

## From Synthesis to Application: The Journey of Conductive Polymer Nanocomposites

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### Abstract

Conductive polymer nanocomposites (CPNs) combine the flexibility of polymers with the exceptional properties of nanomaterials, opening up a new frontier in materials science. This mini-review explores the synthesis, characteristics, and various applications of CPNs. Different synthesis methods, such as in-situ polymerization, solution blending, melt blending, and electrospinning, are examined, highlighting their importance in achieving uniform dispersal and strong interfacial connections. These approaches allow for the creation of CPNs with significantly improved electrical, mechanical, thermal, and optical properties compared to their individual elements. The review delves into different uses of CPNs, including sensors, shielding against electromagnetic interference, energy storage, and biomedical devices, demonstrating their adaptability and potential. Moreover, the paper addresses the challenges linked to the synthesis, stability, and environmental impact of CPNs, emphasizing the need for continuous research to tackle these issues. To conclude, the article looks at the future outlook and potential of CPNs, emphasizing their role in driving technological advancements across various fields and their potential in fostering new innovations.

**Keywords:** conductive polymer composite, electrical conductivity, nanotechnology, nanomaterial synthesis, polymer composites

## 1. Introduction

Conductive polymer nanocomposites (CPNs) represent a promising intersection of nanotechnology. CPNs combine conductive polymers with nanofillers to enhance their properties. They are gaining increasing attention because of their ability to bridge the gap between traditional conductive materials and emerging technologies. Conductive polymers, such as polyaniline (PANI), and polypyrrole (PPy) are known for their inherent electrical conductivity, flexibility, and ease of processing. Incorporating nanomaterials, such as carbon nanotubes (CNTs), graphene, and metallic nanoparticles, within the polymer matrix improves their electrical, mechanical, thermal, and optical properties. This synergy arises from the high surface area, mechanical strength, and electrical conductivity of nanomaterials [1,2].

The foundation of CPNs is the development of conductive polymers. This field of research began with the discovery of polyacetylene in the 1970s. The subsequent breakthrough, which led to the 2000 Nobel Prize in Chemistry for Heeger, MacDiarmid, and Shirakawa, revolutionized the field. Driven by the need for materials that combine the electrical properties of metals with the versatility of polymers, conductive polymers have been developed. These materials are lightweight, corrosion resistant, and flexible. Over the past two decades, significant progress has been made in the synthesis of CPNs with uniform dispersions and stable interfaces. The synthesis of CPNs involves various techniques, each of which has its own advantages and limitations.

In-situ polymerization allows the direct incorporation of nanomaterials during the polymer formation process, ensuring uniform dispersion and strong interfacial interactions. Solution blending offers simplicity and versatility, whereas melt blending is more suitable for thermoplastic polymers. Electrospinning, a technique for producing ultrafine fibers, is gaining popularity owing to its ability to create nanocomposites with high surface area and enhanced properties. These advancements have enabled the production of CPNs with enhanced performance characteristics, making them suitable for various advanced applications. For instance, in-situ polymerization of PPy with gold nanoparticles has resulted in composites with enhanced electrical conductivity and catalytic properties, which are highly desirable for sensor applications. Solution blending and melt blending have also proven to be effective in producing composites with well-dispersed nanomaterials, thereby enhancing the overall properties of polymers.[3-7] In the fields of electronics and optoelectronics, CPNs are being developed for use in flexible electronic devices, sensors, and conductive inks. Their applications in energy storage and conversion include batteries, supercapacitors, and fuel cells, in which their enhanced conductivity and stability are crucial. The biomedical applications of CPNs are expanding, with their use in biosensors, drug delivery systems, and tissue engineering, owing to their biocompatibility and functional versatility. Environmental applications such as wastewater treatment and air purification leverage the unique properties of CPNs for efficient pollutant removal and environmental monitoring [8-10]. Despite significant advancements, challenges remain in optimizing synthesis processes, improving performance, and addressing environmental and economic concerns. Current limitations include achieving a uniform dispersion of nanomaterials, maintaining stability and performance under operational conditions, and scaling up production for industrial applications. Environmental considerations, such as the potential toxicity of nanomaterials and the sustainability of raw materials, are also critical [11].

The primary objective of this review is to provide a comprehensive overview of the current state of CPNs. We discuss the specifics of conductive polymers and the synthesis techniques that have been developed. We will also discuss their properties and broad spectrum of applications, concluding with the challenges and future perspectives that will shape the next phase of research in this dynamic field.

## **2. Types of Conductive Polymers**

### **2.1. Polyaniline (PANI)**

Polyaniline (PANI) is a conducting polymer that has garnered considerable interest due to its unique properties and broad range of potential applications. PANI, derived from the oxidative polymerization of aniline, is processable and electrically conductive. It exists in several oxidation states, including leucoemeraldine (fully reduced), emeraldine (half-oxidized), and pernigraniline (fully oxidized). Among these, the emeraldine state, particularly in its base form, is the most stable and widely studied for its conductive properties. The conductivity of PANI involves the movement of charge carriers such as polarons and bipolarons along the polymer chain. The emeraldine base form of PANI can be doped with protonic acids (e.g., hydrochloric acid) to produce a conductive emeraldine salt. This doping process protonates nitrogen atoms in the polymer backbone, creating positively charged sites that facilitate electron movement [12].

The versatility of PANI is attributed to its ability to switch between insulating and conducting states through protonation (doping) and de-doping processes. This reversible doping mechanism allows PANI to maintain high environmental stability while providing tunable electrical conductivity, which is advantageous for applications such as sensors, batteries, supercapacitors, and electromagnetic interference (EMI) shielding. In addition, PANI is relatively easy to synthesize and process, making it cost-effective for commercial use [13,14].

The synthesis of PANI typically involves chemical oxidative polymerization using oxidants such as ammonium persulfate, which facilitates scalable formation. Electrochemical polymerization offers precise control over film deposition, enabling the creation of PANI films with tailored thicknesses and morphologies. Recent advancements include template-based and emulsion polymerization methods to further refine PANI's properties for specific applications, such as sensors and actuators [15-17].

Despite these advantages, PANI faces several challenges. Its inherent insolubility in common solvents limits the processability of complex structural designs, and its mechanical properties are generally insufficient for standalone structural applications. The brittleness and poor mechanical strength of polymers necessitate blending with other materials to achieve the desired properties. Additionally, while PANI's electrical conductivity is notable, it is still lower compared to metals, which limits its use in high-performance electronic applications. PANI's environmental stability, though better than many conducting polymers, can still be a concern under extreme conditions, affecting its long-term performance and reliability [17,18].

