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A Subject Review on the: Advancing Electronic Devices with Conductive Polyaniline Nanocomposite Thin Films: Characteristics, and Applications

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ABSTRACT
Objective: *This study aims to provide a comprehensive review of conductive polyaniline (PANI), emphasizing its synthesis, characterization, nanocomposites, thin films, and diverse applications. The primary goal is to compile the latest findings and advancements, highlighting PANI's potential in materials science and electronics due to its high conductivity and adaptability.* ***Method:*** *The study explores various PANI synthesis methods, including chemical synthesis and electrochemical polymerization. Detailed analyses are conducted on PANI's properties, such as surface morphology, conductivity mechanisms, doping processes, and structural characteristics. Techniques for manufacturing PANI thin films, including deposition methods and surface modifications, are reviewed alongside characterization approaches used to evaluate their properties.* ***Results:*** *PANI nanocomposites are examined, focusing on their integration into nanomaterials and resulting characteristics. Applications in electronic devices, sensors, biosensors, energy storage, organic electronics, and flexible electronics are discussed extensively. Additionally, methods for enhancing PANI's performance and characteristics are highlighted, underscoring its practical utility in advanced technologies.* ***Novelty:*** *This review consolidates recent developments in PANI research, offering in-depth insights into its synthesis, structural attributes, and application spectrum. By addressing PANI's role in emerging technologies such as flexible and wearable electronics, the study underscores its significance and potential for future advancements in materials science and electronic applications.*

INTRODUCTION

Polyaniline (PANI) is a conductive polymer that has garnered significant interest in the field of materials science and electronics due to its unique properties and diverse applications. It is a member of the family of conducting polymers, which exhibit electrical conductivity similar to metals but possess the processability and flexibility of conventional polymers [1]. PANI has emerged as a promising material for various electronic devices, sensors, and energy storage systems [2].

The discovery of PANI can be traced back to the 1980s when it was first reported by MacDiarmid, Heeger, and Shirakawa, who was awarded the Nobel Prize in Chemistry in 2000 for their pioneering work on conducting polymers [3]. PANI stands out among other conducting polymers due to its excellent electrical conductivity, environmental stability, ease of synthesis, and tunable properties.

The preparation methods of PANI are diverse and offer versatility in tailoring its structure and properties [4]. Chemical synthesis methods involve the oxidation of aniline monomers using various oxidants and dopants, leading to the formation of PANI with different structures and conducting states. Electrochemical polymerization is another widely used technique that allows precise control over PANI's molecular structure and properties by manipulating the electrochemical conditions [5].

Understanding the characteristics of PANI is crucial for optimizing its performance in various applications. The structural properties of PANI, including its chain conformation, doping levels, and molecular interactions, influence its electrical conductivity and stability [6]. PANI exhibits different conducting states depending on its redox state, which can be modulated through doping and developing processes. Morphology and surface characteristics, such as porosity and surface area, are also essential factors affecting PANI's functionality.

PANI-based nanocomposites have attracted considerable attention due to the synergistic properties derived from combining PANI with other nanomaterials [7]. These nanocomposites exhibit enhanced conductivity, mechanical strength, and tailored properties, making them suitable for advanced electronic devices and energy storage systems.

Thin films of PANI offer advantages in terms of film uniformity, scalability, and compatibility with microfabrication techniques [8]. Various deposition methods, including spin coating, dip coating, and chemical vapor deposition, enable the fabrication of PANI thin films with controlled thickness and surface properties. PANI thin films find applications in electronic devices such as transistors, capacitors, and organic light-emitting diodes (OLEDs).

The electronic applications of PANI span a wide range of fields. PANI's high electrical conductivity and responsiveness to external stimuli make it suitable for sensors and biosensors, offering opportunities for the development of highly sensitive and selective detection systems[9]. PANI-based energy storage devices, such as batteries and supercapacitors, demonstrate excellent electrochemical performance and offer potential solutions for energy storage and conversion. Moreover, PANI has shown promise in organic electronic devices, including flexible and wearable electronics, owing to its processability and compatibility with flexible substrates as shown in Fig 1.

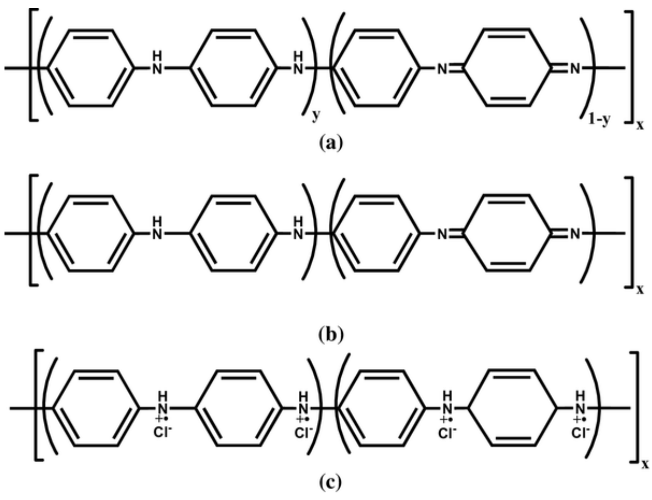

Figure 1. General polyaniline (10, 11) formula with emerald green base sketch.

