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Review

Recent development in hybrid conducting polymers: Synthesis, applications and future prospects

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The hybrid conducting polymers (HCPs) possesses unusual properties of both conducting polymers (CPs) and organic/inorganic nanoparticles, which drawn much attraction to the scientist and researchers. The processing of HCPs have helped in overcoming the drawbacks associated with CPs such as poor processability, solubility, stability and low yield. In view of this, the present review article highlights the important synthesis techniques of HCPs and their conduction mechanism. Additionally, much attention has been paid to their diverse applications in energy storage devices, EMI shielding, sensors, biomedicals, anti-corrosive coatings. Finally, the future prospects and current challenges of such polymers have also been overviewed.

Contents

Abbreviations: CPs, conducting polymers; HCPs, hybrid conducting polymers; OIH, organic–inorganic hybrid; PA, polyacetylene; PANI, polyaniline; PPy, polypyrrole; PTh, polythiophenes; PPh, polyparaphenylene; PPV, polyparaphenylene vinylene; POT, polyorthotoluidine; IPN, interpenetrating polymer network; NHCP, nano hybrid conducting polymer; TEOS, tetraethyl orthosilicate; TMOS, tetramethylorthosilicate; GPTMS, (3-glycidoxypropyl)trimethoxysilane; MWCNT, multi walled carbon nanotube; APS, ammonium peroxydisulfate; PTEB, poly[2-(3thienyl)-ethoxy-4-butylsulfonate]; PDPA, poly(*para*-phenylenediamine); EP, electrochemical polymerization; PCz, polycarbazole; N-GE, nitrogen doped graphene; LED, light emitting diode; OFETs, organic field-effect transistors; FET, field effect transistor; MOFET, metal-oxide field effect transistor; JFET, junction field effect transistors; PEO, polyethylene oxide PEO; P3Th, poly(3-hexylthiophene); OLEDs, organic light emitting diodes; PLEDs, polymer light-emitting diodes; PVK, poly[9-vinylcarbarzole]; MEH-PPV, poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene]; NADH, nicotinamide adenine dinucleotide; GCE, glassy carbon electrode; EES, electrochemical energy storage; ECs, electrochemical capacitors; PV, photovoltaic; CEs, counter electrodes.

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Introduction

Conducting polymers are the conjugated polymers having π-bonds on their backbone, which helps in the migration of electrons throughout its polymeric chain [1]. They are considered to be noteworthy polymers that can act as conductors, semiconductors, superconductors and magnetic materials. The presence of delocalized π electrons on the backbone of these polymers induces unique optical and electrical properties [2]. Generally, conducting polymers find applications in the field of transistor [3], electromagnetic shielding [4], batteries [5], light-emitting diodes (LED) [6], artificial muscles [7,8], sensors [9–12], antistatic coatings [13], corrosion inhibitors [14], anti-corrosive coatings [15], fuel cells [16], solar cells [17–19], supercapacitors [20] etc. The most extensively studied conducting polymers are polyacetylene (PA), polyaniline (PANI), polypyrrole (PPy), polythiophenes (PTh), polyparaphenylene (PPPh), polyparaphenylene vinylene (PPV) and polyorthotoluidine (POT) and their derivatives [21]. The molecular structure of widely studied conducting polymers are presented in Fig. 1. The main characteristic features of conducting polymers are lightweight, conducting, resistance to corrosion, photochromic, electrochromic and low cost. Moreover, they can be tailor-made through their modifications in terms of structure and functional groups [22]. However, the drawbacks of conducting polymers are their poor stability, processability and solubility [23]. In order to overcome these shortcomings, their various modifications are being made in terms of blends, co-polymers, interpenetrating polymer networks (IPNs), hybrid conducting polymers (HCPs).

HCPs are either homogeneous or heterogeneous (nanocomposites) systems, comprising miscible organic and inorganic components in which at least one of the components (domains) dimension should be in nanometer (nm) range [24]. They are further classified into two categories. The first one has weak interactions (Van der Waal's, hydrogen bonding, weak electrostatic interaction etc), while the second one has strong interaction (chemical) between the two phases [25]. Metal [26,27]/metalloid [28]/ceramic [29,30] modified conducting polymers act as a hybrid or composite, which can be synthesized by the incorporation of organic–inorganic materials/dopants into the conducting polymer matrices. The successful incorporation of inorganic moieties into the conducting polymer matrix enhances the electron transfer rate at the modified surface/electrolyte interface [31].

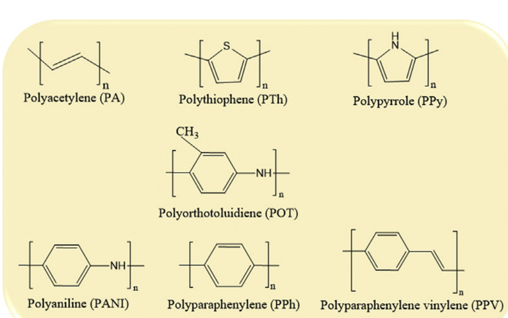

Fig. 1. Molecular structures of some of the important conducting polymers.

Recently, HCP composites have attracted great attention due to their unique microstructures, physiochemical and electro-optical properties [32,33]. Generally, HCP composites are processed through the dispersion of sufficient amount of hybrid conducting phase into the insulating polymer matrix [34]. The nano hybrid conducting polymers (NHCPs) are a special class of materials, which originate from suitable combinations of two or more types of nano moeities using some suitable technique. The resulting NHCPs have unique physical properties, find wide applications in various fields such as battery cathodes, construction of nanoscopic assemblies, sensors [9,35] and microelectronics [36–38]. The properties of NHCPs can be enhanced by controlling the size of its constituent phases and their degree of mixing. Depending on the nature of the components and the methods of preparation, different properties of NHCPs can be achieved [39]. Many papers have been published on the incorporation techniques for the development of nanoparticles and their dispersion into the polymeric matrices [40–44]. In most of the cases blending or mixing of the two components are required, i.e. polymers in solution or in melt form [45].

HCPs, that have enhanced properties over conducting polymer (CPs) open the new window for the generation of new and smart materials exhibiting advanced electrical, optical and mechanical properties, having wider applications in coatings [46,47], sensors [48], catalysis [49] and optics [50,51]. The promising control on physical and chemical properties of metal-conducting polymer nanocomposites by the introduction of nano/metal particles in conducting polymer matrices are the main interest of scientists [52,53]. The metal/carbon conducting polymer nanocomposites can be synthesized by three methods. The first one involves the dispersion of metal nanoparticles into a polymer matrix. In this case, the reduction of metal ions and the process of polymerization occur successively, which causes aggregation of nanoparticles that makes this synthetic procedure often difficult and inconvenient. In the second method, nanoparticles are generated in situ during the polymerization that avoids the agglomeration, making them more useful. Here the polymerization reaction and the synthesis of nanoparticles proceed simultaneously. The third method consists of polymerization of the matrix around a metal nanocore by using chemically compatible ligands [54] or polymeric structures [55]. The various applications of hybrid conducting polymer has been shown in Fig. 2.

During the literature survey, it was observed that most of the reviews published on the topic under consideration are generally