Researchers have addressed these limitations by using various strategies. For instance, Deng et al. (2018) synthesized PANI/PVA and PANI/PVA/Ag composite films using an electrochemical method and demonstrated significant enhancements in conductivity and mechanical properties [19]. Xu et al. (2013) improved the photocatalytic activity of a coordination polymer by loading PANI onto its surface via chemical oxidation polymerization, demonstrating its potential for enhanced photocatalytic applications [20].

## **2.2. Polypyrrole (PPy)**

Polypyrrole (PPy) is a conductive polymer created from the polymerization of pyrrole monomers. PPy is known for its biocompatibility, stability, electrical conductivity, and diverse applications in drug delivery, flexible devices, environmental remediation, and energy storage systems. The morphology of PPy can vary widely, influencing its overall properties. Factors such as synthesis conditions and doping levels impact the polymer's structural characteristics. The synthesis of PPy typically involves oxidative polymerization of pyrrole monomers. Chemical oxidation methods are commonly used. Oxidants like ferric chloride or ammonium persulfate are employed to produce PPy in bulk form. Electrochemical polymerization offers greater control. This method allows for the deposition of PPy films with precise thicknesses and morphologies. Molecular weight, regioregularity, and crystallinity are influenced by the chosen method. These factors subsequently affect the material's electrical and mechanical properties [21]. The electrical conductivity of PPy is intrinsically linked to its doping level. However, in its pure state PPy's conductivity is relatively low. To enhance electrical properties, PPy undergoes a doping process involving the incorporation of suitable dopants (like halide ions or protonic acids) into the polymer matrix. These dopants introduce charge carriers, such as polarons and bipolarons, which significantly improve conductivity.[22]

PPy is widely used in many fields due to its versatility, which is evidenced by the extensive researches conducted on it. PPy is commonly utilized in photocatalytic processes for water and air pollutant degradation, CO<sub>2</sub> reduction, and hydrogen evolution under simulated sunlight irradiation [23]. Furthermore, PPy has been incorporated into composite materials like PPy/BiPO<sub>4</sub>, showcasing excellent sensing properties for humidity sensors with rapid response and recovery times and minimal hysteresis at different relative humidities [24]. These applications underscore the versatility and potential of PPy in various technological advancements, ranging from environmental remediation to energy storage and sensing applications.

Furthermore, recent studies have been concentrating on enhancing the stability of dopants in PPy films using innovative encapsulation methods to tackle the issue of conductivity degradation over time and enhance the material's overall performance in practical uses [25]. The main challenges of Polypyrrole (PPy) polymer revolve around difficulties in its synthesis parameters that affect properties such as hydrophilicity, surface roughness, and conductivity. Moreover, concerns arise about the durability of dopants in PPy films as time passes, leading to a noticeable decrease in conductivity and dopant concentration that impacts the material's prolonged effectiveness. Despite these limitations, PPy remains a prominent conductive polymer with applications across various fields. It is versatile and holds the potential for further development and optimization.

## **3. Synthesis Methods**

### **3.1. In-Situ Polymerization**

In-situ polymerization provides a direct and efficient approach to produce conductive polymer nanocomposites. The method involves polymerizing the monomer within a dispersion or matrix with the nanofiller. Enhanced interfacial interactions, improved nanofiller dispersion, and superior composite properties result from the strong bond between the polymer and filler during synthesis. Initially, the monomer, such as pyrrole or aniline, is dissolved in a suitable solvent to initiate the in-situ polymerization. The process starts by dissolving the monomer, like pyrrole or aniline, in an appropriate solvent. Polymerization begins with the introduction of an oxidizing agent like ammonium persulfate or ferric chloride. Controlled temperature conditions are maintained to achieve the desired molecular weight and structural characteristics. Polymerization within composites takes place in the presence of a host matrix to ensure uniform dispersion. Post-polymerization, treatments including washing and drying are conducted to eliminate unreacted components and enhance properties. Doping, using agents such as halide ions or protonic acids, is commonly performed during or after polymerization to introduce charge carriers for increased electrical conductivity. [26-28]

Key factors influencing in-situ polymerization outcomes encompass monomer selection, initiator choice, reaction conditions, and nanofiller properties. The surface chemistry, size, and dispersion of the nanofiller play a significant role in polymer chain initiation and growth. For instance, hydrophilic nanofillers can serve as initiation sites for hydrophilic monomers, while hydrophobic nanofillers might impact polymer chain configuration.

Additionally, the quantity of nanofiller present can influence the viscosity of the reaction mixture, which in turn affects reactant mobility and polymer chain development. Evaluating the compatibility between monomer and nanofiller is essential for optimal outcomes. The use of surfactants or dispersants can enhance nanofiller dispersion and prevent clumping. Effective control of temperature and reaction duration is vital to managing the molecular weight and polydispersity of the polymer. [29-31]

Furthermore, the combination of in situ polymerization and nanotechnology has also led to significant improvements in scalability and cost-effectiveness, making these advanced materials more accessible for widespread commercial applications. Examples of Conductive nanocomposites created with In-situ Polymerization are seen in research, such as the production of graphene-polyaniline nanocomposites [32] and polypyrrole-coated carbon nanotubes [33].

### **3.2. Solution Blending**

Solution blending synthesis involves mixing polymers and nanoparticles in a solvent to create nanocomposites with enhanced properties. Different studies highlight the efficiency of solution blending in producing nanocomposites with uniform dispersion of nanofillers. To ensure complete dissolution of both the polymer and nanoparticles, it is recommended to dissolve them separately in a common solvent. The polymer matrix and the conductive polymer are dissolved individually in the selected solvent, typically needing agitation at room or slightly higher temperatures. After both have dissolved, the solutions are combined meticulously to guarantee uniform dispersion of the conductive polymer in the matrix. Once the solution is prepared, different methods like spin-coating, dip-coating, or solvent evaporation can be used to mold the solution into films or desired shapes. Solid films or structures that include the mixture of polymer and nanoparticles are obtained by letting the solvent evaporate [34,35]. These nanocomposites can then undergo characterization and testing to evaluate their properties and potential applications. This approach, while simple, proves to be efficient in achieving proper dispersion of nanoparticles in the polymer matrix. It is crucial to take into account the compatibility of solvents during the entire procedure to avoid phase separation and uphold the specific characteristics of the nanocomposite material [36]. The combination of polymers with nanoparticles provides a hopeful path for creating improved materials with enhanced characteristics and functionalities. Researchers developed highly stretchable and conductive polymer films by blending poly(3,4-ethylenedioxythiophene) (PEDOT) with soft polymers and additives, achieving a remarkable combination of mechanical flexibility and electrical conductivity [37].

