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Pani-Based Nanocomposites for Electrical Applications: A Review

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ABSTRACT

Including supercapacitors, rechargeable batteries, and fuel cells, conducting polyaniline (PANI) has been widely used in electrochemical energy storage and conversion technologies due to its high conductivity, ease of synthesis, high flexibility, low cost, and distinctive redox properties. Because of its poor stability as a super-capacitive electrode, pure PANI cannot keep up with the rising demands for more N-active sites, better power/energy densities, and more stable molecular structures. These drawbacks as a super-capacitive electrode can be overcome by combining PANI with other active materials such as carbon compounds, metal compounds, and other conducting polymers (CPs). Recent PANI research focuses mainly on PANI-modified composite electrodes and supported composite electrocatalysts for fuel cells and rechargeable batteries, respectively. Due to the synergistic effect, PANI-based composites with various unique structures have shown superior electrochemical performance in supercapacitors, rechargeable batteries, and fuel cells. PANI typically functions as a conductive layer and network in different PANI-based composite structures. This review also discusses N-doped carbon materials produced from PANI because they are frequently employed as metal-free electrocatalysts for fuel cells. We conclude by providing a quick summary of upcoming developments and future research directions in PANI.

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1. Introduction

Nanotechnology is important in enhancing the functional capability of electrical devices widely used today(Hulla, Sahu, Hayes, & toxicology, 2015). Due to vast advancements in electronic devices, extensive research has been focused on increasing the potential applications of electrical appliances. Out of all the nanocomposites, i.e., ceramic, metal-based, and polymer-based, polymer-based nanocomposites are more widely used for their electrical properties, high conductivity, and enhanced stability(P. Liu et al., 2019; X.-f. Tan et al., 2016). Due to their high sensitivity and capacity to reverse changes in their optical and electrical properties when exposed to specific liquids or gases, conducting polymers like polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh) have been used as sensing active layers in chemical sensors(T. Zhang et al., 2020). Polyaniline is one of the best conducting polymers used in research for its low cost, facile synthesis, and high mechanical stability(Meriga et al., 2015; Paramane, Kumar, & materials, 2016).

Polyaniline (PANI) is one of the most promising materials of particular interest due to its high electrical conductivity, dielectric behavior, and excellent-electrochromic optical properties(Kumar, Kumar, Awasthi, & Engineering, 2018; Seiler & Kindersberger, 2014).

Polyaniline is the best electrode material with a semi-flexible rod polymer family(Zare et al., 2019). Supercapacitors, electrochromic devices like photovoltaic cells, plastic batteries, display devices, microelectronics, chemically modified electrodes, corrosion protection, and polymer light-emitting diode (PLED) displays are just a few examples of the electrical applications where it is widely used(Althubiti, Al-Harbi, Sendi, Atta, & Henaish, 2023; Xue, Fu, Wang, Xing, & Zhang, 2016).

The polyaniline (PANI) bases can be divided into three different oxidation states. The fully reduced (lucoemeraldine base) or half-oxidized (emeraldine base) forms can both be partially oxidized to make them conductors. And three of its states have different morphologies(Arteshi, Aghanejad, Davaran, & Omidi, 2018; He, Yan, Xue, Li, & Wang, 2023). The entirely reduced form is called lucoemeraldine (LB), the half-oxidized form is called emeraldine (EB green), and the oxidized form is called pernigraniline violet color (PB). Contrary to other conducting polymers, PANI's conductivity can be adjusted by adjusting the levels of protonation and oxidation(Goswami, Nandy, Fortunato, & Martins, 2023; Kroutil, Laposa, Povolny, Klimsa, & Husak, 2023).

One of the most crucial properties of PANI-based nanocomposites is their ability to offer total electrical, thermal, and mechanical insulation. Polyaniline conducting polymer is a promising anode material for lithium-ion batteries due to its high Li storage capacity. Polyaniline has the stability, flexibility, and conductivity to create any matrix material. It efficiently produces organic and dye- synthesized solar cells utilizing conjugated polymers(Khan, Gul, Baig, & Akram, 2023; Xie et al., 2023).

Numerous uses for polyaniline include the creation of flexible electrodes, antistatic coatings, electromagnetic shielding, actuators, supercapacitors, and electrochromic. Rechargeable batteries, sensors, electronic devices, light-emitting diodes, conducting paints and glues, gas-separation membranes, coatings, etc., are just a few of the many applications PANI could be used for. Numerous studies have also been done on using PANI in the aerospace industry (Goswami et al., 2023; Nguyen, Soram, Tran, Kim, & Lee, 2023).

Ghadaayadkhadim (Nam et al., 2011) has shown that PANI-based nanocomposites can be widely used as sensors, and electrochemical devices, to detect various gases. Thin films made of polyaniline (PANI) that integrate hydrogen sulfide (H2S) gas sensors have been developed by Mehdi Hassan(Bezzon et al., 2019). In 2019, by electrochemically polymerizing aniline monomer with sulfuric acid in an aqueous solution, which alters its electrical resistance, functionalized single-wall carbon nanotubes (f-SWCNT) with varying concentrations were created. Polyaniline nanowires have been used by H. Song(Z. Han et al., 2019) as chemo-resistive sensors in the solution phase.

