

Enhancing Conductive Polymer Nanocomposites with Nanomaterials for Superior Properties and Versatile Applications: A Review

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Abstract— Conductive polymers (CPs) have received significant attention due to their distinctive benefits over conventional materials, including versatile and adjustable electrical conductivity, straightforward fabrication methods, high mechanical strength, lightweight properties, cost-effectiveness, and ease of processing. By fusing the outstanding mechanical, thermal, and functional properties of nanoparticles with the electrical conductivity of polymers, conductive polymer nanocomposites (CPNCs) have become a ground-breaking class of materials. The electrical, mechanical, and optical properties of these composites are greatly improved by the synergistic integration of nanofillers, such as carbon nanotubes, graphene, metal nanoparticles, and nanoceramics. This makes it possible for these composites to be used in flexible electronics, energy storage, sensors, biomedical devices, and electromagnetic shielding. The synthesis methods, structure-property correlations, and processes controlling the electrical behavior of CPNCs are examined in this review. It also emphasizes their wide range of uses, which include electronic gadgets, coatings, sensors, and energy storage. Additionally covered the difficulties and potential of CPNCs, highlighting their critical role in developing next-generation nanomaterial-based technology.

Index Terms- Composites, Conductive polymer, Energy storage, Fabrication, Nanocomposite.

I. INTRODUCTION

The research interest in conductive polymers (CPs) has been significant in both academic and industrial sectors since the discovery of conductive polyacetylene in the 1970s.[1] This is due to their unique ability to provide adjustable electrical conductivity while retaining the desirable characteristics of conventional polymers, including ease of synthesis and flexibility in processing. Some of the most encountered CPs are (Table 1) Polyaniline (PANI), Polydopamine (PDA), Poly(3, 4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS), Poly(para-phenylene) (PPP), Polyacetylene (PA), Poly(phenylenevinylene) (PPV), Polypyrrole (PPy), Poly-thiophene (PTH), Polyisothianaphthalene, and Polyfuran (PF) etc.[2-4] Three researchers Professors Alan G. MacDiarmid,[5] Alan J. Heeger,[6] and Hideki Shirakawa[7] were awarded the Nobel Prize in 2000 for their work on the invention and improvement of electrically conducting polymers, there has been increased interest in this area.[8-10] The conductivity of CPs is influenced by the molecular structures of the materials and the degree of doping, as well as the arrangement of molecular packing. This provides a significant degree of adjustability and versatility in terms of conductivity. Electrical conductivity, chemical and electrochemical properties, density, flexibility, corrosion resistance, processability, biocompatibility, and low cost have all contributed to CPs widespread consideration for a wide range of properties.[11, 12]

Polymer nanocomposites are a particular kind of nanocomposites where the matrix is a polymer and the nanofiller is another nanoscale component. Conductive polymer nanocomposites (CPNCs) are a special class of polymer nanocomposites that are made conductive by combining conducting or insulating polymer matrix with conducting or insulating nanofillers. Because of the synergistic effects that the polymer matrix and the nanofiller produce, these nanocomposites have a lot of potential applications. The conducting polymers that are most frequently researched are polyaniline (PANI), polypyrrole (PPy), polyacetylene (PAc), polythiophene (PTh), and their derivatives. On the other hand, conducting nanostructures like carbon nanotubes (CNTs), graphene, metals, and insulating ceramic nanostructures make up the most used nanofillers. Conducting polymers have also been transformed into nanostructures and used as nanofillers, giving some insulating polymer matrices a variety of interesting architectures and characteristics. To create conducting hybrid nanostructures that then function as conducting nanofillers to create more complex CPNCs with improved compatibility between the matrix and nanofiller, non-conducting ceramic nanostructures can also be coated with conducting polymers.