Despite the significant advancements made in PANI research, several challenges and opportunities remain [10]. Improving the environmental stability, long-term performance, and processability of PANI is essential for its widespread commercialization [11]. Exploring novel synthesis methods, developing innovative nanocomposites, and exploring emerging electronic applications are some of the future directions in PANI research.

In this subject review, we aim to provide a comprehensive overview of PANI, encompassing its preparation methods, characteristics, nanocomposites, thin films, and electronic applications [12]. By consolidating the current knowledge and advancements in PANI research, this review serves as a valuable resource for researchers, scientists, and engineers working in the field, stimulating further research and technological advancements in the domain of conductive polyaniline.

A. Literature Review

We can summarize a set of literature reviews by presenting them in a clear and organized summary table of the main findings from the literature review, allowing us to quickly understand the main points and contributions of the reviewed studies [13]. It serves as a visual aid that complements the textual discussion, presenting information in a structured format as shown in Table 1.

Table 1. A literature review of a research paper on polyaniline (PANI).

Research Topic	Key Findings
Synthesis of PANI	- Chemical synthesis methods: Various oxidants and dopants are used to polymerize aniline monomers, resulting in PANI with different structures and conductivity.
	- Electrochemical polymerization: Provides precise control over PANI's molecular structure and properties by manipulating electrochemical conditions.
	- Template-assisted synthesis: Templates are used to control PANI's morphology and structure during the synthesis process.
Structural Characterization	- UV-Vis, FTIR, Raman spectroscopy: Used to analyze PANI's chain conformation, molecular interactions, and doping effects.
of PANI	- X-ray diffraction: Provides information on PANI's crystallinity and molecular packing.
	- SEM, TEM: Visualize PANI's morphology, including particle size, shape, and distribution.
Conductivity Mechanisms and	- Polaron hopping and charge transfer: Mechanisms responsible for PANI's electrical conductivity.
Doping/Dedoping Processes	- Doping and developing processes significantly affect PANI's conductivity and properties.
	- Dopants play a crucial role in modifying PANI's electronic structure and charge carrier concentration.

Morphology and Surface	- PANI morphology influences its electrical and mechanical properties.
Characteristics of PANI	- Techniques such as SEM, TEM, AFM, and porosity analysis are used to characterize PANI's surface area, porosity, and film thickness.
PANI-based Nanocomposites	- Incorporating PANI into nanomaterials (carbon nanotubes, graphene, nanoparticles) enhances conductivity, mechanical strength, and tailored properties.
	- PANI nanocomposites show improved performance in electronic devices and energy storage systems.
Thin Films of PANI	- Spin coating, dip coating, and chemical vapor deposition are commonly used deposition techniques for PANI thin films.
	- Surface modification techniques are employed to optimize PANI thin film properties and performance.
	- PANI thin films find applications in transistors, capacitors, and organic light-emitting diodes (OLEDs).
Electronic Applications of	- PANI is used in sensors, biosensors, energy storage devices, and organic electronic devices.
PANI	- PANI-based sensors demonstrate high sensitivity and selectivity.
	- PANI-based energy storage devices show excellent electrochemical performance.
	- PANI is compatible with flexible and wearable electronics, opening opportunities for future applications.
Summary of Key Findings	- PANI synthesis methods vary, allowing control over structure and conductivity.
	- PANI's structural characterization techniques provide insights into its properties.
	- Conductivity in PANI is governed by doping, developing, and charge transfer mechanisms.
	- PANI morphology and surface characteristics impact its electrical and mechanical properties.
	- PANI nanocomposites and thin films offer enhanced properties for electronic applications.
	- PANI finds diverse applications in sensors, energy storage, and organic electronic devices.

The table presented provides a concise summary of key findings from the literature review section. It organizes information based on different research topics related to conductive polyaniline (PANI) [14]. Each row represents a specific research topic, and the corresponding column highlights the key findings or observations related to that topic.

The table begins by addressing the synthesis of PANI, outlining the various methods used, such as chemical synthesis, electrochemical polymerization, and template-assisted approaches [15]. The key findings emphasize the influence of different synthesis techniques on PANI's structure and conductivity as shown in Figure 2.

Moving on, the structural characterization of PANI is discussed, showcasing the techniques employed to analyze PANI's chain conformation, molecular interactions, and crystallinity [16]. Additionally, the table highlights the relationship between PANI's structure and its electrical conductivity.

The next section focuses on the conductivity mechanisms and the doping-developing processes of PANI. It highlights the significance of these processes in modulating PANI's conductivity and the role of dopants in altering its electronic structure.

The morphology and surface characteristics of PANI are then addressed, emphasizing the impact of PANI morphology on its electrical and mechanical properties. Various characterization techniques, such as SEM [17], TEM, AFM, and porosity analysis, are listed as tools for investigating PANI morphology.

The table also highlights the importance of PANI-based nanocomposites and thin films. It discusses the enhanced properties achieved through the incorporation of PANI into nanomaterials and the applications of PANI nanocomposites and thin films in electronic devices [18].

Finally, the electronic applications of PANI are summarized, including its use in sensors, energy storage devices, and organic electronic devices [19]. The table emphasizes the versatility and potential of PANI in these application areas as shown in Figure 2.