The capability of these electrical devices is improved by various composites of polyaniline with various carbon materials, such as activated carbon, porous carbon, carbon nanotubes, carbon nanorods, carbon fibers, and graphene(Sadiq et al., 2023; Zahid, Anum, Siddique, Shakir, & Rehan, 2023).

In this review article, which has yet to be published, we present the synthesis of PANI-based nanocomposites as well as their electrical applications. Although numerous PANI-based nanocomposites have been used to advance energy conversion and storage devices, these materials' review articles are not yet available. This review article focuses on new developments in energy storage technologies and cutting-edge PANI-based nanocomposite technology, which improve electrical qualities by raising conductivity and cyclic stability. In this review paper, PANI is endowed with and displays appropriate performance for usage in electrical applications.

2. Polyaniline (PANI)

A conductive polymer member of the synthetic polymer family is called polyaniline (PANI). Due to its distinctive electrical, optical, and mechanical properties, it has garnered considerable interest from researchers. German chemists Heinrich Hörlein and Paul Morgan created polyaniline (PANI) for the first time in 1862, but it took a long time for researchers to realize that it had conducting qualities. The first known organic conductive polymer was

PANI, which was discovered to have electrical conductivity comparable to metals by Bell Labs researchers in 1963(Okafor, Popoola, Popoola, Uyor, & Ogbonna, 2023). Since then, PANI has undergone substantial research, and several prospective uses for its electrical, optical, and mechanical properties have been investigated. It is regarded as one of the most promising conducting polymers in the market today for various applications in electronics, energy storage, and biomedicine(Yang et al., 2023).

Emeraldine base (EB), emeraldine salt (ES), pernigraniline base (PGB), pernigraniline salt (PGS), lucoemeraldine base (LB), and lucoemeraldine salt (LS) are just a few of the several forms of polyaniline (PANI). These forms' levels of oxidation and protonation vary, which alters their optical and electrical conductivity characteristics. Emeraldine base (EB), which has good electrical conductivity, stability, and environmental compatibility, is the most extensively researched and used type of PANI(Ekande, Kumar, & Waste, 2023).