Some nanoscale CPs have shown great promise as potential components of high-performance devices. Like their bulkier relatives, they have some fascinating features, but they also have some peculiar ones that are typically associated with a large surface area and little volume. Increased interaction between the CP and analytes is what allows nanomaterials (NMs) made of CP to achieve such

great sensitivity. A wide variety of analytes, including hazardous gases, volatile organic chemicals, and biological species, have been detected using CP nanoparticles (NPs). In addition, over the past few years, we have investigated the possibility of fabricating sensors from conducting polymer nanoparticles also known as CP nanocomposites. Evidence from these investigations suggests that CPNCs could be useful building blocks for advanced sensing devices. More in-depth research into the fabrication of CPNCs for many applications, the relationship between nanomaterial characteristics and performance, is necessary to realise next-generation high-performance devices based on nanomaterials.

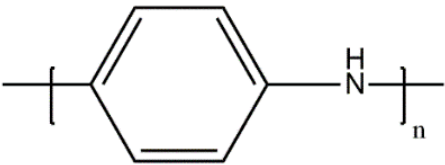
Synthesis of CP nanocomposites can be accomplished by chemical or electrochemical methods. Powdery nanomaterials are typically the product of chemical processes, and they scale up well. However, electro polymerization limits reactions to electrode surfaces, and CP nanostructures are often deposited as films there. The mechanical, optical, thermal, magnetic, chemical, electrical, and biological features of nano-sensors based on nanostructure materials have been comprehensively outlined by Abdel-Karim et al.[13] Three main techniques are often used in the manufacture of conducting polymer nanocomposites: (1) Direct mixing/blending: the polymer is dissolved in a suitable solvent, and then the nanofiller is vigorously stirred into the polymer solution.[14, 15] (2) In-situ polymerization with nanoparticles: usually, the nanofiller is surface treated or altered first, and then the monomer, oxidant, and/or doping agent are added using a selected stirring technique to complete the polymerization and/or create a network of polymers with relatively uniformly embedded nanostructures. In general, this approach improves the interactions between the nanofiller and the polymer matrix, improving characteristics like mechanical strength.[16, 17] (3) In-situ nanoparticle production in the presence of polymer: This method creates a conducting polymer nanocomposite by first dissolving the polymer in a suitable solvent, then adding the nanofiller precursor and treating it thermally or electrochemically. Sixteen years ago, this approach produced very interesting and consistent nanostructures in a variety of morphologies within the polymer nanocomposites, with a primary focus on their synthesis, characteristics, and possible uses. We offer a more comprehensive and modern examination of conducting polymer nanocomposite systems in this review. These

systems consist of either an insulating or conducting polymer as the matrix, but the addition of conducting nanostructures greatly improves their conductive qualities. In order to demonstrate the enormous potential of conducting polymer nanocomposites in cutting-edge devices, the ensuing sections discuss optoelectronic devices (organic light emitting diodes, photovoltaics, and electrochromic devices) as well as other intriguing devices (stretchable electronics, electrochemical energy storage devices, and biosensors). For upcoming processing and developments utilizing conducting polymer nanocomposites, these devices provide significant economic and environmental benefits matrix.[18]

Twenty four years ago, De et al.[19] provided a succinct outline of conducting polymer nanocomposite research, primarily concentrating on their synthesis, characteristics, and possible uses. We offer a more comprehensive and modern examination of conducting polymer nanocomposite systems in this review. These systems consist of either an insulating or conducting polymer as the matrix, but the addition of conducting nanostructures greatly improves their conductive qualities. In order to demonstrate the enormous potential of conducting polymer nanocomposites in cutting-edge devices, the ensuing sections discuss optoelectronic devices (organic light emitting diodes, photovoltaics, and electrochromic devices) as well as other intriguing devices (stretchable electronics, electrochemical energy storage devices, and biosensors) as shown in **Figure 1**. For upcoming processing and developments utilizing conducting polymer nanocomposites, these devices provide significant economic and environmental benefits.

Embedding carbon nanomaterials (CNMs) such as single-walled carbon nanotubes (SWCNTs), multi-walled carbon nanotubes (MWCNTs), carbon nanofibers, fullerenes, carbon nanospheres, graphene (G), and graphene oxide (GO) into a polymeric matrix is the best method for improving and combining their mechanical and electrical properties.[20] The fabrication of solar cells,[21] electrochemical capacitors, electrochemical sensors, transistors, biosensors,[9, 22] gas sensors, etc. all benefit from the use of CNMs because of these properties. In this review paper, we will discuss about the complicated interplay between CPs and NPs. The goal is to learn more about the combined effects, qualities, and uses of these two types of materials. They have the extraordinary potential to synergistically improve one another's attributes, leading to entirely new materials with improved performance.

