAH/MWCNTs nanofibers. Reproduced with permission from ref. 65, Copyright 2015, American Chemical Society. (C) SEM images of PANI/CMC/cellulose nanofibers. Reprinted with permission from ref. 67, Copyright 2015, Elsevier.

1D polymer nanorods are also potential candidates for the modification of PMNFs to fabricate biosensors. For instance, recently Fu *et al.* provided an effective method to transfer polyaniline (PANI) nanorods to the electrospun carboxymethyl cellulose (CMC)-modified cellulose nanofiber surface.[67] In their strategy, the hierarchical CMC/cellulose/PANI nanostructure was fabricated by the in-situ polymerization of aniline on the electrospun CMC/cellulose nanofibers, as shown in Fig. 6c. They found that the obtained CMC/cellulose/PANI nanofibers maintain the cylindrical fibrous structures of the individual fibers as well as the 3D structure of fibrous mats to provide a high electroactive surface area for the facile electron transfer and mass diffusion. As a result, the fabricated catechol biosensor exhibited a fast response time (within 8 s), linear response range from 0.497μM to 2.27mM, and low detection limit of 0.374μM.

3.2 Morphological processing of PMNFs with various structures

The examples introduced above indicate cases that the uniform arrangement of NBBs on the surface of PMNFs could enhance the biosensing performance. However, when the materials are down to the micro- or nano-scales, their morphologies are also vital for the properties of fabricated biosensors.[68] Compared to the PMNFs with solid interior and smooth surface, the PMNFs with various special structures like porous, hollow, and core/shell possess larger surface area and more immobilization sites, which are favourable for the improved performance of a biosensor. **Table 1** demonstrates the advantages and disadvantages for the fabrication and biosensing application of the electrospun porous, hollow, and core-shell nanostructures.

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Table 1. Comparisons of the advantages and disadvantages of several electrospun nanostructures.

Morphology	Advantages	Shortcomings
Porous [19,69-72]	simple versatile equipment-independent	complex pre-treatment inevitable loading of NBB is un-controllable
Hollow[73-79]	large surface area	specific equipment complex operation
Core-shell[81-84]	large surface area unique properties selectable core and shell materials	complex operation harsh post-treatments

3.2.1 Porous structure

The high porosity structures can make the surface area of the nanofibers mesh increase tremendously, which is favourable for the biological detection.[19] One typical process for producing porous nanofibers is blending some removable NBBs, such as nanoscale $CaCO_3$[19] or SiO_2[69], into the polymeric matrix. After washing with corresponding organic chemicals, the NBB additives are removed. As a result, PMNFs with porous nanostructure are created.

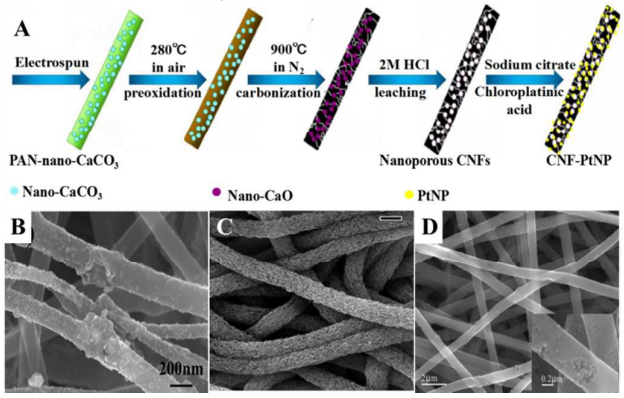

Fig. 7 (A) Preparation of nanoporous CNFs decorated with platinum nanoparticles hybrid. (B) SEM image of the fabricated nanoporous CNF-PtNP hybrids. Open access. (C) FESEM images of porous PAN nanofibers after water treatment. Scale bar: 400 nm. Reproduced with permission from ref. 70, Copyright 2014, American Chemical Society. (D) FE-SEM micrographs of the as-spun nanofibers with 100Tar/PAN/Ag-CNF (the inset at the bottom-right of each micrograph shows a higher magnification image). Reproduced with permission from ref. 71, Copyright 2015, American Chemical Society.