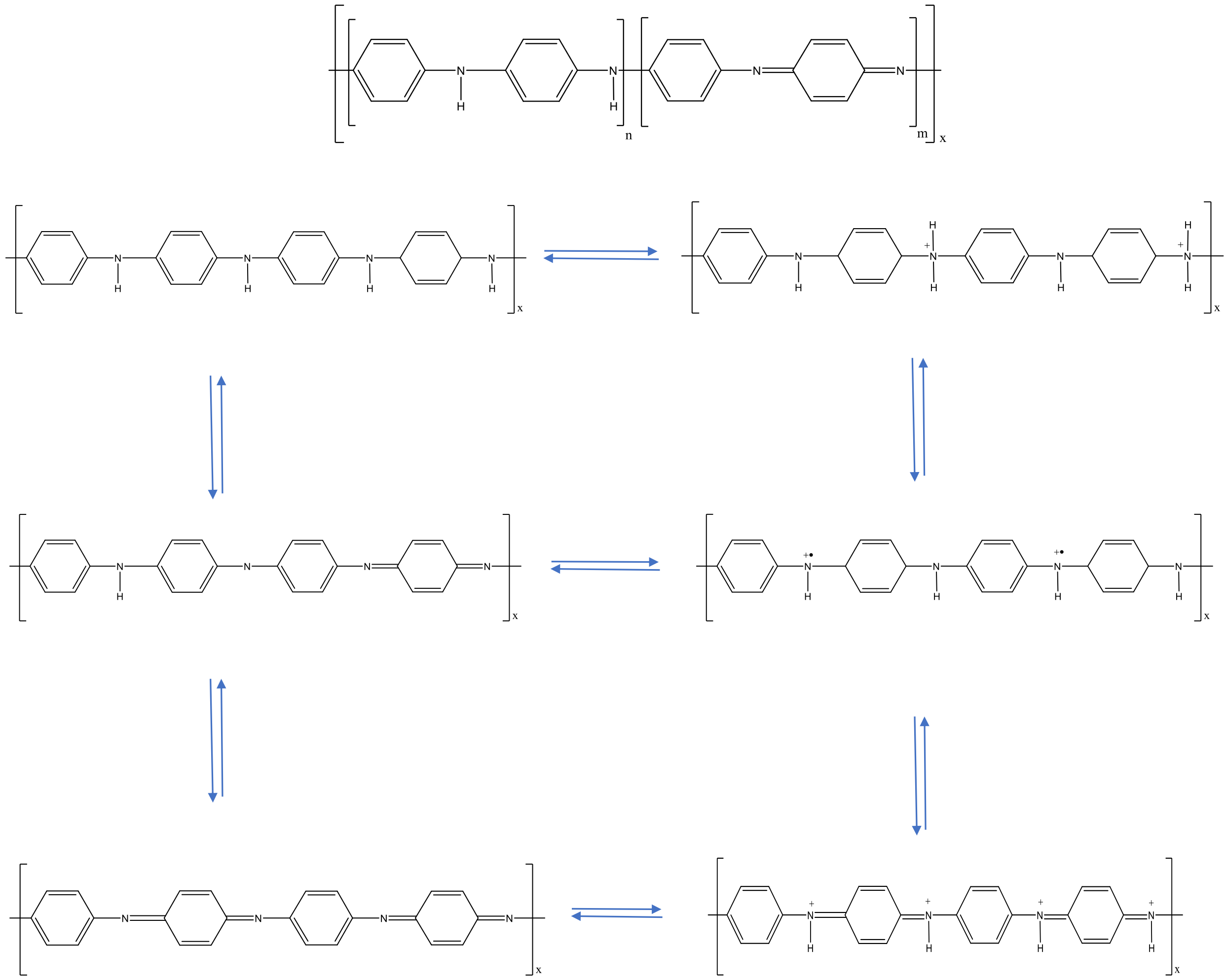

Figure 1: Polyaniline with various redox forms(Dhand et al., 2015)

3. PANI Synthesis

A variety of polyaniline synthesis methods has been discussed in the below section. Methods include emulsion polymerization, sol-gel polymerization, electrochemical polymerization, and matrix polymerization. Some methods, like oxidative polymerization, were used to prepare polyaniline(Varghese, KR, Kausar, & Pinheiro, 2023).

The graphene-based PANI nanocomposites have been fabricated by various methods in the presence of graphene, rGO, or GO, and the PANI is in the form of nanoparticles: nanowires, Nanofibers, hollow spheres, or nanorods. Most graphene-based PANI nanocomposites were prepared using in situ polymerization approaches, including in situ chemical oxidative polymerization(W. Tan et al., 2023).

3.1. In Situ Chemical Oxidative Polymerization

In situ, chemical oxidative polymerization, which includes chemically oxidizing aniline monomers in the presence of oxidizing agents such as ammonium persulfate, ferric chloride, or hydrogen peroxide, is a frequently used method for producing polyaniline (PANI) and its derivatives. This method involves dissolving aniline monomers in an acidic solution containing an oxidizing agent. The polymerization process is then started by heating the reaction mixture, which produces PANI(Ko, Yeap, & Bakar, 2023).PANI can modify graphene through a variety of interactions, including covalent functionalization, noncovalent functionalization, and other processes. By carefully manipulating the reaction conditions, it is possible to create graphene-based PANI nanocomposites with various topologies, including nanowires, nanofibers, nanoparticles, nanotubes, and nanorods. Nanotubes having an outer diameter of 250 nm might be produced by polymerizing in 0.1 M aniline and 0.05 M HCl solution at 0 C for 90 minutes. It is crucial in determining how big the nanotubes are. A nanosphere shape was discovered as the solution acidity rose from 0.05 M to 0.2 M. This technique successfully creates hierarchical nanocomposites of PANI nanowire arrays on GO sheet substrate(Imali, Perera, Kaumal, & Dissanayake, 2023; Y. Zhao et al., 2015).

3.2. In Situ Electropolymerization

Electrochemical polymerization of aniline monomers on a conducting electrode surface is known as in situ electropolymerization, and it is a process used to create polyaniline (PANI) and its derivatives. The electrode functions as a support for the polymerization process and a way to regulate how quickly the PANI film grows.

PANI is created when aniline monomers undergo oxidation at the anode surface during the electropolymerization process. An acidic electrolyte solution containing aniline and an oxidizing agent, such as ammonium persulfate or ferric chloride, is commonly used to conduct the oxidation process(Rathnayake et al., 2023).

The creation of PANI/GO nanocomposites using in situ electropolymerization and their characteristics have been covered in several research. According to a study by Zhang (2016), for instance, PANI/GO nanocomposites were created utilizing a two-step in situ electropolymerization technique, and it was demonstrated that the resulting materials exhibited outstanding electrochemical characteristics, making them ideal candidates for use as supercapacitors. Similar to this, a 2019 study by Xiong described the synthesis of PANI/GO nanocomposites utilizing an electrochemical co-deposition approach, demonstrating that the resulting nanocomposites exhibited large surface area and increased conductivity, making them exciting candidates for use as biosensors(Eftekhari & Kim, 2017; Yong Zhang, Wang, Lu, Li, & Zhang, 2021).

3.3. Interfacial Polymerization

Interfacial polymerization is a flexible method for creating several kinds of polymers, including polyaniline (PANI). The process entails polymerizing two immiscible phases at their interface, commonly an organic and an aqueous phase(Kyomuhimbo & Feleni, 2023).