### **3.3. Melt Blending**

Melt blending is a process with high throughput that is suitable for producing conductive polymer nanocomposites on a large scale. This technique involves directly mixing the conductive polymer and the nanofiller in a molten state, then cooling to form the composite. This method does not require solvents and is suitable for thermally stable polymers. It is widely used in industrial applications due to its scalability and simplicity. Melt blending is especially useful for thermoplastic polymers and offers benefits like high production rates and energy efficiency. Achieving a uniform dispersion of the nanofiller within the viscous polymer matrix during melt blending is a significant challenge. The shear forces produced in the mixing process are crucial for breaking down agglomerates and distributing the nanofiller evenly.[34,38,39] However, excessive shear may cause polymer degradation and harm the composite properties. The compatibility between the polymer and the nanofiller is also important for dispersion efficiency. Various processing aids, such as compatibilizers or coupling agents, can be used to enhance nanofiller dispersion. Furthermore, employing advanced mixing equipment like twin-screw extruders can boost mixing efficiency and enhance the final composite properties. In addition to processing aids and advanced mixing equipment, optimizing the processing parameters such as temperature, screw speed, and residence time can further improve the dispersion quality of nanofillers in polymer matrices [40].

### **3.4. Electrospinning**

Electrospinning is a versatile technique employed in producing conductive polymer nanocomposites. It forms nanofibers with diameters spanning from tens of nanometers to several micrometers. The process begins with creating a polymer solution through the dissolution of a polymer such as polyaniline PANI or PPy in an appropriate solvent. Afterwards, nanoparticles like carbon nanotubes (CNTs) or graphene are distributed in the liquid to form the nanocomposite. The liquid is then placed into a syringe that has a needle attached to a high-voltage power supply, while a grounded collector is placed at a specific distance from the needle. Once the high voltage is applied, electrostatic forces come into play, influencing the surface tension of the polymer solution. A Taylor cone emerges at the needle's tip, resulting in the expulsion of a solution stream. The solution is stretched, and the solvent evaporates as a consequence. Continuous nanofibers are produced, which build up on the grounded collector [41,42].

Adjusting factors like applied voltage, solution concentration, flow rate, and the distance between the needle and collector can control the fibers' morphology and diameter. Post-treatment processes, such as annealing or crosslinking, can be applied to improve the stability and mechanical properties of the electrospun nanofibers. These nanofibers have a high surface area-to-volume ratio, providing benefits for applications like sensors, tissue engineering and catalytic supports [43]. For example, Zarei et al. (2021) incorporated polypyrrole (PPy) into a

blend of chitosan, collagen, and polyethylene oxide and developed conductive nanofiber scaffolds for tissue healing. Their target was applications in electrically dynamic tissues such as the heart and nerves.[44]

Despite its benefits, electrospinning encounters challenges like achieving uniform dispersion of nanoparticles in the polymer matrix, selecting compatible solvents, and maintaining consistent fiber properties during large-scale production. Nevertheless, advancements in electrospinning technology, such as multi-needle systems and advanced collectors, are directed toward enhancing the scalability and consistency of nanofiber production [45]. Ongoing exploration of new polymers and nanomaterials will further broaden the scope of applications for electrospun nanocomposites.

#### **4. Properties of Conductive Polymer Nanocomposites**

Conductive polymer nanocomposites show enhanced mechanical, thermal, optical, and electrical properties, which increases their effectiveness in various applications.

##### **4.1. Electrical Properties**

The addition of conductive nanomaterials like carbon nanotubes (CNTs), graphene, and metallic nanoparticles significantly boosts the electrical conductivity of CPNs. Unlike conventional metals that rely on electron mobility, conductive polymers operate through a distinct mechanism involving both electronic and ionic transport. These nanomaterials establish percolation networks within the polymer matrix, which aids in efficient charge transport [46]. Generally, higher nanoparticle loading results in lower resistivity and increased conductivity in these composites due to their inverse relationship. Factors such as polymer morphology, including crystallinity and chain orientation, also impact conductivity levels [47]. Studies have revealed that as the size of nanomaterial particles decreases, their conductivity diminishes, and a transition from spherical to tetrahedral shapes alters their electrical characteristics. A more organized structure can enhance charge carrier mobility, thereby boosting conductivity. Moreover, the type of dopant and its interaction with the polymer chain are crucial in determining overall conductivity. Incorporating conductive nanoparticles can further enhance the electrical conductivity of nanocomposites, enhancing electroporation efficiency by amplifying the local electric field at the cell surface [48,49].

While conductive polymers typically have lower electrical conductivity than traditional metals, their flexibility, processability, and potential for large-scale production make them attractive for various applications where extreme conductivity is not the primary concern [50]. Metal oxide nanoparticles in polymer nanocomposites enhance electrical breakdown strength by creating scattering obstacles and trap sites. This, in turn, reduces carrier mobility and increases homocharge buildup at electrodes [51]. Gold nanoparticles are selectively positioned on the surfaces of live bacteria to create electrically conductive connections. This can be improved by applying electric-field annealing following a percolation mode [52]. These discoveries collectively showcase the various ways in which conductive nanoparticles interact with their environment to demonstrate fascinating electrical properties.

##### **4.2. Mechanical Properties**

The incorporation of nanofillers into a conductive polymer matrix significantly affects the mechanical properties of the resulting nanocomposites. While conductive polymers usually exhibit limited mechanical strength, the strategic addition of nanomaterials can enhance qualities such as strength, stiffness, and toughness. Nanofillers, such as carbon nanotubes, graphene, and various inorganic nanoparticles, serve as reinforcing agents in the polymer matrix. Their exceptional strength-to-weight ratio and unique structural characteristics play a significant role in enhancing the overall mechanical properties of the nanocomposite. It is crucial to ensure efficient load transfer between the nanofiller and the polymer matrix to optimize these properties. The dispersion and interfacial adhesion of nanofillers within the polymer matrix are key factors that impact the mechanical behavior. A homogeneous distribution of nanofillers is crucial for maximizing their strengthening effect, while effective bonding at the interface aids in preventing detachment and improving the transfer of loads. Moreover, the aspect ratio and arrangement of nanofillers play a significant role in defining the mechanical characteristics [53,54]. For instance, nanofillers with a high aspect ratio such as carbon nanotubes can significantly enhance the rigidity and durability of the composite. Research shows that graphene nanoparticles (GNPs) demonstrate high Young's modulus, hardness, and yield strength, which makes them appealing for various applications [55,56]. Similarly, MoS<sub>2</sub> nanoribbons are characterized as rigid, quasi one-dimensional formations, although they do not possess the same level of strength as graphene and boron nitride (BN) nanoribbons [57]. Achieving a balance between mechanical properties and other desired characteristics, such as electrical conductivity, poses a significant challenge when developing conductive nanocomposites. Factors such as nanofiller concentration, processing conditions, and the selection of polymer matrix play a crucial role in determining this balance.