Table 1. Some conductive polymer with their conductivity and structure

Conductive Polymer	Structure	Conductivity (S _{cm} ⁻¹)	Doping type
Polyaniline		1-100	n,p

Polyparaphenylene		500	n,p
Polyacetylene		200-1000	n,p
Polypyrrole		40-200	p
Polythiophene		10-100	p
Polyparaphenylene vinylene		1-1000	p
Polyisothianaphthalene		1-50	p

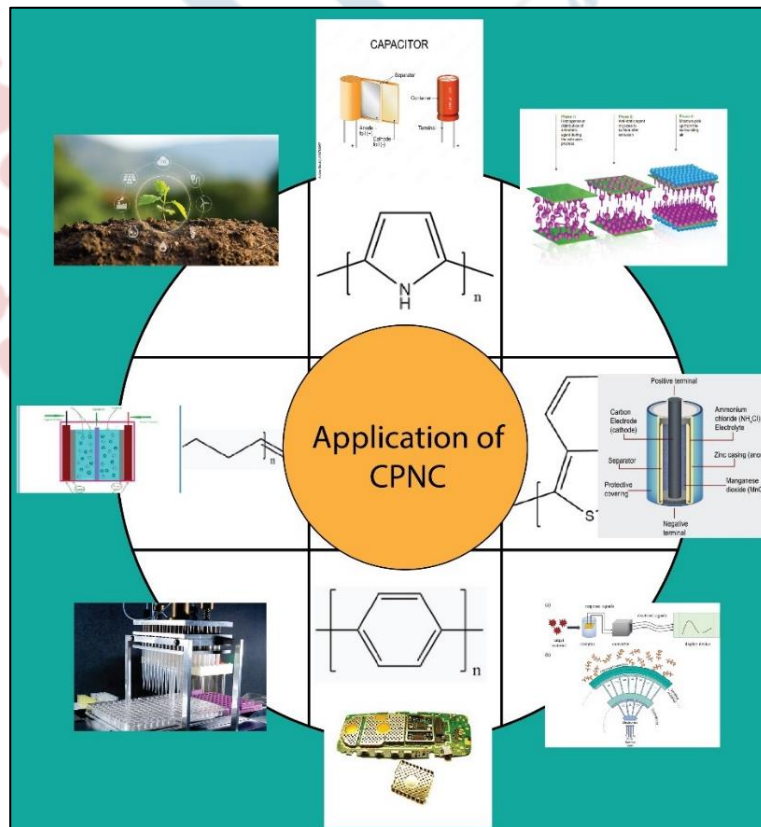


Figure 1: Application of conductive polymer nanocomposites

II. FABRICATION OF CONDUCTIVE POLYMER NANOCOMPOSITES

The practical use of technologies utilising conducting-polymer nanoparticles has been limited primarily due to the absence of dependable and consistent synthetic methods. The utilisation of conducting-polymer nanoparticles has promise in the development of compact sensors that offer advantages such as reduced sample quantities, mobility, and the ability to create high-density arrays. In addition, the utilisation of nanoparticles exhibiting a limited size distribution fulfils the criteria for transparent and flexible sensor platforms. Hence, the exploration of synthetic pathways to produce nanomaterials composed of conducting polymers has emerged as a highly intriguing area of focus in current nanoscale investigations. The methods used to produce conducting polymer nanoparticles can be categorised as hard-template synthesis, soft-template synthesis, and template-free synthesis.[23, 24]