An oxidant is often present in the aqueous phase of PANI, whereas aniline and a dopant are typically present in the organic phase. The oxidant diffuses into the organic phase when the two phases come into contact at the interface, starting the polymerization of aniline into PANI. The resulting PANI is typically deposited at the interface as a thin film that can later be separated and treated(Male, Srinivasan, & Singu, 2015).

In a 2015 study, Zhang reported on the interfacial polymerization process used to create PANI/GO nanocomposites. They demonstrated that the produced materials exhibited high specific capacitance, making them interesting candidates for use as supercapacitor electrodes. Similarly, a 2017 work by Yin described the creation of PANI/GO nanocomposites using interfacial polymerization and showed that the resulting nanocomposites had good catalytic activity for reducing nitroarenes(Ji et al., 2015; Wei, Yang, Hu, Li, & Jiang, 2021).

3.4. Solution Mixing

The initial ingredients are disseminated in a common solvent and combined in solution mixing to create a homogeneous combination. The stability and dispersion of the nanocomposite are highly dependent on the solvent chosen. Dimethylformamide (DMF), N-methyl-2-pyrrolidone (NMP), and water are frequently employed as solvents for combining PANI and GO solutions(Q. Wang et al., 2017).

In the resulting PANI/GO nanocomposite, the GO sheets are enmeshed inside the PANI matrix, giving the material a composite structure. By modifying the preparation parameters, such as the concentration of the starting materials, mixing time, and temperature, the dispersion and distribution of the GO sheets inside the PANI matrix may be managed(Chang, Lin, Peng, Zhang, & Huang, 2018).

The PANI/GO nanocomposites were created by solution mixing, as described by Li et al., and it was demonstrated that these nanocomposites exhibited good electrical conductivity and electrochemical characteristics, making them appropriate for supercapacitor electrodes. Similarly, Zhang described the solution-mixing method used to create PANI/GO nanocomposites and showed that these materials had a high catalytic activity for reducing nitroarenes(Olad, Barati, & Shirmohammadi, 2011; Rahmawati, Suendo, & Hidayat, 2018).

3.5. Self-Assembly Approach

In the self-assembly method, PANI is created by guiding the assembly of PANI monomers into nanostructures with regulated size, shape, and morphology using surfactants or templates(J. Wu, Wang, Huang, Bai, & Science, 2018). The self-assembly method has several benefits, including gentle reaction conditions, excellent purity of the resultant PANI, and controllable PANI nanostructure characteristics. In the self-assembly method, PANI nanocrystals are stabilized in aqueous or organic solvents using surfactants or templates(W. Song et al., 2017). The PANI monomers are next added to the mixture, where they go through a self-assembly process to create nanocrystals with precise size and shape. PANI nanocrystals that have been produced can be further treated to create films, fibers, or other structures with the desired characteristics.(Ran, Tan, & Nanocomposites, 2018).

Various surfactants and templates have been employed for PANI self-assembly, including block copolymers, dodecyl benzenesulfonic acid, and cetyltrimethylammonium bromide (CTAB). The preferred PANI nanostructure features and the application requirements determine the best surfactant or template (D. Zhang et al., 2018). Zhang, X(X. Song et al., 2021) synthesized self-assembled polyaniline nanowires for ultrasensitive ammonia gas detection.

3.6. Pickering Emulsion Polymerization

The emulsifier particles used in this method are typically inorganic substances like metal oxides, silica, or clay minerals(W. J. Han, Piao, & Choi, 2017). Organic ligands are surface-functionalized onto them to make these particles compatible with the monomer and solvent utilized in the polymerization process. An oxidizing agent is then introduced to the emulsion after the monomer, typically aniline, to cause the polymerization of the monomer into PANI nanoparticles(Huang et al., 2023).

Compared to conventional surfactant-based emulsions, Pickering emulsion polymerization uses solid particles as emulsifiers and provides several benefits. For instance, the solid particles can stabilize the emulsion by reducing nanoparticle coalescence, which results in a more uniform size distribution(Jun, Kwon, Choi, Seo, & interfaces, 2017). Additionally, following synthesis, it is simple to separate the solid particles from the polymer nanoparticles(Y. Wang, Hu, Luo, Gu, & Liu, 2021). R Liu(K. Wu, Gui, Dong, Luo, & Liu, 2022) prepared PANI nanocapsules by Pickering emulsion polymerization for anticorrosion coating.

4. PANI-Based Binary and Ternary Composites

Composite materials made of polyaniline (PANI) are those in which PANI has been combined with one or more other materials to produce a new material with improved or distinctive features. Because pure PANI has limitations in terms of its mechanical, electrical, and thermal properties, PANI composites are required. PANI composites can be customized to specific applications and desired qualities by integrating different components(Althubiti et al., 2023). PANI/graphene oxide, PANI/carbon nanotubes, and PANI/metal nanoparticle composites are a few examples of PANI composites. When compared to pure PANI, these composites have been found to have better mechanical strength, electrical conductivity, and other qualities(Nasir et al., 2023).