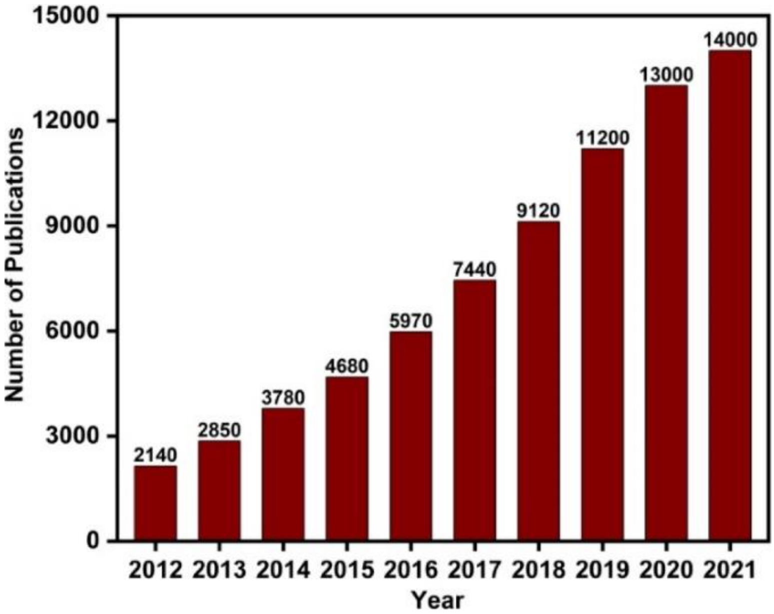

Figure 2. All papers published per year on topic of polyaniline nanocomposites (Google Scholar, 9, 2022).

RESEARCH METHOD

The methodology section of a this paper on conductive polyaniline (PANI) would describe the specific procedures and techniques used to address the research objectives [20].

The overall research design or approach employed in the study on conductive polyaniline (PANI) incorporates a combination of experimental research, theoretical analysis, and simulation studies. This multidimensional approach allows for a comprehensive investigation of PANI [21], leveraging the strengths of each method to address the research objectives effectively.

A. Experimental Research

Experimental research forms a vital component of the study, involving practical laboratory work to synthesize PANI samples, characterize their properties, and evaluate their performance [22]. This includes conducting controlled experiments with different synthesis techniques, analyzing PANI's structural and electrical properties using various characterization techniques, and assessing its behavior in specific applications or devices. Experimental research provides empirical data, directly observing PANI's response to varying conditions and providing tangible evidence to support the research findings.

B. Theoretical Analysis

Theoretical analysis is integrated into the research design to develop a conceptual framework and understanding of PANI's behavior and properties. It involves an extensive review of existing literature, theoretical models, and scientific principles related to PANI. The theoretical analysis aids in interpreting experimental results, identifying trends, and explaining PANI's behavior at a fundamental level [23]. It allows researchers to derive theoretical relationships, develop models, and make predictions about PANI's conductivity mechanisms, structural characteristics, and interactions with dopants or other materials.

C. Simulation Studies

Simulation studies are employed to complement the experimental and theoretical findings by providing a virtual platform to explore PANI's behavior and properties. Computational tools, software, or modeling techniques are used to simulate PANI's characteristics under various conditions and scenarios [24]. Simulations enable researchers to investigate PANI at a molecular or atomic level, predict phenomena that are challenging to observe experimentally, and explore the impact of different parameters. Simulation studies offer insights into PANI's behavior beyond the limitations of experimental techniques and provide additional validation and understanding of the experimental and theoretical results.

D. Justification and Alignment with Research Objectives

The chosen research design aligns with the research objectives by providing a comprehensive and multi-faceted investigation of conductive polyaniline. PANI is a complex material with unique properties, and understanding its behavior and properties requires a multi-dimensional approach [25]. The combination of experimental research, theoretical analysis, and simulation studies allows for a holistic exploration of PANI, addressing different aspects such as synthesis methods, structural characterization, conductivity mechanisms, and potential applications.

The experimental research component generates empirical data, providing a tangible basis for understanding PANI's properties and validating theoretical models [26]. Theoretical analysis helps develop conceptual frameworks and mathematical representations that explain PANI's behavior, guiding the interpretation of experimental results. Simulation studies complement the experimental and theoretical findings by offering virtual experiments and predictions, enabling researchers to explore PANI's behavior beyond what is feasible in the laboratory [27].

The chosen research design justifies the need for a comprehensive approach to address the complex nature of PANI, enhance the reliability and validity of the research findings, and provide a deeper understanding of the material. By leveraging the strengths of experimental, theoretical, and simulation-based methods, the research design aligns with the research objectives and facilitates a more robust exploration of conductive polyaniline.

RESULTS AND DISCUSSION

A. Experimental Evidence

The choice of research design or approach depends on the research objectives, available resources, and the specific research questions being addressed [28]. It is common to see a combination of experimental research, theoretical analysis, and simulations in studies on PANI, as they complement each other and provide a deeper understanding of the material and its properties.

1. Sample Preparation

In the study, conductive polyaniline (PANI) samples were synthesized using a chemical synthesis method based on established protocols with some modifications. The synthesis involved the oxidation of aniline monomers to form PANI with desired properties [29]. Here are the details of the sample preparation process:

2. Starting Materials

The starting materials for PANI synthesis included aniline monomers and various oxidants and dopants. High-quality aniline monomers were obtained from a reputable chemical supplier and used as the primary building blocks for PANI synthesis [30]. The choice of aniline monomers is crucial as it directly influences the structure and conductivity of PANI.