A. Synthesis of Template-Technique

Hard-Template Synthesis

Basically, the synthesis of the hard template method has been used in the fabrication of one-dimensional nanostructures like nanotubes, nanorods, and nanofibers made up of conducting polymers. The templates usually utilised by hard-template synthesis are anodic aluminium oxide (AAO) and track-etched polycarbonate (PC) membranes.[25, 26] The range of pore sizes spans from 10 nanometres (nm) to 100 micrometres (μm). Much research has been already conducted in recent years on the hard template synthesis for the fabrication of conducting polymer nanomaterials. Typically, the polymerization of a conductive monomer has been conducted within nanochannels as nanoreactors, with subsequent removal of hard templates. According to Martin et al.[27-29] prepared the hard template approach to synthesise polymer nanomaterials. Particularly, in this research conductive polymers were used in the fabrication process to create nanotubes and nanofibers within the microscopic pores of nanoporous membranes. The researchers conducted the synthesis of nano-tubes composed of PPy, PANI, and poly(3-methylthiophene) using hard templates by using the processes of chemical oxidation and electrochemical polymerization are of significant interest in the field of materials science and chemistry. During the process of polymerization, the conducting polymer exhibits a preference for nucleation and growth on the surfaces of membrane pores. In a recent study conducted by Jang et al.,[30] the authors successfully synthesised PPy nanotubes and carbon nanotubes (CNTs) by the process of vapour deposition. More attention has been paid to the synthesis of conducting polymer nanomaterials by using rigid templates, such as colloidal nanoparticles, nanofibers, and porous membranes. A straightforward method for synthesising

polypyrrole (PPy) nanotubes has been recently established using an alumina membrane template. Poly(p-phenylene) nanotubes were synthesised using a combination of vapour deposition polymerization (VDP) and template synthesis techniques. Significantly, the wall thickness of the nanotubes was precisely regulated to be within a narrow range of a few nanometres. The results of this study demonstrate that the template-mediated vapour deposition polymerization (VDP) technique is a highly successful approach for producing polymer nanotubes with perfect control over their wall thickness. Another noteworthy example involves the production of carbon nanofibers (CNFs) coated with PPy by a one-step vapour deposition polymerization (VDP) process. [30, 31]

Soft-Template Synthesis

In recent times, the soft template method has been used for the designing of diverse morphologies of polymer nanoparticles. There exist multiple soft templates includes surfactants, liquid crystalline polymers, cyclodextrins, and functionalized polymers. Surfactants, encompassing cationic, anionic, and non-ionic amphiphiles, block copolymers, and polyelectrolytes are predominantly employed in the creation of soft-template synthesis.[32] The topics of interest include liquid crystals and biomolecules. It has been observed that sodium bis(2-ethylhexyl) sulfosuccinate (AOT) molecules resulting in the formation of cylindrical micelles. This study focuses on the interaction between iron cations and an apolar solvent.[33, 34] In AOT cylindrical micelles consist of iron cations that are adsorbed onto the anionic head of the micelle structure. The iron cations behaves as an oxidising agent in the chemical polymerization using certain monomers, such as pyrrole, and 3,4-ethylenedioxythiophene (EDOT). Thus, the incorporation of pyrrole or EDOT monomer into the cylindrical micelle played a pivotal role in the development of polymer nanoparticles in the cylindrical interface between the AOT and water, where the monomer was interaction with the iron cations. The fabrication of one-dimensional (1D) nanostructures was achieved through the manipulation of synthetic factors. Moreover, it is crucial to note that the micelle templating technique was discovered for the purpose of producing conducting-polymer nanomaterials on a wide scale.[31, 35, 36]

Template-Free Synthesis

The process of template-free synthesis is simple.[31] Nevertheless, this methodology is constrained to specific precursor materials. The synthesis of PANI nanofibers via template-free synthesis has been a subject of significant research interest. It is noteworthy that the fibrillar structure was shown to be inherent in water based PANI, and it shows the nanofibers was the inhibition of secondary growth resulting in particle agglomeration. Additionally, it also shows the use of dispersion polymerization to produce polyaniline (PANI) nanorods.[37-39] The dispersion

polymerization was conducted utilising hydrochloric acid as a dopant and ammonium peroxydisulfate as an oxidant. PANI nanofibers can be synthesised with a high yield, resulting in a significant quantity on a multigram scale. Extensive research has been conducted on the utilisation of template-free approaches in the production process of conducting polymer nanoparticles. When comparing the methodologies of hard and soft template methods, it becomes evident that these approaches offer a straightforward and pragmatic pathway to produce pure, uniform, and high-quality nanofibers. Template-free methods refer to a range of techniques including electrochemical synthesis, chemical polymerization, aqueous/organic interfacial polymerization, radiolytic synthesis, and dispersion polymerization.[40-42]