Recently, we developed a facile strategy to fabricate nanoporous carbon nanofibers (CNFs) decorated with PtNPs by electrospining polyacrylonitrile (PAN) nanofibers and subsequent carbonization and binding of PtNPs, as shown in Fig. 7A and B.[19] The fabricated nanoporous CNF-PtNP hybrids were further utilized for the electrochemical detection of H_2O_2. The electrochemical experiments indicated that CNF-PtNPs modified electrode shows a linear detection range of 0.1–30mM and a detection limit of 1.9μM.

Besides the nanoscale inorganic NPs, polymers can also be used as porogen to get the porous nanostructure, which are called sacrificial template polymers. Their remove depend largely on the difference of the physical properties of polymers, such as the thermal decomposition temperature and the difference of solubility in particular solvent. In another typical case, Huang and co-workers synthesized nanoporous CNFs decorated with Ag–Pt bimetallic nanoparticles by combining the template carbonization and seed-growth reduction approach.[70] In their study, a polymer blend of PAN and PVP in dimethyl formamide (DMF) was first electrospun to PAN/PVP nanofibers, followed by subsequent water extraction and heat treatment to obtain porous CNFs. The water extraction was used to remove PVP component to obtain porous PAN nanofibers, while the heat treatment was used to carbonize the nanofibers, and the final porous nanostructure is shown in Fig. 7C. Subsequently, Ag–Pt NPs were loaded onto the porous CNFs via the chemical reduction of $H_2PtCl_6{\cdot}6H_2O$ and $AgNO_3$. The fabricated CNF/Ag-PtNP based DA biosensor shows several advantages like high sensitivity, wide linear range (10–500μM), low detection limit (0.11μM), and excellent selectivity under the interference of uric acid and ascorbic acid. Very recently, Song *et al.* synthesized continuous microporous CNFs from biomass tar/PAN/$AgNO_3$ hybrids with antimicrobial capabilities through electrospinning and subsequent thermal carbonization.[71] During the high temperature processing, $AgNO_3$ was reduced to AgNPs. In addition, the phase separations of the tar and PAN as well as the further thermal decompositions of tar components resulted in the formation of CNFs with high specific surface area (>400 m^2/g) and microporosity (Fig. 7D). In a similar study, Bhunia *et al.* reported the electrospinning synthesis of a porous pyrimidine containing urea-functionalized nanofibers.[72] They found that this nanoporous fiber possesses aggregation induced white light emission in the presence of suitable polar solvents and holds the pockets (donor–donor–acceptor array) for specific biomolecular interaction, which reveals great potential for biosensing application.

The above methods for creating porous nanostructures have a few disadvantages. For example, the contents as well as the distribution of pore-foaming agent are not controllable. Once their aggregation appears, not only is the attachment performance of NBBs disturbed, but also the physical properties of nanofibers change sharply. In addition, the location and orientation of NBBs on nanofibers are also not controllable. A desired situation is that the NBBs can insert onto the nanofibers without wrapping and traversing.[19,69]

3.2.2 Hollow structure

In addition to the pore-forming procedure, hollowness is another popular way to increase the surface area of electrospun PMNFs. Comparing to the porous structures, hollow morphologies provide larger surface area.[73-75] However, the fabrication process of this kind of operation is more stringent.[76,77] Firstly, a coaxial electrospinning device is needed, which consists of coaxial two spinnerets to replace the single nozzle in the conventional setup.[73] Secondly, there are several factors, such as the solvent/solution miscibility and incompatibility, solvent vapor pressure, solution conductivities, and solution flow rates of each component, restrict the co-axial electrospinning procedure for producing uniform hollow nanostructures.[74]

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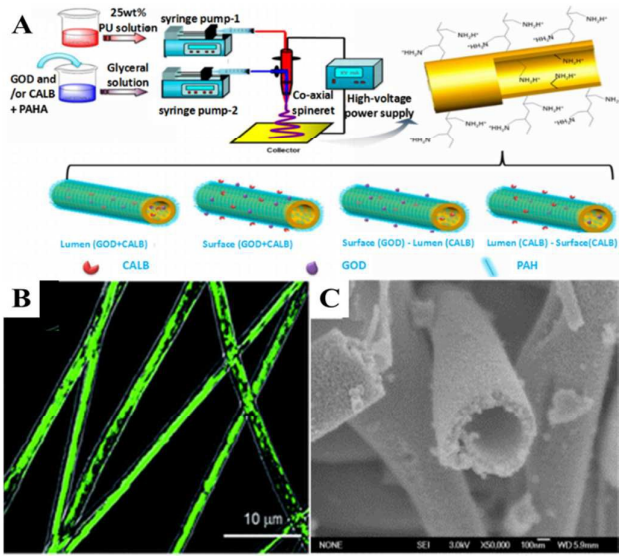