##### **4.3. Thermal Properties**

The thermal properties of conductive nanoparticles differ significantly from those of bulk materials, as highlighted in various literature sources. Metallic nanoparticle-packed beds (NPBs) exhibit an ultra-low thermal conductivity mainly due to the high thermal contact resistance among particles, especially at interfaces, which significantly affects the material's overall thermal conductivity. It is feasible to manipulate thermal and electrical conductivity

in composites containing specific nanoparticles, as nanofillers establish conductive pathways within the composite matrix, thereby impacting its functional properties [58,59]. Nanomaterials often display altered thermal characteristics compared to bulk materials, with changes in melting points, enthalpy, and entropy commonly observed [60]. Despite the majority of nanomaterials having lower melting points, exceptions like Si, Ge, and Sn atomic clusters have higher melting points than their bulk counterparts, leading to distinct phase diagram alterations in nanoalloy systems [61]. The size-dependent thermodynamic properties of nanomaterials are responsible for these unique phase diagram changes in nanoalloy systems, significantly influencing their behavior at the atomic level. Conductive nanoparticles, such as CuO and carbon nanotubes, demonstrate significant improvements in thermal properties when dispersed in fluids. The incorporation of 5 vol.% CuO nanoparticles into water results in an approximately 20% enhancement in effective thermal conductivity, whereas even less than 1 vol.% of CuO particles can boost the heat transfer coefficient of water by more than 15% [62]. Ultrasonication plays a vital role in dispersing nanoparticles and breaking up agglomerates, affecting thermal conductivity and viscosity. For example, subjecting carbon nanotubes to sonication in an ethylene glycol-based nanofluid can lead to a maximum increase of 23% in thermal conductivity with prolonged sonication time. Viscosity initially rises and then decreases, approaching that of the pure base fluid [63].

## **5. Applications**

Conductive nanoparticles find diverse applications in various fields such as printed electronics, energy storage, sensors, and biomedical devices.

### **5.1. Electronic Applications**

Conductive nanoparticles have a broad range of electronic applications and show promise for future advancements. Nanoparticles are essential for creating self-assembled monolayers and monolayer-protected clusters used in electronic device networks [64]. These nanoparticles are produced through various methods to build both 2D arrays and 3D networks. Moreover, metal and semiconductor nanoclusters display unique characteristics because of quantum size effects, opening the door to innovative technologies and electronics applications [65]. The current electronic uses of conductive nanoparticles involve creating junctions, heterojunctions, and single-electron-transfer devices, demonstrating their potential for enhancing electronic devices and systems. Conductive nanoparticles are also increasingly employed in diverse electronic applications like thin film transistors (TFT), dye-sensitized solar cells (DSSC), Radio Frequency Identification (RFID) tags, and sensors. Amjadi et al. (2014) created highly adaptable and elastic strain sensors by incorporating a network of silver nanowires into Polydimethylsiloxane (PDMS) elastomer. They attained robust piezoresistivity with customizable sensitivity and 70% stretchability, and demonstrated their application in a glove for controlling virtual environments [66]. Nanoparticles like Ag nanoparticles, Cu/Ag core-shell nanoparticles, graphene conductive ink, biocompatible CNT ink, and conductive indium tin oxide (ITO) enhance electrical conductivity for printable, flexible, and wearable electronics. These nanoparticles are crucial for improving the functionality of electronic devices. Noble metal nanoparticles exhibit electromagnetic field enhancement due to surface plasmon oscillations. This makes them suitable for applications that utilize radiative properties, underscoring their importance in various technological advancements [67,68].

### **5.2. Energy Storage Applications**

Conductive nanoparticles play a vital role in modern energy storage applications, especially in the field of electrochemical energy storage. Nanostructured materials, such as composites utilizing graphene, have shown significant promise [69]. These materials, employed in the anodes and cathodes of lithium-ion batteries exhibit extensive surface area, enhanced kinetics, and greater energy densities. The addition of nanoparticles like SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and TiO<sub>2</sub> to polymer-salt matrices in lithium-ion batteries enhances ionic conductivity, leading to improved energy storage capabilities [70-72]. Nanoparticle decoration of carbon structures in electrodes also enhances charge-storage performance, pore refinement, and charge-transfer kinetics, crucial for advanced energy storage materials. These materials provide benefits such as excellent electron transport properties, high-rate capability, and fast ion transport, making them well-suited for extremely rapid energy storage [73]. Future progress in this field might concentrate on refining the structure of nanomaterials to further improve charge transport, boost areal capacity, and enhance the overall performance of energy storage tools. Furthermore, progress in producing conductive nanoparticles, like uniform FePt nanoparticles, may result in innovative applications in data storage, permanent magnetic nanocomposites, and medical science [74,75].

### **5.3. Biomedical Applications**

CPNs are beneficial in the field of biomedical applications because of their biocompatibility, conductivity, and mechanical properties. Conductive polymers are commonly utilized in biosensors to detect biomolecules and monitor physiological signals. For example, PANI/graphene composites are employed in glucose sensors, providing high sensitivity and quick response times. These sensors have revolutionized medical diagnostics by allowing real-time monitoring of glucose levels in diabetic patients, resulting in improved disease management and quality of life [76,77]. In drug delivery systems, CPNs enable controlled drug release and targeted delivery. Polypyrrole-based nanocomposites have been studied for their capability to release drugs upon electrical

stimulation, offering precise control over dosage and timing [78]. In tissue engineering, CPNs-based conductive scaffolds are used to facilitate cell growth and differentiation by delivering electrical stimulation, crucial for regenerating electrically active tissues like nerves and muscles [79]. Research suggests that PPy/gelatin composites enhance neural cell growth and scaffold conductivity, promoting improved tissue regeneration [80]. Silver nanoparticles (AgNPs) are indispensable in cancer treatment and diagnosis due to their unique characteristics. AgNPs play a crucial role in nanomedicine, providing various bio-applications such as antibacterial, antifungal, antiviral, anti-inflammatory, anti-angiogenic, and anti-cancer properties [81,82].