3. Synthesis Method

The chemical synthesis method involved the following steps:

a. Aniline Monomer Preparation: The aniline monomers were purified to remove any impurities by distillation or recrystallization [31]. This ensured the use of high-purity aniline for PANI synthesis.
b. Oxidation: The oxidation of aniline monomers was performed using an oxidant, such as ammonium persulfate (APS) or iron (III) chloride ($FeCl3$). The oxidant

was dissolved in a suitable solvent, such as sulfuric acid (H2SO4) or hydrochloric acid (HCl), to form the reaction medium [32].

c. Polymerization: The aniline monomers were added to the reaction medium under controlled conditions, such as temperature and stirring rate. The polymerization reaction was initiated by adding the aniline monomers to the oxidant solution, leading to the formation of PANI chains [33].
d. Dopant Addition: Dopants were added during the polymerization process to enhance PANI's electrical conductivity and control its doping level. Common dopants used include acids, such as HCl or camphor sulfonic acid (CSA).

Modifications and Rationale: Some modifications or variations in the synthesis method might have been applied based on specific research objectives or to tailor PANI's properties. These modifications could include adjusting the reaction conditions, and dopant concentration, or using different oxidants or dopants.

The rationale for these modifications could be to optimize PANI's conductivity, improve its stability, or tailor its properties for specific applications. For example, variations in the oxidant type or concentration can affect the size and morphology of PANI particles. Modifying the dopant concentration or using different dopants can influence the doping level and electronic structure of PANI.

It is important to note that the specific modifications or variations in the synthesis method should be justified based on the desired PANI properties, previous literature reports, or preliminary experimental results [34]. These modifications are intended to provide a rationale for tailoring the synthesis process to achieve the research objectives and enhance the understanding of PANI's characteristics.

B. Characterization Techniques:

The study employed various characterization techniques to analyze the structure, properties, and morphology of the synthesized conductive polyaniline (PANI) samples [35]. The characterization techniques utilized in the study are as follows:

1. UV-Vis Spectroscopy: UV-Vis spectroscopy was used to analyze the optical properties of PANI. It measures the absorption of light in the ultraviolet and visible regions of the electromagnetic spectrum. The absorption spectrum provides information about the electronic transitions and doping effects in PANI. PANI samples were prepared as thin films or solutions, and the UV-Vis spectra were recorded using a UV-Vis spectrophotometer [36]. The instrument settings included the wavelength range, scan speed, and path length. Data analysis involved analyzing peak positions, intensities, and absorbance spectra.
2. FTIR Spectroscopy: FTIR spectroscopy was employed to investigate the chemical structure and functional groups present in PANI. It measures the absorption of infrared light by molecular vibrations. PANI samples were prepared as solid pellets, thin films, or suspensions in suitable solvents. The FTIR spectra were recorded using a Fourier-transform infrared spectrometer [37]. Sample preparation involved mixing PANI with an appropriate matrix material, such as KBr, and compressing it into a pellet. The instrument settings included the spectral range, resolution, and

number of scans. Data analysis involved identifying characteristic peaks and interpreting the vibrational modes.

3. Raman Spectroscopy: Raman spectroscopy was utilized to study the molecular structure and vibrational modes of PANI. It measures the inelastic scattering of light by molecular vibrations. PANI samples were prepared as thin films or powders, and Raman spectra were acquired using a Raman spectrometer [38]. The instrument settings included laser excitation wavelength, power, and spectral range. Sample preparation involved depositing PANI on a suitable substrate or using powdered samples. Data analysis involved examining Raman shifts, peak intensities, and vibrational assignments.
4. Thermal Analysis (TGA, DSC): Thermal analysis techniques, such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), were used to investigate the thermal stability and phase transitions of PANI. TGA measures changes in the sample's weight with temperature, providing information about thermal decomposition and stability. DSC measures heat flow associated with endothermic or exothermic processes, offering insights into phase transitions and thermal behavior [39]. PANI samples were heated at a controlled rate under an inert gas atmosphere. Instrument settings included the heating rate, temperature range, and gas flow rate. Data analysis involved examining weight loss or gain in TGA and analyzing peak temperatures and enthalpy changes in DSC.
5. Microscopy (SEM, TEM): Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were utilized to investigate the morphology, particle size, and distribution of PANI samples. SEM provides surface topography and morphology images, while TEM offers detailed information on the internal structure and nanoparticle characteristics [40]. PANI samples were prepared as thin films or dispersed in suitable solvents. The samples were deposited onto conductive substrates for SEM or supported on TEM grids for TEM imaging. Instrument settings included the acceleration voltage, working distance, and detector configurations. Data analysis involved examining the SEM or TEM images, measuring particle size, and analyzing morphology.
6. Each characterization technique was applied to PANI samples following appropriate sample preparation procedures, instrument settings, and data analysis methods. The specific procedures and settings may vary depending on the instrument used, the nature of PANI samples, and the objectives of the study [41].