Fig. 8 (A) Schematic illustrations of the setup for co-axial electrospinning and creation of hollow nanostructures. Reproduced with permission from ref. 76, Copyright 2014, American Chemical Society. (B) CLSM image of hollow nanofibers with encapsulated 3a-HSD labelled with FITC. Reproduced with permission from ref. 77, Copyright 2014, Royal Society of Chemistry. (C) The SEM images of Au/SnO_2/MTs. Reprinted with permission from ref. 78, Copyright 2014, Elsevier.

Previously, Ji and co-workers fabricated the polyelectrolyte doped hollow PMNFs for positional assembly of bienzyme system, and the schematic process is shown in Fig. 8A.[76] They found that the hollow nanofibrous membrane based bienzyme can spontaneously float at the interface, thus making it particularly attractive for the biphasic biosensing reaction. In a further study, they fabricated another hollow PMNF-based artificial cell by a facile co-axial electrospinning process.[77] They used 3a-hydroxysteroid dehydrogenase (3a-HSD), diaphorase (DP), and NADH as the core phase, and a N,N-dimethylacetylamide solution with 30 wt% PU as the shell phase during the co-axial electrospinning. Confocal laser scanning microscopy (CLSM) image of the hollow PMNFs labelled with fluorescein isothiocyanate (FITC) proved the successful formation of hollow nanostructure, as shown in Fig. 8B. The hollow nanofiber-based artificial cells were successfully used for the bile acid assay, yielding good linearity for bile acid concentrations ranging from 0–200μM.

Similarly, with the coaxial electrospinning method, Liu and co-workers prepared Au-loading SnO_2 hollow microtubes (Au/SnO_2/MTs).[78] In their study, the sol solution containing PVP and metal salts were used as outer solution while the paraffin was used as inner solution. The morphological characterization indicated the successful preparation of Au/SnO_2/MTs with a tube diameter of about 500-600nm and a thickness of tube wall of about 70-80nm (Fig. 8C). The created Au/SnO_2/MTs hollow nanostructure shows high catalytic activity for the electrochemical reduction of H_2O_2. The fabricated H_2O_2 biosensor reveals a linear detection range from 10μM to 1mM (r = 0.997) and low detection limit of 0.60μM.

In an interesting study, Mondal *et al.* developed a strategy for fabricating aligned hollow structure with micro/nano channels immobilized on the Pt-decorated carbon electrodes and then used it for the detection of aflatoxin B1 (AFB1) via antigen–antibody interactions.[79] In their study, they used electrospun PMMA nanofibers as the sacrificial polymers for the creation of channels embedded on a PAN-derived carbon film. By a pyrolysis process, continuous channels were created by sacrificial removal of the PMMA matrix. Meanwhile, the channels were decorated with PtNPs by the in-situ thermal reduction of the precursor metal salt. They found that the fabricated immunosensor is reproducible, stable, and highly sensitive to 1pg/mL of AFB1 with a linear detection range of 10^{-12}–10^{-7} g/mL.

It is well known that the typical morphology of nanofibers prepared by coaxial electrospinning is core-shell. By the post-treatment process, such as washing or calcination, the polymer core can be removed to create hollow. However, from a contrary view, if the shell part was disposed, an identical surface area and an opposite nanofiber morphology can be obtained.