III. SYNTHESIS AND PROCESSING OF CONDUCTIVE POLYMER NANOCOMPOSITES

Nanocomposites of conductive conjugated polymers shows high performance due to its high surface area. They are known to be conductive polymer nanocomposites because of its integration of polymer matrix polymer matrix (which can conduct or insulate) with nanofillers (which can also conduct or insulate). This combination results in synergistic effects that have the potential for various applications in different fields. Conducting polymer nanocomposites are a preferable and feasible option for creating lightweight materials also which are required in various practical applications, including construction structures and transportation vehicles. They can also serve as alternatives to traditionally heavy components like ceramics and metals, offering improved electrical, thermal, mechanical, morphological, and in addition, certain conducting polymers can be applied as a coating on non-conducting nanomaterials to create conducting hybrid nanomaterials. These hybrid nanomaterials can then be used as conductive nanofillers in the production of complex conductive polymer nanocomposites.

A. PANI-Based Polymer Nanocomposites

According to researcher Meng et al. synthesized PANI/graphite nanocomposite by using situ polymerization of aniline (monomer) in the presence of graphite nanosheets. The results concluded that the graphite shows the more effect on the thermal stability of PANI and conducts electrical conductivity of 33.3 S/Cm.[43] Dong et al. also fabricated the Ni/PANI nanocomposites by chemical polymerization method and concluded that the permittivity and permeability can increase the microwave absorption.[44] Mostafei and Zolriasatein[45] prepared the PANI based nanocomposites containing ZnO nanorods via chemical oxidative method. This synthesis method shows that the electrical conductivity of PANI-ZnO is much lesser than the PANI. Moreover, Chitosan-polyaniline-nickel (II) oxide nanocomposite was also synthesized showing binding energies of 854.6, 856.9, 861.1 and 864.2 eV showing the application in its medical

field. Xianlong and team[46] improved the glass transition temperature by synthesizing molybdenum carbide (Mo_2C) doped PANI nanocomposite.

B. PTh-Based Polymer Nanocomposites

Iguchi et al.[47] fabricated the nanocomposite using a combination of poly(3-hexylthiophene) and graphene. In the process of in situ polymerization, graphene was evenly distributed in a solution containing a mixture of toluene and N-methylpyrrolidone (NMP) solvents. Li et al. investigated the impact of changed graphene dispersion on significant characteristics. π - π interactions facilitated the formation of a heat transfer interface between the poly(3-hexylthiophene) matrix and the modified graphene. The nanocomposite exhibited an in-plane thermal conductivity of $4.17 \text{ W m}^{-1} \text{ K}^{-1}$, surpassing that of the original polymer matrix. The observed result can be attributed to the enhanced dispersal and interfacial properties of the matrix and nanofiller.[48] Kausar et al.[49] synthesised a nanomaterial made from polythiophene and graphene. Due to improved dispersion of graphene, a percolation threshold was achieved at a nanofiller level of 1.5 wt.%, resulting in a high electrical conductivity of $1.8 \times 10^{-3} \text{ S cm}^{-1}$. The nanocomposite exhibited a significant thermal conductivity of 1.22 W/mK because of the formation of a thermal interface. Sharif et al.[50] synthesised a nanocomposite by polymerizing the thiophene monomer in the presence of nanocarbon, produced from polythiophene and graphene oxide. The phenomenon of graphene oxide dispersion was noticed during the formation of conductive routes within the polymer matrix. The polythiophene/graphene nanocomposite exhibited a greater electrical conductivity ($2.5 \times 10^{-8} \text{ S cm}^{-1}$) compared to pure polythiophene ($1.3 \times 10^{-7} \text{ S cm}^{-1}$). The nanocomposite's thermal stability was improved by the dispersion of graphene and its interactions with the polymer, in addition to its electrical conductivity. An increase in weight of 15–22% was recorded at a temperature of 600 °C because of improved thermal stability characteristics.