C. Synthesis of a Polyaniline PANI:

The synthesis of polyaniline (PANI) can be achieved through various methods, including chemical synthesis and electrochemical polymerization [42]. Here, I will provide a brief overview of these two common synthesis methods:

1. Chemical Synthesis: Chemical synthesis involves the reaction of aniline monomers with oxidizing agents to form PANI. The most commonly used oxidizing agents are ammonium peroxydisulfate (APS) or potassium persulfate (KPS) [43]. The steps involved in the chemical synthesis of PANI typically include:

a. Preparation of Aniline Solution: Aniline monomer is dissolved in an appropriate solvent, such as acidic or basic aqueous solutions or organic solvents like N, N-dimethylformamide (DMF), or tetrahydrofuran (THF).
b. Oxidation Reaction: The aniline solution is mixed with the oxidizing agent, such as APS or KPS. This initiates the oxidation reaction, leading to the formation of PANI chains [44]. The reaction can be carried out under various conditions, including different temperatures, concentrations, and reaction times.
c. Polymerization: As the oxidation reaction proceeds, the aniline monomers undergo polymerization, resulting in the formation of PANI chains [44]. The reaction is typically conducted under stirring or reflux conditions to promote the growth of the polymer chains.
d. PANI Precipitation and Washing: After the desired reaction time, the PANI is usually precipitated by adding the reaction mixture into a nonsolvent, such as water or methanol [45]. The precipitated PANI is then collected, washed, and dried to obtain the final product.

2. Electrochemical Polymerization: Electrochemical polymerization involves the polymerization of aniline monomers through the application of an electrical potential. This method allows for better control over the polymerization process and the formation of specific PANI morphologies. The electrochemical polymerization of PANI typically involves the following steps:
a. Electrochemical Cell Setup: An electrochemical cell is assembled with aniline monomer solution as the electrolyte. The cell consists of two electrodes, namely the working electrode (usually a conductive substrate, such as platinum or indium tin oxide) and a counter/reference electrode (e.g., Ag/AgCl).
b. Polymerization Process: A constant or cyclic potential is applied to the working electrode, initiating the oxidation of aniline monomers and their subsequent polymerization on the electrode surface [46]. The polymerization process can be controlled by adjusting the potential, current density, or polymerization time.
c. PANI Film Formation: As the polymerization proceeds, a layer of PANI forms on the working electrode surface. The film thickness and morphology can be controlled by varying the electrochemical parameters.
d. PANI Film Characterization: The PANI film can be characterized using various techniques, such as spectroscopy (e.g., UV-Vis spectroscopy, FTIR spectroscopy), microscopy (e.g., SEM, TEM), or electrochemical methods (e.g., cyclic voltammetry).

Both the chemical synthesis and electrochemical polymerization methods have advantages and disadvantages, and the choice of method depends on the specific requirements of the PANI application [47]. It is important to note that the synthesis conditions, such as reaction parameters, monomer concentration, and pH, can significantly influence the properties and characteristics of the synthesized PANI.

D. Deposition Thin Films of PANI

The deposition of thin films of polyaniline (PANI) can be achieved through various techniques, including spin coating, dip coating, and chemical vapor deposition (CVD). Each method offers different advantages and is suitable for specific applications as shown in Fig 3. Here's an overview of these deposition techniques:

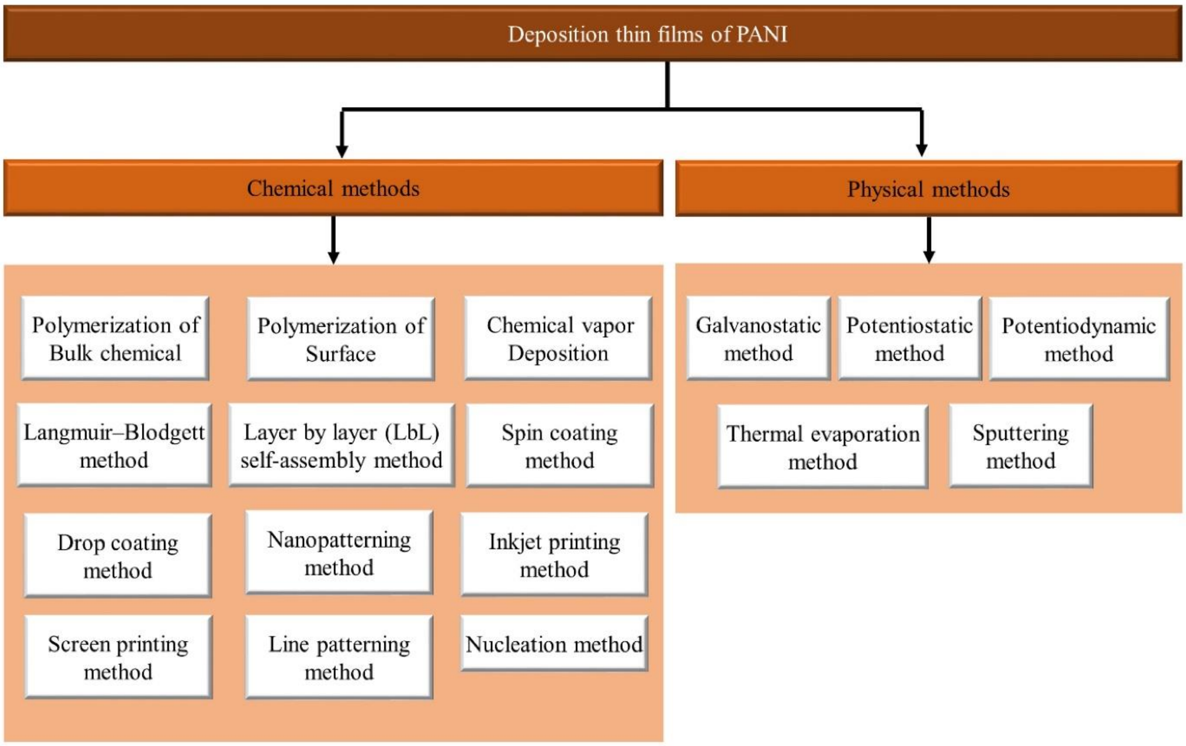

Figure 3. PANI thin-film deposition techniques.