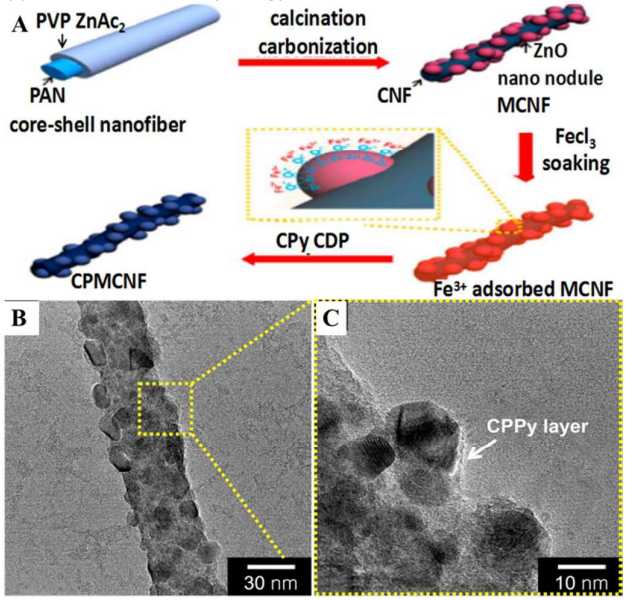

Fig. 9 (A) Illustrative presentation for the formation of hollow CPMCNFs. (B,C) TEM and HR-TEM image of CPMCNFs with 3 nm CPPy layer on the nanofiber surface. Reproduced with permission from ref. 12, Copyright 2014, American Chemical Society.

For example, Jun *et al.* provided a field-effect transistor (FET)-type biosensor using a platelet-derived growth factor (PDGF)-binding aptamer conjugated with carboxylic polypyrrole (CPPy)-coated metal oxide-decorated carbon nanofibers (CPMCNFs) to detect the target molecule, and the schematic diagram is presented in Fig. 9A.[12] The CPMCNFs they used was fabricated via single-nozzle co-electrospinning and vapour deposition polymerization. Interestingly, due to the formation of ZnO nanonodules on the MCNF surface, the authors did not carry out any further treatment for surface functionalization to form the CPPy layer (Fig. 9B and C). The sensing test results showed that this FET-type biosensor is highly selective (5fM) and selective for the target analytes and reusable over a large concentration range of the target molecules.

3.2.3 Core-shell structures

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Recently, the core-shell nanofibers, as novel 1D nanostructures, have also gained great interests in biological field. It is well known that the template-directed method is the most effective and common method to prepare this kind of PMNFs. In general, the two components of core and shell can be different, which means the advantageous properties of both materials can be combined.[80] However, the complex and demanding post-treatments restrict the broader applications of core-shell structures.[81-83]

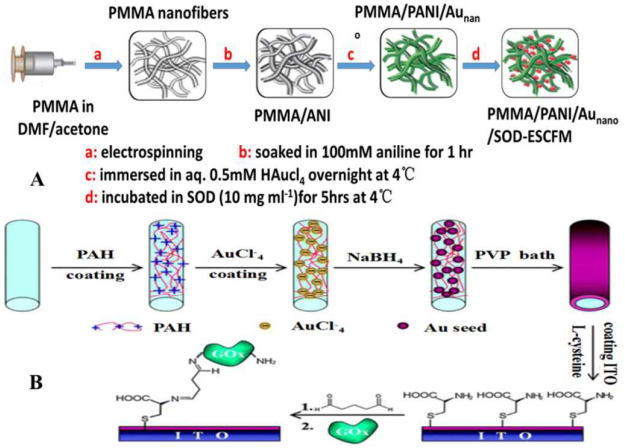

Fig. 10 (A) Illustrative diagram of the sequential fabrication steps for core-shell 3-carboxylated PPy coated hybrid carbon nanofibers. Reproduced with permission from ref. 81, Copyright 2011, Royal Society of Chemistry. (B) Fabrication methodology of core-shell nanostructure. Reproduced with permission from ref. 84, Copyright 2010, Royal Society of Chemistry.

Previously, Baranowska-Korczyc and co-workers adopted a surface passivation technique to fabricate core-shell ZnO/ZnS nanofibers.[80] They prepared ZnO nanofibers by electrospinning in the first place, then ZnS layer was formed on ZnO nanofibers by treating ZnO with hydrogen sulfide in gas phase under ambient conditions. The obtained ZnS shell consisted of 2nm sphalerite crystals surrounding a ZnO core of 5 nm wurtzite crystals. The conductivity of the nanofibers increases by three orders of magnitude after the formation of ZnS shell due to the passivation process inhibiting the effect of oxygen molecules, which is favorable for the fabrication of a biosensor. In another study, Santhosh *et al.* demonstrated the electrospun synthesis of AuNPs modified PMMA–PANI core–shell nanofibers (Fig. 10A) and further utilized for fabricating a biosensor of superoxide anion.[81] Interestingly, the dispersion of AuNPs over PANI can greatly affect the sensitivity and selectivity of the biosensor due to the synergistic influences from AuNPs and PANI. The direct electron transfer achieved between superoxide dismutase (SOD) and the electrode resulted in an electron transfer rate constant of 8.93 s^{-1}. The SOD immobilized at the electrode retains its biocatalytic property and offers bi-functional enzymatic catalytic activity for the detection of superoxide anion. At an applied potential of +300mV, the fabricated enzymatic biosensor is highly sensitive (0.3μM) for the detection of superoxide anion.