## **6. Current Limitations**

The limitations currently faced in the application of conductive nanoparticles are a result of various factors as discussed in research papers. One of the primary challenges is the stability of these nanoparticles within composite materials, with their conductive properties being susceptible to degradation over time due to environmental factors like moisture and temperature variations. This degradation often occurs because of the instability of dopants utilized in the synthesis of conductive polymers such as polyaniline and polypyrrole. Ongoing research is focusing on encapsulation techniques and the development of more stable dopants to address these issues. Another key limitation lies in achieving a uniform dispersion of conductive nanoparticles within polymer matrices, which is essential for maintaining consistent electrical conductivity and mechanical properties [83]. The clustering of nanoparticles is caused by their elevated surface energy, resulting in uneven characteristics and reduced efficiency. This underscores the significance of investigating sophisticated dispersion techniques like employing surfactants and surface functionalization. Furthermore, economic constraints arise from the high cost of synthesizing and processing conductive nanoparticles, along with challenges related to scalability, which hinder their widespread commercial viability. The expensive materials and complex procedures involved in producing high-quality nanoparticles make it difficult to scale up for industrial use, prompting researchers to work on cost-effective synthesis techniques and enhance scalability for broader industrial applications. Lastly, the environmental and health implications associated with the utilization of conductive nanoparticles are significant and cannot be ignored [84,85]. Concerns regarding the potential toxicity of nanoparticles underscore the importance of understanding the long-term effects on health and the environment. This understanding is crucial to ensure safe and sustainable usage in biomedical and environmental settings. Establishing regulatory frameworks and conducting thorough risk assessments are crucial to harnessing the benefits of conductive nanoparticles while upholding safety and sustainability standards.

## **7. Conclusion and Future Perspectives**

The future outlook for the application of conductive nanoparticles seems promising, with a focus on enhancing innovation and competitiveness across various industries. Ongoing research is devoted to exploring environmentally friendly materials like biodegradable metal nanoparticles for use in printed electronics. The integration of CNPs in the electronics sector is expected to push the development of more efficient and adaptable electronic devices, including advanced sensors, flexible displays, and high-performance conductive inks. Progress in nanocomposite materials will also contribute to reducing electronic components, thus enhancing the efficiency and longevity of wearable technologies and smart textiles. Remarkably, investigations on carbon nanotube-based inks are progressing towards creating printable and stretchable electronics, which offer potential for next-generation wearable devices and flexible displays. CNPs have the capacity to revolutionize batteries, supercapacitors, and fuel cells in energy storage and conversion. These nanoparticles have unique electrical properties that can improve the efficiency and capacity of energy storage devices, making them more suitable for large-scale applications such as electric vehicles and renewable energy systems. Additionally, CNPs are under scrutiny for their potential application in next-generation photovoltaic cells to enhance solar energy conversion efficiency. The incorporation of graphene and silicon nanoparticles into lithium-ion batteries has shown promising results in significantly enhancing battery performance and lifespan. Biomedical applications of CNPs are projected to undergo significant growth due to the materials' biocompatibility and distinctive electrical properties, enabling their utilization in various applications like biosensors, drug delivery systems, and tissue engineering. Future research is expected to concentrate on enhancing the functionality and safety of CNPs in medical settings, leading to innovative diagnostic and therapeutic technologies. Advances in nanomedicine, including drug delivery systems utilizing gold nanoparticles, offer more precise and efficient treatments for various diseases. The continual progress of safe and cost-effective synthesis methods will have a crucial role in unlocking the full potential of conductive nanoparticles in diverse industries. In conclusion, the field of conductive nanoparticles is set for significant advancements that have the potential to revolutionize multiple industries, from electronics and energy storage to biomedical applications. Despite existing challenges such as stability, uniform dispersion, and high costs, continuous research and innovation are pushing the boundaries of what is achievable with these materials. As scientists develop more stable, efficient, and cost-effective methods for synthesizing and utilizing CNPs, we can anticipate witnessing even more groundbreaking applications emerge, solidifying the role of conductive nanoparticles in future technological advancements.

## **Nomenclature**

**AgNPs:** Silver Nanoparticles

**BN:** Boron Nitride

**CPNs:** Conductive Polymer Nanocomposites

**CNTs:** Carbon Nanotubes  
**DSSC:** Dye-Sensitized Solar Cells  
**EMI:** Electromagnetic Interference  
**GNPs:** Graphene Nanoparticles  
**ITO:** Indium Tin Oxide  
**NPBs:** Nanoparticle-Packed Beds  
**PANI:** Polyaniline  
**PDMS:** Polydimethylsiloxane  
**PEDOT:** Poly(3,4-ethylenedioxythiophene)  
**PPy:** Polypyrrole  
**RFID:** Radio Frequency Identification  
**TFT:** Thin Film Transistors  
**2D:** Two-Dimensional  
**3D:** Three-Dimensional