PANI composites with two components are referred to as binary composites, while those with three components are referred to as ternary composites. By fusing PANI with various materials, binary and ternary composites allow for even more precise control of characteristics(Shanmuganathan, Raghavan, & Ghosh, 2023).

4.1. PANI-Based Binary Composites

Binary composites made from polyaniline (PANI) and another element, such as graphene oxide, carbon nanotubes, metal oxides, or conductive polymers, are called polyaniline-based binary composites. Compared to pure PANI, the properties of the resulting composite can be enhanced or made to stand out(Lee et al., 2017).

The PANI/graphene oxide composite illustrates a PANI-based binary composite(Yanlin Zhang et al., 2016). This composite is a potential supercapacitor material due to its outstanding electrical conductivity and high specific capacitance(Palsaniya, Nemade, & Dasmahapatra, 2018). Another illustration is the composite of PANI and carbon nanotubes, which has shown enhanced mechanical strength and thermal stability and is, therefore, appropriate for use in structural materials or high-temperature applications. The potential use of PANI/ZnO and PANI/TiO2 composites in fields like photocatalysis and gas sensing has also been researched(Gaikwad, Patil, Patil, Naik, & B, 2017).

Usually, in situ, polymerization, solution mixing, or interfacial polymerization are used to create these binary composites. The qualities of the final composite can vary depending on the preparation process chosen.

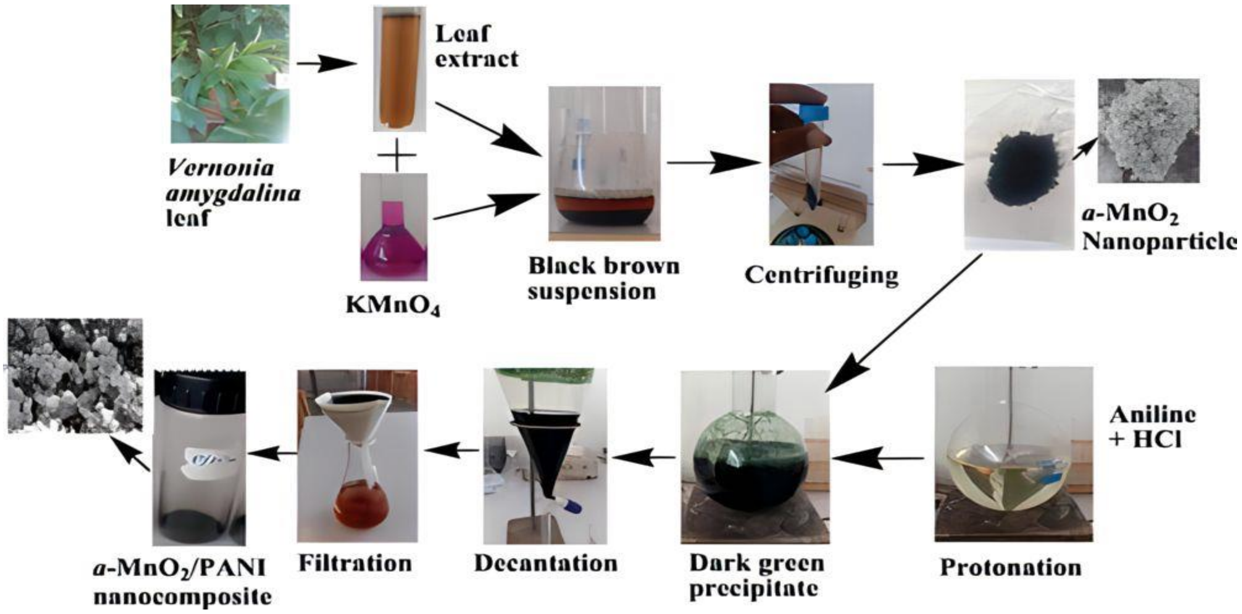

Figure 2: Synthesis protocol for a-MnO2/PANI binary composite (Dessie, Tadesse, Eswaramoorthy, & Adimasu, 2021)

All things considered, PANI-based binary composites are a significant class of materials with a variety of possible uses (Torvi, Naik, & Kariduraganavar, 2018). They are appealing for usage in a variety of industries, including energy storage, electronics, and biology, due to their improved features and distinctive qualities (Omar et al., 2017).Yilkal Dassie(Dessie, Tadesse, Eswaramoorthy, & Adimasu, 2021) prepared a MnO2/PANI binary composite as an efficient anode catalyst for microbial fuel cells.

4.2. PANI-Based Ternary Composites

PANI-based ternary composites comprise three distinct parts comprising PANI and two other substances, such as metals, metal oxides, or other polymers. These composites are made to maximize the benefits of each component's unique characteristics, producing a material with improved electrical, mechanical, or optical capabilities(Azman, Mamat@ Mat Nazir, Ngee, & Sulaiman, 2018).