Recently, Li and co-workers reported a design of the ethanol sensor based on hollow ZnO/SnO_2 core–shell nanofibers.[82] In their study, the hollow SnO_2 nanofibers were synthesized by electrospinning, and then a ZnO shell with a thickness of 10–15nm was directly grown on the hollow SnO_2 nanofibers, forming a new core–shell nanostructure on the nanofibers via a hydrothermal reaction. The authors revealed that this ZnO/SnO_2 sensor shows dramatically improved sensing performance to ethanol. Similarly, via a template-directed method, Miao *et al*. represented a synthesis method of Ag/SnO_2 composite nanotubes by combining the electrospinning of SnO_2 and the in-situ photocatalytic reduction of Ag^+ to Ag.[83] The electrochemical results indicated that the novel Ag/SnO_2 based H_2O_2 biosensor exhibits a fast amperometric response to H_2O_2 with a wide linear range (10μM to 35mM) and a low detection limit (5μM). Kang *et al.* prepared mesoporous silica nanofiber-gold core-shell nanostructure (SiO_2/Au core-shell fibers) by introducing gold seeds onto nanofiber surface via the in-situ reduction of $AuCl_4^-$.[84] The SiO_2/Au core-shell nanostructure was further created by seed-mediated growth of AuNPs in PVP solution, as shown in Fig. 10B. The SiO_2/Au core-shell nanostructure-based glucose biosensor exhibited excellent bio-electrochemical activity with rapid response and high sensitivity. Shen *et al.* fabricated a novel type of H_2O_2 biosensor with core-shell hybrid material, which consists of a continuous gold shell that encapsulates the silica fiber.[85] They synthesized hybrid nanofibers by electrospinning silica sol, and then golden seeds were in situ grown on the fiber by mixing K_2CO_3 and $HAuCl_4 \cdot H_2O$ in ultrapure water to continuous gold shells. The biosensor showed high sensitivity and fast response upon the addition of H_2O_2 and the linear range to H_2O_2 was from 5μM to 1mM with a detection limit of 2 μM (S/N = 3), which indicated that SiO_2@Au nanocomposites have potential for constructing of a variety of electrochemical biosensors.

4. Suitability of electrospun nanostructures for biosensors

Electrospinning is one of the most convenient and useful techniques to fabricate PMNF-NBB based biosensors, just as we discussed in this review. Firstly, it can endow the PMNFs with controlled sizes, conformations, and chemical functionalities. These properties of electrospun PMNFs will be benefit for the fabrication of novel materials with nanostructures for biosensor application. Secondly, electrospun PMNFs can be functionalized via incorporating NBBs like metallic nanoparticles or quantum dots within the spinning dope or onto the surface of nanofibers after spinning. The conjugated nanoparticles or quantum dots with specific optical and electrical properties are necessary for fabricating various biosensors. Thirdly, the binding of biomolecules like enzymes, antibodies, and antigen onto the electrospun PMNFs make it possible to achieve biomolecule-biomolecule interaction and create signals to detect with the fabricated biosensor architectures. Finally, the large surface area and high porosity provided by electrospun PMNFs can increase the availability of immobilization sites within biosensors, and further afford an enhanced current response for the test biomolecules. Therefore, the electrospun design of electroactive nanomaterials for biosensor from these aspects like materials (nanoparticles, quantum dots), properties (biomodification), and structure (porous, hollow) is the

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potential way to improve the performances of fabricated biosensors.