## References

- [1] Gómez, I. J., Vázquez Sulleiro, M., Mantione, D., & Alegret, N. (2021). Carbon Nanomaterials Embedded in Conductive Polymers: A State of the Art. *Polymers*, 13(5).
- [2] Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. *Journal of Nanobiotechnology*, 20(1), 262. <https://doi.org/10.1186/s12951-022-01477-8>
- [3] Acosta, M. A.-O., Santiago, M. A.-O., & Irvin, J. A. Electrospun Conducting Polymers: Approaches and Applications. LID - 10.3390/ma15248820 [doi] LID - 8820. (1996-1944 (Print)).
- [4] Kannan, A., & Radhakrishnan, S. (2020). Fabrication of an electrochemical sensor based on gold nanoparticles functionalized polypyrrole nanotubes for the highly sensitive detection of l-dopa. *Materials Today Communications*, 25, 101330. <https://doi.org/https://doi.org/10.1016/j.mtcomm.2020.101330>
- [5] Yang, C. Y., Cao, Y., Smith, P., & Heeger, A. J. (1993). Morphology of conductive, solution-processed blends of polyaniline and poly(methyl methacrylate). *Synthetic Metals*, 53(3), 293-301. [https://doi.org/https://doi.org/10.1016/0379-6779\(93\)91098-M](https://doi.org/https://doi.org/10.1016/0379-6779(93)91098-M)
- [6] Zhan, C., Yu, G., Lu, Y., Wang, L., Wujcik, E., & Wei, S. (2017). Conductive polymer nanocomposites: a critical review of modern advanced devices [10.1039/C6TC04269D]. *Journal of Materials Chemistry C*, 5(7), 1569-1585. <https://doi.org/10.1039/C6TC04269D>
- [7] Machida, S., Miyata, S., & Techagumpuch, A. (1989). Chemical synthesis of highly electrically conductive polypyrrole. *Synthetic Metals*, 31(3), 311-318. [https://doi.org/https://doi.org/10.1016/0379-6779\(89\)90798-4](https://doi.org/https://doi.org/10.1016/0379-6779(89)90798-4)
- [8] Jadhav, P., Muhammad, N., Bhuyar, P., Krishnan, S., Razak, A. S. A., Zularisam, A. W., & Nasrullah, M. (2021). A review on the impact of conductive nanoparticles (CNPs) in anaerobic digestion: Applications and limitations. *Environmental Technology & Innovation*, 23, 101526. <https://doi.org/https://doi.org/10.1016/j.eti.2021.101526>
- [9] Kant, T., Shrivastava, K., Dewangan, K., Kumar, A., Jaiswal, N. K., Deb, M. K., & Pervez, S. (2022). Design and development of conductive nanomaterials for electrochemical sensors: a modern approach. *Materials Today Chemistry*, 24, 100769. <https://doi.org/https://doi.org/10.1016/j.mtchem.2021.100769>
- [10] Mabrouk, M., Das, D. B., Salem, Z. A., & Beherei, H. H. (2021). Nanomaterials for Biomedical Applications: Production, Characterisations, Recent Trends and Difficulties. *Molecules*, 26(4).
- [11] Sharma, S., Sudhakara, P., Omran, A. A. B., Singh, J., & Ilyas, R. A. (2021). Recent Trends and Developments in Conducting Polymer Nanocomposites for Multifunctional Applications. *Polymers*, 13(17).
- [12] Chauhan, N. P. S., & Mozafari, M. (2019). Chapter 3 - Synthetic route of PANI (II): Enzymatic method. In M. Mozafari & N. P. S. Chauhan (Eds.), *Fundamentals and Emerging Applications of Polyaniline* (pp. 43-65). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-12-817915-4.00003-8>
- [13] Beygisangchin, M., Abdul Rashid, S. A.-O., Shafie, S. A.-O., Sadrolhosseini, A. R., & Lim, H. A.-O. Preparations, Properties, and Applications of Polyaniline and Polyaniline Thin Films-A Review. LID - 10.3390/polym13122003 [doi] LID - 2003. (2073-4360 (Electronic)).
- [14] Wang, Y., Wang, J., Zhang, X. F., & Liu, Y. Q. (2017). Synthesis, Characterization and Properties of PANI/(La-Nd Doped BaFe<sub>12</sub>O<sub>19</sub>) Composites. *Key Engineering Materials*, 727, 327-334. <https://doi.org/10.4028/www.scientific.net/KEM.727.327>
- [15] Zarrintaj, P., & Saeb, M. R. (2019). Chapter 5 - Synthetic route of polyaniline (IV): Irradiation path. In M. Mozafari & N. P. S. Chauhan (Eds.), *Fundamentals and Emerging Applications of Polyaniline* (pp. 91-103). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-12-817915-4.00005-1>
- [16] Ben, J., Song, Z., Liu, X., Lü, W., & Li, X. (2020). Fabrication and Electrochemical Performance of PVA/CNT/PANI Flexible Films as Electrodes for Supercapacitors. *Nanoscale Research Letters*, 15(1), 151. <https://doi.org/10.1186/s11671-020-03379-w>



- [17] Bhadra, J., Alkareem, A., & Al-Thani, N. (2020). A review of advances in the preparation and application of polyaniline based thermoset blends and composites. *Journal of Polymer Research*, 27(5), 122. <https://doi.org/10.1007/s10965-020-02052-1>
- [18] Upadhyay, L. S. B., Rana, S., & Kumar, N. (2022). Chapter 20 - Nanomaterials in tissue engineering: Applications and challenges. In A. Das Talukdar, S. Dey Sarker, & J. K. Patra (Eds.), *Advances in Nanotechnology-Based Drug Delivery Systems* (pp. 533-554). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-323-88450-1.00018-1>
- [19] Deng, S.-h., Wang, Y., & Yang, X. (2018). The study of electrochemical synthesis, properties and composite mechanism of PANI/PVA and PANI/PVA/Ag composite films. *Pigment & Resin Technology*, 47(2), 133-141. <https://doi.org/10.1108/PRT-11-2016-0101>
- [20] Xu, X.-X., Cui, Z.-P., Qi, J., & Liu, X.-X. (2013). Fabrication of a PANI/CPs composite material: a feasible method to enhance the photocatalytic activity of coordination polymers [10.1039/C2DT32636A]. *Dalton Transactions*, 42(11), 4031-4039. <https://doi.org/10.1039/C2DT32636A>
- [21] Liu, Y., & Wu, F. (2023). Synthesis and application of polypyrrole nanofibers: a review. *Nanoscale Advances*, 5(14), 3606-3618. <https://doi.org/https://doi.org/10.1039/d3na00138e>
- [22] Sood, Y., Singh, K., Mudila, H., Lokhande, P. E., Singh, L., Kumar, D., Kumar, A., Mubarak, N. M., & Dehghani, M. H. (2024). Insights into properties, synthesis and emerging applications of polypyrrole-based composites, and future prospective: A review. *Heliyon*, 10(13), e33643. <https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e33643>
- [23] Abu-Sari, S. M., Patah, M. F. A., Ang, B. C., & Daud, W. M. A. W. (2022). A review of polymerization fundamentals, modification method, and challenges of using PPy-based photocatalyst on perspective application. *Journal of Environmental Chemical Engineering*, 10(6), 108725. <https://doi.org/https://doi.org/10.1016/j.jece.2022.108725>
- [24] Zhu, Z., Lin, W.-D., Lin, Z.-Y., Chuang, M.-H., Wu, R.-J., & Chavali, M. (2021). Conductive Polymer (Graphene/PPy)-BiPO<sub>4</sub> Composite Applications in Humidity Sensors. *Polymers*, 13(12).
- [25] Fonner, J. M., Forciniti, L., Nguyen, H., Byrne, J. D., Kou, Y.-F., Syeda-Nawaz, J., & Schmidt, C. E. (2008). Biocompatibility implications of polypyrrole synthesis techniques. *Biomedical Materials*, 3(3), 034124. <https://doi.org/10.1088/1748-6041/3/3/034124>
- [26] Collu, M., Rossi, E., Giamberini, M., Sebastiani, M., Del Pezzo, R., Smets, J., & Bemporad, E. (2023). A Methodology for Multivariate Investigation on the Effect of Acrylate Molecular Structure on the Mechanical Properties and Delivery Efficiency of Microcapsules via In Situ Polymerization. *Polymers*, 15(20).
- [27] xu, Z., & Gao, C. (2010). In situ Polymerization Approach to Graphene-Reinforced Nylon6 Composites. *Macromolecules*, 43, 6716-6723. <https://doi.org/10.1021/ma1009337>
- [28] Masoumi, S., O'Shaughnessy, S., & Pakdel, A. (2022). Organic-based flexible thermoelectric generators: From materials to devices. *Nano Energy*, 92, 106774. <https://doi.org/https://doi.org/10.1016/j.nanoen.2021.106774>
- [29] Zhao, W., Gody, G., Dong, S., Zetterlund, P. B., & Perrier, S. (2014). Optimization of the RAFT polymerization conditions for the in situ formation of nano-objects via dispersion polymerization in alcoholic medium [10.1039/C4PY00855C]. *Polymer Chemistry*, 5(24), 6990-7003. <https://doi.org/10.1039/C4PY00855C>
- [30] Ober, C. K., & Hair, M. L. (1987). The effect of temperature and initiator levels on the dispersion polymerization of polystyrene. *Journal of Polymer Science Part A: Polymer Chemistry*, 25(5), 1395-1407. <https://doi.org/https://doi.org/10.1002/pola.1987.080250516>
- [31] Sosnowski, S., & Szymanski, R. (2022). Living polymerization in nano-scale volumes. Impact of process conditions on polymerization kinetics and product characteristics. *Chemical Engineering Journal*, 449, 137729. <https://doi.org/https://doi.org/10.1016/j.cej.2022.137729>
- [32] Li, X., Zhong, Q., Zhang, X., Li, T., & Huang, J. (2015). In-situ polymerization of polyaniline on the surface of graphene oxide for high electrochemical capacitance. *Thin Solid Films*, 584, 348-352. <https://doi.org/https://doi.org/10.1016/j.tsf.2015.01.055>
- [33] Stejskal, J., Sapurina, I., Trchová, M., Šeděnková, I., Kovářová, J., Kopecká, J., & Prokeš, J. (2015). Coaxial conducting polymer nanotubes: polypyrrole nanotubes coated with polyaniline or poly(p-phenylenediamine) and products of their carbonisation. 69(10), 1341-1349. <https://doi.org/doi:10.1515/chempap-2015-0152> (Chemical Papers)
- [34] Wang, G., Chen, X. Y., Huang, R., & Zhang, L. (2002). Nano-CaCO<sub>3</sub>/polypropylene composites made with ultra-high-speed mixer. *Journal of Materials Science Letters*, 21(13), 985-986. <https://doi.org/10.1023/A:1016044204168>
- [35] Lago, E., Toth, P. S., Pugliese, G., Pellegrini, V., & Bonaccorso, F. (2016). Solution blending preparation of polycarbonate/graphene composite: boosting the mechanical and electrical properties [10.1039/C6RA21962D]. *RSC Advances*, 6(100), 97931-97940. <https://doi.org/10.1039/C6RA21962D>
- [36] Hernández-Guerrero, O., Campillo-Illanes, B. F., Domínguez-Patiño, M. L., Benavente, R., Martínez, H., Sedano, A., & Villanueva, H. (2020). Comparative studies of the mechanical and thermal properties of clay /