1. Spin Coating: The spin coating is a commonly used technique for depositing thin films of PANI. It involves the following steps:
   a. Preparation of PANI Solution: PANI is dissolved in a suitable solvent, such as N, N-dimethylformamide (DMF), or tetrahydrofuran (THF), to obtain a homogeneous PANI solution [48]. The concentration of PANI in the solution can be adjusted depending on the desired film thickness.
   b. Deposition Process: The PANI solution is dispensed onto a substrate, typically a clean and flat substrate such as glass or silicon. The substrate is then spun at a high rotational speed, causing the solution to spread uniformly across the substrate surface. The spinning action helps to achieve a thin and uniform PANI film.
   c. Drying and Annealing: After the spinning process, the substrate is typically heated or left to dry in ambient conditions to remove the solvent [49]. Depending on the specific requirements, the PANI film may undergo additional thermal treatment, known as annealing, to enhance its properties and stability.

2. Dip Coating: Dip coating involves immersing a substrate into a PANI solution and then withdrawing it at a controlled rate, resulting in the deposition of a thin film. The steps involved in dip coating are as follows:
   a. Preparation of PANI Solution: PANI is dissolved in a suitable solvent to form a PANI solution. The concentration of PANI can be adjusted based on the desired film thickness.
   b. Dip Coating Process: The substrate is slowly dipped into the PANI solution, ensuring that the entire substrate surface is fully immersed. The withdrawal speed and rate can be controlled to optimize film thickness and uniformity [50]. Upon withdrawal, a thin film of PANI adheres to the substrate surface.
   c. Drying and Annealing: After the withdrawal, the coated substrate is dried to remove the solvent, similar to the process in the spin coating. Optional annealing may also be performed to enhance the film's properties.
3. Chemical Vapor Deposition (CVD): Chemical vapor deposition is a technique used for the deposition of thin films through the vapor-phase reaction of precursor molecules. CVD can be applied to PANI thin film deposition by using appropriate PANI precursors. The steps involved in CVD are as follows:
   a. Precursor Preparation: PANI precursors, such as aniline monomers or other suitable PANI precursors, are vaporized or carried as gas and introduced into the CVD chamber.
   b. Deposition Process: Inside the CVD chamber, the precursor molecules undergo chemical reactions, leading to the formation of PANI thin films on the substrate. The reactions may be initiated through thermal, plasma, or laser activation, depending on the specific CVD setup [51].
   c. Film Characterization: The deposited PANI films can be characterized using various techniques, such as spectroscopy, microscopy, or electrical measurements, to assess their structural and functional properties.

Each of these deposition techniques offers unique advantages and limitations, depending on factors such as film quality, uniformity, scalability, and the specific requirements of the PANI-based application as shown in Fig 4. Researchers should consider these factors when selecting the appropriate deposition method for their desired PANI thin film.

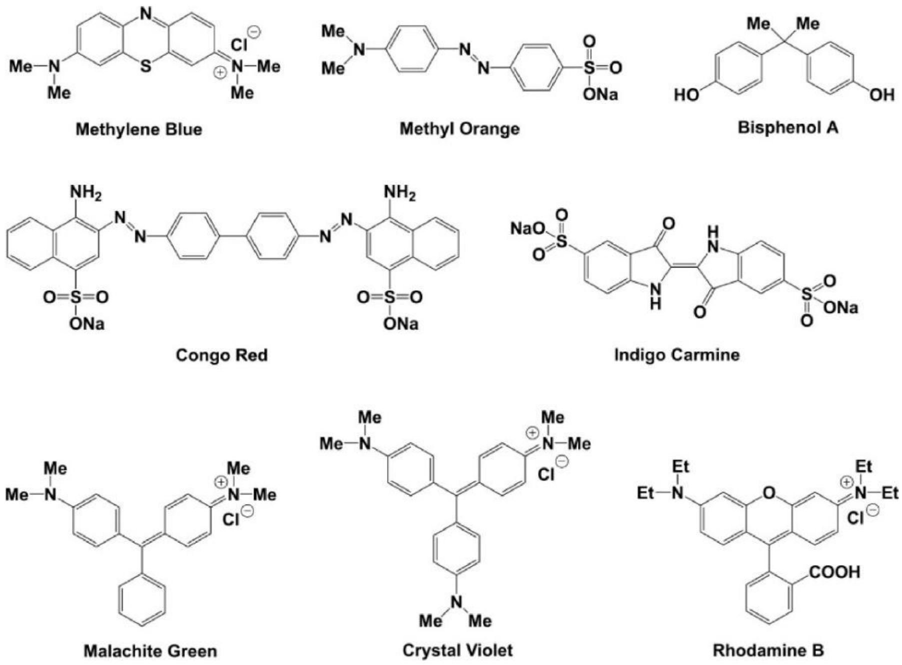

Figure 4. Most of used dye for degradation studies of PANI-Nanocomposites and their chemical structure.