Theoretically, biosensor is an analytical device that can transfer biological responses into current signal, which consist of both biological detection part and signal transduction part. In the first part, biosensor should selectively identify the bio-tests, and change this detection into current signal by redox reaction. In the second part, current is passed as receipt signal to the receiving system for further amplification. Among this two components, the detection part is the central one. Generally speaking, the electrospun PMNFs possess no reactive ability, and they serve as more like upholder to NBBs as well as bio-tests. Both the detection and transduction parts depend on NBBs, they possess high surface reaction activity and strong adsorption ability for analytes via physical adsorption or chemical binding. Besides, NBBs can be modified by a wide range of biomolecules or anisotropic materials, which makes them easier to be dispersed in PMNFs uniformly, resulting in increased number of biosensing sites for tested biomolecules and enhanced electron transfer between electrode and analytes. **Table 2** presents the comparisons of modification methods and sensing performance of several biosensors fabricated by pre-processing and post-processing.

Table 2. Comparisons of the H2O2 biosensors fabricated by pre-processing and post-processing.

Pre-processing					
NBBs	**Polymer matrix**	**Dispersion method (NBBs-carrier)**	**Detection limit**	**Linear detection range**	**Ref.**
GQDs	PVA	ultrasonication incubation	1μM	0.05-35mM	17
Pt	PVDF	MWCNT	0.61μM	0.1-75mM	49
Ag	PVA	graphene	0.56μM	0.005-47mM	52
Ag	PVA	In situ reduction	5μM	0.005-0.6mM	59
Post-processing					
NBBs	**Polymer matrix**	**Morphology processing**	**Detection limit**	**Linear detection range**	**Ref.**
Au	PVA	None	0.5μM	1-500μM	64
Pt	PAN	Porous	1.9μM	0.1-30mM	19
Au	PVP paraffin	Hollow	0.6μM	10μM-1mM	78
Au	Silica	Core-shell	2μM	5μM-1mM	85

From the above tables it can be found that although many influence factors contribute the final performance of a biosensor together, as long as the detecting and transforming system were secured, the high-performance biosensors by both pre-processing and post-processing could be obtained.

In the pre-processing methods, biosensors introduced with 1D or 2D conductive additives show lower detection limit and broader linear detection range. We can attribute this improvement to the addition of MWCNTs and graphene. They tend to orient along the fiber axis and are embedded in the fiber core due to the high elongation of the polymer jet during the electrospinning process.[86] The assembly of MWCNTs and PtNPs can effectively facilitate the electron transfer, thus boosting the conductivity and improving the electrocatalytic performance of the fabricated materials. A good comparison appears in the last two samples, whose components are PVA-Ag, the introduction of graphene improve the biosensors with better performance as we can see.

In the post-processing cases, these four biosensors with different morphologies illustrate similar biological performance. In principle, PMNFs with special structures like porous, hollow and core-shell possess larger surface area as well as more electroactive points for bio-tests than PMNFs with solid interior and smooth surface, that's why people prefer these modifications to fabricate their biosensors.

When it comes to the comparison of pro-processing and post-processing methods, the comparable terms shouldn't just be limited to the biosensing performance, the operational approach and utilization efficiency of NBBs of biosensors should also be considered. As for the first factor, the pro-processing shows more superiorities, and it needs few harsh conditions like carbonization treatment and in-situ growth of NBBs, or complicated equipment like coaxial electrospinning device. However, the post-processing have higher utilization efficiency of NBBs in biosensor, by this means NBBs can be generated on the surface of PMNFs directly, which indicates that it is possible to maximize the potential capabilities of NBBs on the biological detection due to the exposed surface area. Previous reports indicated that the detection limit of the fabricated biosensors by post-processing can reach the fM level,[12] but such a high accuracy haven't been reported in pro-processing cases.

5. Conclusions and outlooks

Although there are certain technique and mechanism difficulties still need to be solved or improved, electrospinning has become one of the most effective routes to fabricate functional PMNFs with desired compositions and structures. The binding and assembling NBBs with PMNFs via electrospinning technique have been proved to be a powerful strategy to prepare biosensors. However, to obtain a high-performance biosensor, some challenges, such as how to improve NBBs contents without aggregation, and how to increase immobilization sites for tested biomolecules, should be overcome.