- copolymer nanocomposites synthesized by two in-situ methods and solution blending method. *Journal of Polymer Research*, 27(5), 106. <https://doi.org/10.1007/s10965-019-1966-3>
- [37] Li, P., Sun, K., & Ouyang, J. (2015). Stretchable and Conductive Polymer Films Prepared by Solution Blending. *ACS Applied Materials & Interfaces*, 7(33), 18415-18423. <https://doi.org/10.1021/acsami.5b04492>
- [38] Li, Y., Iwakura, Y., Zhao, L., & Shimizu, H. (2008). Nanostructured Poly(vinylidene fluoride) Materials by Melt Blending with Several Percent of Acrylic Rubber. *Macromolecules*, 41(9), 3120-3124. <https://doi.org/10.1021/ma7027402>
- [39] Pötschke, P., Bhattacharyya, A. R., Janke, A., Pegel, S., Leonhardt, A., Täschner, C., Ritschel, M., Roth, S., Hornbostel, B., & Cech, J. (2005). Melt Mixing as Method to Disperse Carbon Nanotubes into Thermoplastic Polymers. *Fullerenes, Nanotubes and Carbon Nanostructures*, 13(sup1), 211-224. <https://doi.org/10.1081/FST-200039267>
- [40] Li, J., Ton-That, M. T., Leelapornpisit, W., & Utracki, L. A. (2007). Melt compounding of polypropylene-based clay nanocomposites. *Polymer Engineering & Science*, 47(9), 1447-1458. <https://doi.org/10.1002/pen.20841>
- [41] Sundaramurthi, D., Krishnan, U. M., & Sethuraman, S. (2014). Electrospun Nanofibers as Scaffolds for Skin Tissue Engineering. *Polymer Reviews*, 54(2), 348-376. <https://doi.org/10.1080/15583724.2014.881374>
- [42] Rahmati, M., Mills, D. K., Urbanska, A. M., Saeb, M. R., Venugopal, J. R., Ramakrishna, S., & Mozafari, M. (2021). Electrospinning for tissue engineering applications. *Progress in Materials Science*, 117. <https://doi.org/10.1016/j.pmatsci.2020.100721>
- [43] Huang, Z.-M., Zhang, Y. Z., Kotaki, M., & Ramakrishna, S. (2003). A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Composites Science and Technology*, 63(15), 2223-2253. [https://doi.org/10.1016/s0266-3538\(03\)00178-7](https://doi.org/10.1016/s0266-3538(03)00178-7)
- [44] Zarei, M., Samimi, A., Khorram, M., Abdi, M. M., & Golestaneh, S. I. (2021). Fabrication and characterization of conductive polypyrrole/chitosan/collagen electrospun nanofiber scaffold for tissue engineering application. *International Journal of Biological Macromolecules*, 168, 175-186. <https://doi.org/https://doi.org/10.1016/j.ijbiomac.2020.12.031>
- [45] Ni, Q. Q., Jin, X. D., Xia, H., & Liu, F. (2014). 7 - Electrospinning, processing and characterization of polymer-based nano-composite fibers. In D. Zhang (Ed.), *Advances in Filament Yarn Spinning of Textiles and Polymers* (pp. 128-148). Woodhead Publishing. <https://doi.org/https://doi.org/10.1533/9780857099174.2.128>
- [46] Zhou, J., & Lubineau, G. (2013). Improving Electrical Conductivity in Polycarbonate Nanocomposites Using Highly Conductive PEDOT/PSS Coated MWCNTs. *ACS Applied Materials & Interfaces*, 5(13), 6189-6200. <https://doi.org/10.1021/am4011622>
- [47] Wang, G., Wang, C., Zhang, F., & Yu, X. (2018). Electrical percolation of nanoparticle-polymer composites. *Computational Materials Science*, 150, 102-106. <https://doi.org/https://doi.org/10.1016/j.commatsci.2018.03.051>
- [48] Kausar, A., & Taherian, R. (2019). 3 - Electrical Conductivity Behavior of Polymer Nanocomposite with Carbon Nanofillers. In R. Taherian & A. Kausar (Eds.), *Electrical Conductivity in Polymer-Based Composites* (pp. 41-72). William Andrew Publishing. <https://doi.org/https://doi.org/10.1016/B978-0-12-812541-0.00003-3>
- [49] Tan, H.-x., & Xu, X.-c. (2016). Conductive properties and mechanism of various polymers doped with carbon nanotube/polyaniline hybrid nanoparticles. *Composites Science and Technology*, 128, 155-160. <https://doi.org/https://doi.org/10.1016/j.compscitech.2016.03.027>
- [50] Nezakati, T., Seifalian, A., Tan, A., & Seifalian, A. M. (2018). Conductive Polymers: Opportunities and Challenges in Biomedical Applications. *Chemical Reviews*, 118(14), 6766-6843. <https://doi.org/10.1021/acs.chemrev.6b00275>
- [51] Guo, N., DiBenedetto, S. A., Tewari, P., Lanagan, M. T., Ratner, M. A., & Marks, T. J. (2010). Nanoparticle, Size, Shape, and Interfacial Effects on Leakage Current Density, Permittivity, and Breakdown Strength of Metal Oxide–Polyolefin Nanocomposites: Experiment and Theory. *Chemistry of Materials*, 22(4), 1567-1578. <https://doi.org/10.1021/cm902852h>
- [52] Faria-Tischer, P. C. S., Costa, C. A. R., Tozetti, I., Dall'Antonia, L. H., & Vidotti, M. (2016). Structure and effects of gold nanoparticles in bacterial cellulose–polyaniline conductive membranes [10.1039/C5RA25332B]. *RSC Advances*, 6(12), 9571-9580. <https://doi.org/10.1039/C5RA25332B>
- [53] Latif, Z., Ali, M., Lee, E.-J., Zubair, Z., & Lee, K. H. (2023). Thermal and Mechanical Properties of Nano-Carbon-Reinforced Polymeric Nanocomposites: A Review. *Journal of Composites Science*, 7(10).
- [54] Atchudan, R., Arumugam, P., & Joo, J. (2015). Effects of Nanofillers on the Thermo-Mechanical Properties and Chemical Resistivity of Epoxy Nanocomposites. *Journal of nanoscience and nanotechnology*, 15, 4255-4267.
- [55] Bhattacharya, M. (2016). Polymer Nanocomposites—A Comparison between Carbon Nanotubes, Graphene, and Clay as Nanofillers. *Materials*, 9(4).