PANI/Fe3O4/GO, a ternary composite made from PANI, iron oxide (Fe3O4) nanoparticles, and graphene oxide (GO), is an illustration of a PANI-based ternary composite(Mezgebe et al., 2017). Thanks to the GO, the Fe3O4 nanoparticles give the composite magnetic characteristics and have a high surface area and strong electrical conductivity. The PANI keeps the composite together as a binder and improves its electrical characteristics(Mu, Tang, Zhang, & Wang, 2017). This composite is a potential material for EMI shielding applications since it has been demonstrated to have better electromagnetic interference (EMI) shielding effectiveness than PANI/Fe3O4 binary composites(Luo et al., 2015; Hou Wang et al., 2015).

PANI/Fe3O4/MoS2 is another illustration; it is made up of PANI, Fe3O4 nanoparticles, and MoS2. While Fe3O4 enhances electrical conductivity and serves as a template for PANI growth, MoS2 nanoparticles provide UV-blocking properties and act as reinforcement. The usage of this composite in UV-blocking, magnetic, conductive, dielectric, and photocatalytic applications has shown promise(X. Wang et al., 2022).

5. Electrical Properties of PANI

A conductive polymer with electrical characteristics, polyaniline (PANI) can undergo reversible redox reactions. It is a specific kind of conjugated polymer with delocalized electrons that can conduct electricity.

Duan and Yuan(2022)(B. Liu et al., 2022)explained the PANI conductivity mechanism. They suggested that protons are transferred from the dopant to the polymer backbone as part of the doping process in PANI, producing charged sites that serve as mobile charge carriers. These charged sites cause the delocalized -electron system to develop in the polymer backbone, which gives PANI its electrical conductivity.

5.1. Effect of Dopants on Electrical Properties of PANI

Doping degree, chemical structure, molecular weight, and morphology are just a few variables that can affect PANI's electrical conductivity. PANI can suffer p- and n-type doping depending on the dopant employed. As a result of the dopant accepting electrons from the PANI backbone during p-type doping, there are fewer charge carriers and more electrical resistance. In contrast, n-type doping increases the number of charge carriers and decreases electrical resistance as the dopant donates electrons to the PANI backbone. Double doping of PANI, which is done by adding sulfuric acid, is also important while enhancing the electrical properties of PANI.

Hisham A. Saleh (2022) (Saleh & Younis, 2022) studied how polyaniline's (PANI) electrical characteristics are affected by double doping. According to the study, PANI's electrical conductivity and thermal stability both improve due to the double doping method. The findings also demonstrate that the twofold doping procedure reduces the bandgap of PANI, which is advantageous for its use in electrical devices. In conclusion, the work offers insightful information about the potential of double doping to improve PANI's electrical characteristics.AwzarManaf(Manaf, Hafizah, & Riyadi, 2019) showed variation in electrical conductivity of PANI by Anionic Surfactant as shown in fig below.

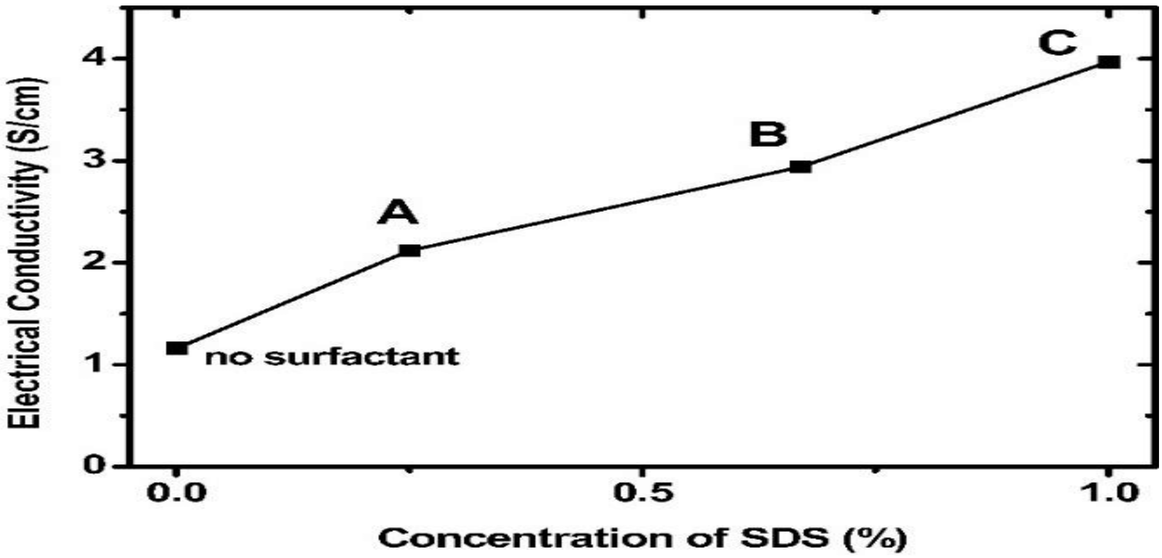

Figure 3: Electrical conductivity of PANI by SDS (Manaf et al., 2019)

6. Electrical Applications of PANI

Polyaniline (PANI) has a variety of electrical applications due to its unique electrical properties including