C. PPy-Based Polymer Nanocomposites

Mazeika et al. produced $\text{CoFe}_2\text{O}_4/\text{PPy}$ composites dispersed in ferrofluid using high energy milling and applied them in biomedical applications.[51] Zhu et al.[52] utilised a one-step co-electrodeposition technique to synthesise a nanocomposite film consisting of graphene oxide (GO) and PPy. GO was incorporated into the Ppy nanocomposite during electrochemical polymerization, where it functioned as a feeble electrolyte and an effective charge balancing dopant. It presented favourable potential uses in high-performance electrochemical supercapacitors. In addition, Nahrawy et al.[53] investigated the impact of Ppy doped sodium silicate nano-gel/ TiO_2 nanocomposites. The dielectric constant, tangent loss, and conductivity exhibited a non-linear relationship with dopant concentration, initially decreasing and thereafter increasing. Hu et al.[54] conducted

a review of an article that focused on graphene-polymer nanocomposites for structural and functional applications. They found that these devices exhibited improved electrical, mechanical, chemical, and thermal performance. In a separate study, Taban et al.[55] utilised the in-situ chemical polymerization technique to produce nanocomposites of GO/Ppy/polymethylmethacrylate (PMMA). An increase in both electrical and thermal conductivity was seen as the graphene oxide (GO) and polypyrrole (Ppy) concentrations in the polymethyl methacrylate (PMMA) were increased. It was determined to be advantageous for use in the manufacturing of further large-scale polymer-based composites. Lee et al.[56] developed a nanocomposite of Prussian blue (PB) and Ppy utilising a self-assembly method, resulting in improved electrochemical characteristics. The PB/Ppy nanocomposites, as they were originally synthesised, significantly augmented the pseudo-capacitive behaviour by a factor of ten, mostly attributed to the presence of conductive PPy. However, the author proposed that the duty cycle might be enhanced by incorporating graphene oxide (GO) and reduced graphene oxide (rGO).

D. PEDOT-Based Polymer Nanocomposite

Han et al.[57] synthesised PEDOT/GO nanocomposites doped with poly(sodium styrenesulfate) (PSS) with the situ polymerization method showing specific capacitance of 108 F/g. Chen et al.[58] fabricated core-shell PEDOT/PSS-MWCNTs nanocomposite showing specific capacitance of 198.2 F/g. According to Swiegers et al. reported the PEDOT/nano-Co₃O₄/rGO nanocomposites which can be beneficial as a photo catalyst of oxygen production from water.[59]

IV. APPLICATIONS OF CONDUCTIVE POLYMER NANOCOMPOSITES

Conducting polymer nanocomposites have found extensive use in optoelectronic devices and biomedical disciplines, including organic light-emitting diodes (OLEDs), photovoltaic devices, electronic devices, sensors, actuators, and memory devices. And also they have been widely utilised in diverse optoelectronic devices owing to their facile processing, robust structural stability, cost-effective synthesis, and exceptional optical, electrical, and mechanical capabilities.[60]

A. Sensors and Biosensors

For the application in chemical and biological uses, many sensors are using conducting polymers. The conductivity of conducting polymers can be readily affected by their intrinsic reversible mechanisms of doping and dedoping (oxidation and reduction), resulting in fluctuations in oxidation levels. Hence, conducting polymers possess the ability to demonstrate heightened reactivity towards chemical or biological entities. Due of these attributes, a significant amount of effort has been dedicated to the development of

sensor devices that rely on conducting materials. In recent times, a diverse array of conducting polymer nanoparticles has been utilised for the purpose of detecting a broad spectrum of chemical and biological entities. It is important to mention that nanostructures, such as nanorods, nanofibers, and nanotubes, possess a significant surface-to-volume ratio, which facilitates efficient diffusion of analytes into and out of the material.[61-64]