It should be noted that no matter what kind of method is used to fabricate biosensors, the appropriate modifications and hybridizations of both NBBs and PMNFs are necessary. Generally speaking, all the modification and fabrication methods of biosensors can be classified as pre-processing and post-processing based on the sequence of introducing NBBs and electrospinning. In the pre-processing method, NBBs are mixed into polymer matrix before electrospinning, whose operation steps are similar with that of preparing nanocomposites. This is a universal and effective method. What's more, NBBs are more stable because they are encapsulated within PMNFs by this means, which ensure the excellent reusability and the long-term storage stability. In the post-processing mothod, NBBs are coated onto the surface of electrospun nanofibers for the sake of the more immediate interactions between NBBs and bio-tests, which can improve the performance of biosensor. In this review, we presented the recent achievements on the electrospun design of functional nanostructures for biosensing applications by these two methods.

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Based on our experience in fabricating PMNF-NBBs based biosensors, it can be concluded that the suitable modification of NBBs could improve their dispersion in polymer matrix and increase the conductivity and biocompatibility of the created PMNF-NBB nanohybrids. In addition, the modification of PMNFs and the subsequent formation of porous, hollow, and core-shell nanostructures have also shown significant enhancement on the biosensing performances for increasing more surface area as well as immobilization sites for analytes.

For the further development of fabrication and biosensor applications of electrospun nanostructures and nanomaterials, we suggest the following areas that could be focused on. Firstly, the signal sensing and transmission mechanism as well as their relationship should be further studied. Secondly, as for pre-processing route, the controllable self-assembly of 1D and 2D functional materials like CNTs, graphene, MoS2, and others during electrospinning processing, the synergistic effect among different NBBs (or different dimensions) should be highly valued, these interactions can contribute both dispersion of NBBs and the current conduction. Besides, the interfacial bonding between NBBs and matrix should also been concerned, which is one key point in all kinds of nanocomposites. Thirdly, more in-depth studies need to be done to optimize the coating of NBBs on the surface electrospun PMNFs in post-processing. In principle, the sensing ability of biosensors fabricated by in this strategy is better, hence, the signal transmission dominate the final performance of a biosensor fabricated by this way. Fourthly, more novel coating methods should be explored to decorate PMNFs in the post-processing of PMNFs. So far, the physical absorption and electrochemical deposition are the most widely used due to their simpleness and versatility. However, both methods have obvious shortcomings for causing the desorption of NBBs from PMNFs and further reduce the reusability. Finally, the biological modification or functionalization of electrospun nanostructures with enzymes and aptamers could be very helpful for the fabrication of biosensors for the selective detection of DNA, protein, virus, and so on.

Abbreviations

PMNFs	polymer nanofibers
NBBs	nanoscale building blocks
NPs	nanoparticles
GQDs	graphene quantum dots
CNTs	carbon nanotubes
GNs	graphene nanosheets
PVA	polyvinyl alcohol
PVP	polyvinylpyrrolidone
PU	polyurethane
MWCNTs	multi-walled carbon nanotubes
AgNPs	silver nanoparticles
H_2O_2	hydrogen peroxide
LOD	detection limit
PVDF	polyvinylidene difluoride
PtNPs	platinum nanoparticles
GCE	glass carbon electrodes
PMMA	polymethyl methacrylate
AuNPs	gold nanoparticles
MPTES	mercaptopropyltrimethoxysilane
PA6	polyamide 6
PAH	poly-(allylamine hydrochloride)
TEM	transmission electron microscope
SEM	scanning electron microscope
PBIBA	poly-4-(4,7-di(thiophen-2-yl)-1H-benzo[d]imidazol-2-yl) benzaldehyde
PANI	polyaniline
CMC	carboxymethyl cellulose
CNFs	carbon nanofibers
PAN	polyacrylonitrile
DMF	dimethyl formamide
PMMA	polymethyl methacrylate
PMAA	polymethacrylic acid
PEI	polyetherimide
FESEM	field emission scanning electron microscopy
3a-HSD	3a-hydroxysteroid dehydrogenase
CLSM	confocal laser scanning microscopy
FITC	fluorescein isothiocyanate
AFB1	aflatoxin B1
FET	field-effect transistor
CPPy	carboxylic polypyrrole
CPMCNFs	carboxylic polypyrrole-coated metal oxide-decorated carbon nanofibers
SOD	superoxide dismutase

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