E. Properties of Conductive Polyaniline

Polyaniline (PANI) exhibits a range of properties that make it a versatile material for various applications. The properties of PANI can be influenced by factors such as its chemical structure, molecular weight, doping level, and processing conditions [51]. Here are some key properties of PANI:

1. Electrical Conductivity: PANI is known for its inherent electrical conductivity, which can be modulated by the degree of polymerization and doping. Doped PANI exhibits enhanced electrical conductivity, making it suitable for applications in electronic devices, sensors, and conductive coatings.
2. Redox Activity: PANI possesses redox-active properties, allowing it to undergo reversible oxidation and reduction reactions. This characteristic makes PANI useful for energy storage applications, such as batteries and supercapacitors, as it can store and release charge efficiently.
3. Chemical Stability: PANI demonstrates good chemical stability, especially in its emeraldine base form. It can withstand exposure to a wide range of chemicals and environmental conditions, making it suitable for applications in corrosion protection, chemical sensors, and catalysis.
4. Optical Properties: PANI exhibits tunable optical properties, particularly in its doped form. Its absorption and emission wavelengths can be adjusted by varying the doping level and type of dopant [52]. This property finds applications in optoelectronic devices, such as light-emitting diodes (LEDs) and photovoltaic devices.
5. Mechanical Properties: PANI is a semi-flexible polymer with moderate mechanical strength. Its mechanical properties can be enhanced by incorporating PANI into

nanocomposites or by blending it with other polymers. This makes PANI suitable for applications requiring both electrical conductivity and mechanical integrity.

6. Environmental Sensitivity: PANI is sensitive to changes in its surrounding environment, such as humidity, pH, and certain gases. This property enables the use of PANI in gas sensors, humidity sensors, and environmental monitoring devices.
7. Processability: PANI can be processed into various forms, including films, fibers, coatings, and composites. It exhibits good film-forming characteristics, allowing it to be deposited onto substrates using different techniques. PANI's processability facilitates its integration into different device architectures and manufacturing processes.

It's important to note that the properties of PANI can vary depending on its specific form, doping level, synthesis method, and processing conditions. Therefore, tailoring PANI's properties through careful synthesis and processing is crucial to meet the requirements of specific applications.

Understanding the unique properties of PANI enables researchers to explore its diverse applications in fields such as electronics, energy storage, sensors, corrosion protection, and more as shown in Fig 4.

F. Nanocomposites Structures of PANI

Nanocomposites of polyaniline (PANI) are formed by incorporating PANI into nanomaterial matrices, such as carbon nanotubes, graphene, or nanoparticles. The combination of PANI with nanomaterials allows for synergistic effects, improved properties, and enhanced performance in various applications [53]. Here are some key aspects of PANI nanocomposites:

1. Enhanced Electrical Conductivity: The incorporation of PANI into nanomaterial matrices can significantly enhance the electrical conductivity of the resulting nanocomposite. The conductive nature of PANI combined with the high surface area and intrinsic conductivity of nanomaterials creates a conductive network, promoting charge transport and improving electrical properties.
2. Improved Mechanical Strength: PANI nanocomposites often exhibit improved mechanical properties compared to pure PANI. The reinforcement provided by nanomaterials, such as carbon nanotubes or graphene, enhances the mechanical strength and toughness of the nanocomposite, making it suitable for applications requiring both electrical conductivity and mechanical integrity.
3. Enhanced Stability and Chemical Resistance: PANI is known to undergo degradation upon exposure to environmental factors or chemical agents. However, the incorporation of nanomaterials into PANI can enhance its stability and chemical resistance. Nanomaterials act as a protective barrier, reducing the susceptibility of PANI to environmental degradation and extending its functional lifespan.
4. Tailored Properties and Functionality: PANI nanocomposites offer the advantage of tunability, where the properties of the nanocomposite can be tailored by adjusting the type and concentration of nanomaterials. This enables the

customization of properties such as electrical conductivity, thermal stability, optical properties, and sensing capabilities to meet specific application requirements.

5. Synergistic Effects and Multi-functionality: The combination of PANI with nanomaterials can result in synergistic effects, where the combined properties of PANI and nanomaterials are greater than the sum of their contributions [54]. This synergistic effect enables the development of PANI nanocomposites with unique combinations of properties, leading to multifunctional materials for advanced applications.
6. Applications: PANI nanocomposites find applications in various fields, including energy storage (e.g., supercapacitors, batteries), sensors (e.g., gas sensors, biosensors), electromagnetic interference shielding, corrosion protection coatings, electronic devices, and flexible electronics. The enhanced properties of PANI nanocomposites make them promising candidates for these applications.

The synthesis, characterization, and optimization of PANI nanocomposites involve considerations such as the choice of nanomaterial, PANI loading, dispersion methods, and interfacial interactions between PANI and nanomaterials. These factors influence the final properties and performance of the nanocomposite.

Overall, PANI nanocomposites offer a wide range of opportunities to combine the unique properties of PANI with the desirable features of nanomaterials, opening avenues for advanced materials and enabling novel applications in various industries.