It is widely recognised that conducting polymers exhibit electrocatalytic properties when interacting with a diverse range of substrates, encompassing both ions and organic molecules. In recent years, there has been a significant focus on the development of chemo- and biosensors using conductive polymer modified electrodes. Electrochemical polymerization represents a highly convenient approach for the synthesis of a thin conducting polymer layer. The conducting polymers most employed in the advancement of novel sensor technologies were polypyrrole (PPy) and polyaniline (PANI).[62, 65, 66] Primarily, PPy nanoparticles have shown utility in a diverse range of sensor applications, including toxic gas detection, non-toxic gas detection, fragrance sensing, humidity sensing, and microbiological detection. Like, gas sensors based on carbon nanotube-poly (pyrrole) (CNT-PPy) composites were synthesised using a straightforward chemical polymerization method, thereafter, deposited onto pre-patterned electrodes using spin-casting technique. Wallace et al.[67] created a modified electrode consisting of a composite of polypyrrole (PPy), carbon nanotubes (CNTs), and glucose oxidase (GOX) using the process of electrochemical co-deposition. This modified electrode demonstrated a significantly enhanced sensitivity towards glucose, approximately ten times greater than that observed with a flat PPy film grown on a gold electrode. The increased sensitivity seen can be due to the expansion of the surface area, facilitating the accessibility of glucose to the GOX included in the ultrathin PPy film.

B. Batteries

The role of conductive polymers as electrodes in rechargeable batteries was investigated during the 1980s and thoroughly examined by Haas et al. in 1997.[68] While it is possible to utilise CPs as either anodic or cathodic substances in batteries and the predominant focus of research has been on employing CPs as cathodic materials in conjunction with a metallic anode. Cathode materials possess several notable advantages include their cost-effectiveness, ease of processing, and the capacity to conveniently modify their chemical structures. Nevertheless, it is important to acknowledge that CP cathodes do have certain limitations, such as suboptimal cyclability and lower conductivity in their reduced condition. To address these limitations, carbon-based polymers (CPs) have commonly been combined with inorganic metal oxides or carbon nanotubes (CNTs) to create nanostructured hybrid electrode materials. Like, composite electrodes consisting of polyaniline (PANI)

and carbon nanotubes (CNT) were fabricated using the process of electrochemical polymerization on CNT substrates. The inclusion of carbon nanotubes (CNTs) in the composite material leads to an augmentation in surface area, hence enhancing the conductivity of the composite through the reduction of polyaniline (PANI). Consequently, the lithium battery, which was constructed using a cathode composed of PANI/CNT and a gel polymer electrolyte, demonstrated a notable energy density of 86 mAhg^{-1} and exhibited favourable cyclability.[69, 70]

C. Electrochromic Devices

Electrochromic refers to the reversible alteration of colour in a substance, which is initiated by the application of an electric field. The initial investigations into electrochromic mostly concentrated on inorganic chemicals, such as tungsten trioxide (WO_3), as well as organic molecules, like bipyridiliums. However, current studies have primarily concentrated on investigating conductive polymers such as PPy, PANI, and PT.[71-73] Conducting polymers has several advantages over other electrochromic materials, such as their facile processability, rapid switching speed, notable contrast and coloration efficiency, adjustable bandgap, and other notable attributes. Nanostructured conducting polymers have the potential to exhibit significantly quicker switching times in comparison to their bulk counterparts. Recently, there have been successful advancements in the fabrication of electrochromic devices that exhibit rapid switching speeds. These devices are constructed using meticulously arranged arrays of PEDOT nanotubes. The rapid diffusion of counterions during the redox process was facilitated by the thin walls of PEDOT nanotubes, which had a thickness of approximately 10-20 nm. This characteristic enabled the achievement of extraordinarily fast switching rates, below 10ms. Furthermore, it should be noted that the utilisation of micrometre-sized PEDOT nanotubes has the potential to provide a significant level of colouring.[73]