6.1. Supercapacitors

Supercapacitors, often called electrochemical capacitors, are energy storage systems capable of storing a lot of energy and power. They are appropriate for various applications, including electric vehicles, portable devices, and renewable energy systems, since they offer fast charging and discharging capabilities(N. Ma, Yang, Riaz, Wang, & Wang, 2023). PANI-based materials can be used to overcome the poor energy density of conventional supercapacitors, which restricts their use in many applications. Since PANI-based composites have a high specific capacitance and good cycling stability, they have been thoroughly studied for use in supercapacitors. PANI/graphene oxide (GO) is one such composite, and due to the synergistic interaction between the two materials, it possesses a high specific capacitance. A specific capacitance of up to 900 F/g, which is substantially higher than that of pure PANI, has been observed for PANI/GO composites.

PANI/carbon nanotubes (CNTs) are another PANI-based composite that has been researched for application in supercapacitors. Due to the high surface area and good electrical conductivity of the CNTs, PANI/CNT composites have a high specific capacitance and exceptional cycling stability. There have been reports of PANI/CNT composites with a specific capacitance of up to 450 F/g(Eftekhari, Li, & Yang, 2017).

PANI-based hydrogels have also been investigated for usage in supercapacitors in addition to these composites. PANI hydrogels have a three-dimensional porous structure that offers a significant surface area for electrolyte ion adsorption, resulting in high specific capacitance. According to some reports, PANI hydrogels can have a specific capacitance of up to 711 F/g(Sardana, Gupta, Singh, Maan, & Ohlan, 2022).

Overall, improving supercapacitors' energy density and cycling stability by introducing PANI-based materials has shown considerable potential. More research is required to enhance the synthesis and performance of these materials and investigate their potential for usage in real-world applications(Mir, Kumar, & Riaz, 2022).

6.2. Fuel Cells

Fuel cells are machines that use a chemical reaction to transform chemical energy from fuel into electrical energy. For its possible use as an electrode material in fuel cells, polyaniline (PANI) has undergone substantial research(Q. Xu et al., 2022). PANI is a prime candidate for application in fuel cells due to its demonstrated strong electrochemical activity, high electrical conductivity, and strong chemical stability. Proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells (DMFCs), and microbial fuel cells (MFCs) have all used PANI as a cathode and anode material(Dessie, Tadesse, & Adimasu, 2022; Huanhuan Wang, Lin, Shen, & devices, 2016).

PANI is a cathode material used in PEMFCs, where it can catalyze the oxygen reduction reaction that results in the production of electrical energy. The methanol oxidation reaction can be catalyzed by using PANI as an anode material in DMFCs(Papiya, Pattanayak, Kumar, Kumar, & Kundu, 2018). PANI can be employed as a cathode material in MFCs, enhancing the fuel cell's electrochemical performance and stability(Papiya et al., 2018; Sudarsono et al., 2022).

PANI composites and hydrogels have been employed in numerous research investigations for fuel cells. In one such study, X. Yang (2023) (Y. Xu et al., 2023) discusses creating and applying a composite material comprised of porous carbon nanoparticles and polyaniline in microbial fuel cells. The authors discovered that the composite material performed better than pure polyaniline and other composite materials with a maximum power density of 700 mW/m2 and a current density of 1200 A/m2. The better performance was due to the porous carbon nanoparticles' greater conductivity and active spots for electrochemical processes. The study shows the potential of composite materials based on polyaniline for enhancing the efficiency of microbial fuel cells. Cc Xing (2022) (D. Jiang et al., 2022)demonstrated that with a maximum power density of 800 mW/m2, the composite material PANI/Mxene/-coated carbon cloth yielded excellent electrochemical performance and outperformed many previously reported MFC anode materials. The performance of the MFC was strengthened by the authors' observation of increased bacterial adherence on the anode surface. The findings imply that the carbon cloth coated with polyaniline-MXene may be a potential anode material for high-performance MFCs.

6.3. Rechargeable Batteries

Due to its high theoretical specific capacity, quick electron and ion transport, and simplicity of production, polyaniline has received substantial study as an electrode material in rechargeable batteries. Numerous rechargeable battery systems, including lithium-ion, sodium-ion, and zinc-ion batteries, have used PANI. PANI-based electrodes have demonstrated remarkable electrochemical stability and performance results, highlighting their potential as a workable substitute for conventional electrode materials(Ahmad, Farooqui, & Hamid, 2018; F. Zhang et al., 2017). Supercapacitors are machines that can store electrical charge and quickly release it when necessary(Zhu et al., 2022). PANI-based materials can be employed as active materials in these machines. PANI's unique electrical and mechanical qualities make it highly suitable for energy storage applications(H. Jiang et al., 2022).