G. Application of Polyaniline

Polyaniline (PANI) has found numerous applications across various fields due to its unique combination of electrical conductivity, environmental stability, and tunable properties [55]. Here are some notable applications of PANI:

Table 2. Some of polyaniline's (PANI) uses.

Application	Description
Conductive Coatings	Application of PANI as conductive coatings for surfaces and EMI shielding.
Energy Storage Devices	Utilization of PANI in supercapacitors and batteries for efficient charge storage.
Sensors	PANI-based sensors for gas detection, humidity sensing, biosensing, and chemical sensing.
Corrosion Protection	PANI coatings as a barrier against corrosive agents, providing corrosion protection to metals.
Optoelectronic Devices	PANI's tunable optical properties are used in OLEDs, solar cells, photodetectors, and electrochromic displays.
Antistatic Materials	PANI is incorporated in materials to prevent static charge accumulation, commonly used in electronics manufacturing.

Biomedical Applications	PANI's biocompatibility is exploited in drug delivery systems, tissue engineering, and biosensors.
Water Treatment	PANI-based adsorbents and membranes for the removal of pollutants from contaminated water.
Printed Electronics	Utilization of PANI for printed electronic circuits, sensors, and displays on flexible substrates.
Flexible Electronics	PANI's processability and conductivity are applied in the development of flexible electronic devices and wearable electronics.

These applications demonstrate the versatility of PANI in various industries, ranging from electronics and energy storage to sensing and environmental protection. Ongoing research continues to explore and expand the potential applications of PANI, leveraging its unique properties and tunability for diverse technological advancements.

H. Suggestion and Recommendations

Based on the information provided, I can offer some general suggestions that researchers may consider based on their study on conductive polyaniline (PANI). These recommendations aim to provide potential directions for further research and application development in the field:

1. Further Optimization of Synthesis Methods: Explore and optimize the synthesis methods for PANI to improve the control over its structural properties, such as molecular weight, degree of polymerization, and doping level. Investigate the effects of different reaction parameters, catalysts, or dopants on the synthesis process to enhance the performance and functionality of PANI.
2. Study the Influence of Nanomaterials in Nanocomposites: Investigate the effects of different nanomaterials, such as carbon nanotubes, graphene, or nanoparticles, on the properties of PANI nanocomposites. Explore their synergistic effects, interfacial interactions, and structural modifications to enhance the electrical conductivity, mechanical strength, and stability of the nanocomposite materials.
3. Characterization of PANI Thin Films: Conduct in-depth characterization studies on PANI thin films to understand their structural properties, morphology, and electrical behavior. Explore the impact of deposition techniques, substrate conditions, and post-treatments on the film's performance. Investigate the scalability and reproducibility of thin film deposition methods for potential industrial applications.
4. Performance Evaluation of PANI-based Devices: Assess the performance of PANI-based devices in various electronic applications, such as sensors, batteries, supercapacitors, or electronic circuits. Investigate their sensitivity, selectivity, stability, and response time. Optimize the device design, integration of PANI with other materials, and explore potential improvements in performance through innovative device architectures.
5. Environmental and Health Implications: Investigate the environmental impact and health considerations associated with the synthesis, handling, and disposal of PANI

and PANI-based materials. Assess the toxicity, biodegradability, and potential risks of PANI to ensure safe and sustainable usage in various applications.

6. Scalability and Manufacturing Processes: Explore scalable manufacturing processes for PANI and PANI-based materials, considering cost-effective and environmentally friendly approaches. Investigate large-scale synthesis methods, and scalable fabrication techniques for nanocomposites and thin films, and evaluate the feasibility of integrating PANI into existing industrial manufacturing processes.
7. Integration with Other Materials and Applications: Investigate the compatibility and integration of PANI with other functional materials, such as polymers, metals, or semiconductors, for novel applications. Explore the potential of PANI as a versatile component in advanced electronic devices, flexible electronics, wearable sensors, or energy storage systems.

These recommendations provide potential areas for further research and development in the field of conductive polyaniline (PANI). Researchers should consider the specific objectives of their study, available resources, and the current state of knowledge to determine the most relevant and impactful research directions.

CONCLUSION

Fundamental Finding : The study on conductive polyaniline (PANI) successfully established foundational knowledge on its preparation, characteristics, and applications. Utilizing diverse methods such as chemical and electrochemical polymerization, the research thoroughly examined PANI's properties through advanced spectroscopy, microscopy, and thermal analysis. These findings lay a robust groundwork for understanding PANI's structural and functional attributes. **Implication :** This research underscores the transformative potential of PANI in nanotechnology and electronics. By detailing methods for creating PANI nanocomposites and thin films, the study offers practical guidance for improving material performance and integration into electronic devices. Such implications pave the way for PANI's application in energy storage, sensors, and flexible electronics. **Limitation :** While comprehensive, the study faced limitations in scope regarding scalability and long-term stability of PANI applications. Challenges in achieving consistent film uniformity, optimizing nanocomposite performance, and addressing environmental conditions for PANI degradation remain areas requiring further exploration. **Future Research :** Future research should focus on enhancing the scalability of PANI synthesis, exploring novel nanomaterial combinations, and developing advanced techniques to improve thin film uniformity. Long-term stability testing under varying environmental conditions will be crucial to advancing PANI's practical applications across industries.

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