Conducting polymers have been widely regarded as a highly suitable material for actuator applications due to their ability to undergo reversible volume changes, specifically expansion and contraction, during the processes of oxidation and reduction. Smela conducted a comprehensive analysis of the current research trends related to conducting polymer actuators. PPy was classified under the extensive category of electrically actuated polymeric materials referred to as electroactive polymers. It has numerous advantageous characteristics, such as significant strain (ranging from 3% in-plane to over 30% out-of-plane), high strength, functioning at low voltages, biocompatibility, and other notable attributes. Jager et al. have authored a series of publications that detail the innovative manufacturing process of conducting polymer microactuators.[74] The researchers have successfully created microactuators, also known as micro-muscles, utilising a PPy-Au bilayer. The Au layer had dual functions as both a structural layer and an electrode. The

micromuscles were employed for the purpose of elevating plates and manipulating the opening and closing of boxes. Furthermore, the microbotic arms possess the capability to grasp, elevate, manipulate, and position objects of micrometer-scale dimensions within a confined region measuring around $250 \times 100 \mu\text{m}^2$. The precise manipulation of the robot arm was achieved through the utilisation of microactuators that were individually regulated. Lee et al. synthesised nanocomposites of polyethylenedioxythiophene/anodized aluminium oxide, which exhibited a remarkably rapid colour exchange rate ($<10 \text{ ms}$) and robust coloration, significantly outperforming the PEDOT film in terms of duration.[73]

D. Coating Surface

The design of a superhydrophobic surface considers the surface morphology and surface free energy of the material. It is very important to highlight that the thin films of conductive polymers can be easily applied onto the conductive surfaces.[75-77] Conductive polymers can be utilised to create a superhydrophobic coating on the substrates can conduct electricity. Several innovative ways have been used to create CP nanostructured films by reducing the surface free energy. More importantly, superhydrophobic conductive polymer also behaves as an anticorrosion coating due to its formation of passive oxide layer at the metal and coating interface. According to Franssila et al., fabricated the elastic, conductive and wear-resistant superhydrophobic composite material by using polydimethylsiloxane (PDMS)/Cu superhydrophobic composite material. The results concluded that the resistivity varied from $0.7 \times 10^{-5} \Omega\text{m}$ (virgin) to $5 \times 10^{-5} \Omega\text{m}$ (1000 abrasion cycles) and $30 \times 10^{-5} \Omega\text{m}$ (3000 abrasion cycles).[78]

E. Transistors and Switch

The utilisation of conducting polymers as logic or switching components is crucial in the advancement of novel electronic gadgets.[79-81] An organic field-effect transistor typically consists of a gate, drain, source, dielectric layer, and semiconducting layer.[82] The applied gate voltage modulates the current flow between the drain and source electrodes. The "off" state of a transistor occurs when there is no voltage difference between the gate and source electrodes. A nanowire consisting of cobalt-PPy-cobalt was created by electrochemical synthesis within an alumina membrane. Field-effect transistors were then made by applying a gate design to one side of the nanowire.[83] The measured output and transfer properties of the PPy film field-effect transistors are comparable to or superior to those of other devices. The amplification of the nanowire field-effect transistors could be regulated by sequentially electrochemically doping the PPy segment.

V. CONCLUSION

CPNCs have emerged as a groundbreaking class of materials that combine the unique electrical, mechanical, and thermal properties of conductive polymers with the enhanced functionalities provided by nanomaterials. These materials exhibit exceptional performance in various applications, including flexible electronics, energy storage, sensors, biomedical devices, and electromagnetic shielding. The synergistic interaction between the polymer matrix and nanofillers, such as carbon nanotubes, graphene, metal nanoparticles, and ceramics, has enabled significant advancements in conductivity, mechanical strength, and processability.

Despite their immense potential, challenges remain in terms of large-scale synthesis, stability, and cost-effective fabrication methods. Ongoing research is focused on optimizing synthesis techniques, enhancing interfacial interactions between polymer matrices and nanofillers, and exploring novel nanostructures to further improve the performance of CPNCs. Poor processability is frequently the result of adding more conductive nanofillers to the polymer matrix, particularly for nanocomposites that have a high concentration of nanofillers. While polyaniline and polypyrrole are processable, doped polyacetylene and polyphenylene are notoriously difficult to process. One of the greatest achievements of the materials science community will be the cheap cost and potential large-scale production of these kinds of devices. Given the rapid advancements in this fascinating sector, large-scale and useful applications are anticipated soon. Future developments in this field are expected to drive the creation of next-generation materials with enhanced durability, efficiency, and multifunctionality, paving the way for innovative applications in advanced electronics, healthcare, and energy sectors.

Conflict of Interest:

The authors declare that they have no conflict of interest.

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