A new anode material for lithium-ion batteries (LIBs) based on a composite of polyaniline (PANI) matrix with sulfonated graphene-encapsulated Fe2N nanoparticles was described by M. Idress (2023)(Idrees et al., 2023), along with its production and electrochemical characteristics. The PANI matrix contains well-dispersed and evenly distributed Fe2N nanoparticles, which enhances the anode's overall electrochemical performance. Comparing the composite anode to its PANI and pure Fe2N equivalents reveals that it has a higher specific capacity, superior cycle stability, and rate capability. Fe2N nanoparticles, sulfonated graphene, PANI's high electrical conductivity, and PANI's electrochemical activity are all said to work together synergistically to improve the composite anode's electrochemical characteristics. According to the study, composites based on PANI could make potential anode materials for high-performance LIBs(Hu, Jia, & Song, 2017; Sarkar et al., 2016).

6.4. Metal Electro Catalyst

Metal electrocatalysts are substances that reduce the activation energy of an electrochemical reaction to improve the pace of the reaction. They are frequently utilized in batteries and fuel cells for energy conversion and storage(S. Zhang et al., 2023). Due to PANI's strong electrical conductivity, good electrochemical stability, and capacity to bind metal ions, it is utilized as a metal electrocatalyst. Metal ions like Pt, Pd, and Ni can be added to PANI to create composite materials with increased catalytic activity. These composites have proven to be efficient in several applications, including hydrogen evolution reactions (HER) in water electrolysis and oxygen reduction reactions (ORR) in fuel cells(L. Zhang et al., 2017; S. Zhao et al., 2023).

For effective electrocatalytic CO2 reduction, polyaniline gold nanoparticle core-shell nanofiber (PANI|Au) synthesis is described by TH Wang(T.-H. Wang, Lin, Huang, & Li, 2023). When compared to pure PANI, the PANI|Aunanofiber has significantly higher electrocatalytic activity and excellent selectivity.L.Zhang(J. Zhang et al., 2022) also synthesized Pd/Pani/Ti composite as an electrocatalyst due to the high surface area of polyaniline. They showed that the degradation efficiency of 2,4-DCP was up to 96.54%, which proves Pani to be a promised material being used as an electrocatalyst.

7. Comparison in Tabulated Form

Table 1
Various PANI composites for electrical applications

PANI Nanocomposite	Method of Synthesis	Application	Capacitance and Cycles	Reference
V2CT2$_x$/Mxene/Pani	In situ oxidation	Zn ion batteries	267.7mAh/g	(L. Wang et al., 2023)
Pani/C	carbonization	Electrode in supercapacitor.	372F/g 78% after 6000 cycles.	(Uppugalla, Male, & Srinivasan, 2014)
Pani/Fe3O4	In situ polymerization	Supercapacitor	620F/g 85% after 2000 cycles.	(Y. Ma et al., 2019)
CoWO4/Pani	Chemical oxidative polymerization	Electrode for energy storage devices	653F/g 93.3% after 5000 cycles.	(Rajkumar, Ezhilarasi, Saranya, Merlin, & Solids, 2022)
CuV2O6/Pani	In situ polymerization	Supercapacitor	375F/g 98% after 2000 cycles.	(Barik, Barik, Tanwar, & Ingole, 2022)
Pani/Pd	Thermal evaporation technique	Direct alcohol fuel cell	3mA/cm2 for methanol	(Eswaran, Rahimi, Pandit, Chokkiah, & Mijakovic, 2023)
ZnIn2S4/Pani/TiO2/Ti	Coating method	Photocatalytic fuel cell	18.83 Uw power density	(Mou et al., 2023)

Conclusion and Future Perspectives

PANI is regarded as one of the helpful intrinsic and electronic CPs, and this paper carefully details the uses of PANI in the field of electrochemical energy storage and conversion. It is suggested that PANI be used in different fields, which can considerably expand its area of usage. PANI is known to have many distinctive and promising features, and it is expected to be beneficial in electrical devices to enhance their electrical properties. Due to the synergistic effect, PANI generally serves as a conductive layer and network in various PANI-based composite structures, and the resulting PANI-based composites with various unique structures have demonstrated superior electrochemical performance in supercapacitors, rechargeable batteries, and fuel cells. However, there are still some drawbacks that could be resolved.

PANI is difficult to maintain a stable structure due to the de-doping phenomenon caused by light, electricity, magnetism, thermal, etc. Also, PANI is challenging to commercialize in the electrochemical field due to its relatively high cost and low practicability compared to conventional inorganic materials. It is challenging to balance the mechanical qualities and electrochemical performance when using PANI in electrochemical energy storage technologies such as supercapacitors, rechargeable batteries, and fuel cells. For instance, PANI coating could reduce the instability of nano-fluids brought on by nanoparticles' slow sedimentation (or scale formation) concurrent with agglomerating or clustering of nanoparticles inside the base fluid.

By reading this review, researchers can learn about PANI's inclination to develop new technologies in the area of electrochemical energy storage and conversion. In conclusion, future advancements will necessitate ongoing research and endeavors in designing distinctive nanostructures of PANI with higher surface areas and conductivities, extending application fields, and developing cost-effective manufacturing technologies.

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