- [56] Jin, Z., Pramoda, K. P., Xu, G., & Goh, S. H. (2001). Dynamic mechanical behavior of melt-processed multi-walled carbon nanotube/poly(methyl methacrylate) composites. *Chemical Physics Letters*, 337(1), 43-47. [https://doi.org/https://doi.org/10.1016/S0009-2614\(01\)00186-5](https://doi.org/https://doi.org/10.1016/S0009-2614(01)00186-5)
- [57] Ataca, C., Şahin, H., Aktürk, E., & Ciraci, S. (2011). Mechanical and Electronic Properties of MoS<sub>2</sub> Nanoribbons and Their Defects. *The Journal of Physical Chemistry C*, 115(10), 3934-3941. <https://doi.org/10.1021/jp1115146>
- [58] Ordonez-Miranda, J., Yang, R., & Alvarado-Gil, J. J. (2014). Thermal Conductivity of Particulate Nanocomposites. In X. Wang & Z. M. Wang (Eds.), *Nanoscale Thermoelectrics* (pp. 93-139). Springer International Publishing. [https://doi.org/10.1007/978-3-319-02012-9\\_3](https://doi.org/10.1007/978-3-319-02012-9_3)
- [59] Elsahtati, M., Clarke, K., & Richards, R. (2016). Thermal conductivity of copper and silica nanoparticle packed beds. *International Communications in Heat and Mass Transfer*, 71, 96-100. <https://doi.org/https://doi.org/10.1016/j.icheatmasstransfer.2015.12.034>
- [60] Coetzee, D., Venkataraman, M., Militky, J., & Petru, M. (2020). Influence of Nanoparticles on Thermal and Electrical Conductivity of Composites. *Polymers*, 12(4).
- [61] Zhang, B. (2018). Chapter 7 - Thermal Properties of Nanomaterials. In B. Zhang (Ed.), *Physical Fundamentals of Nanomaterials* (pp. 251-289). William Andrew Publishing. <https://doi.org/https://doi.org/10.1016/B978-0-12-410417-4.00007-1>
- [62] Eastman, J. A., Choi, U. S., Li, S., Soyey, G., Thompson, L. J., & DiMelfi, R. J. (1999). Novel Thermal Properties of Nanostructured Materials. *Materials Science Forum*, 312-314, 629-634. <https://doi.org/10.4028/www.scientific.net/MSF.312-314.629>
- [63] Ruan, B., & Jacobi, A. M. (2012). Ultrasonication effects on thermal and rheological properties of carbon nanotube suspensions. *Nanoscale Research Letters*, 7(1), 127. <https://doi.org/10.1186/1556-276X-7-127>
- [64] Dhand, C., Dwivedi, N., Loh, X. J., Jie Ying, A. N., Verma, N. K., Beuerman, R. W., Lakshminarayanan, R., & Ramakrishna, S. (2015). Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview [10.1039/C5RA19388E]. *RSC Advances*, 5(127), 105003-105037. <https://doi.org/10.1039/C5RA19388E>
- [65] Fendler, J. H. (2001). Chemical Self-assembly for Electronic Applications. *Chemistry of Materials*, 13(10), 3196-3210. <https://doi.org/10.1021/cm010165m>
- [66] Amjadi, M., Pichitpajongkit, A., Lee, S., Ryu, S., & Park, I. (2014). Highly Stretchable and Sensitive Strain Sensor Based on Silver Nanowire–Elastomer Nanocomposite. *ACS Nano*, 8(5), 5154-5163. <https://doi.org/10.1021/nn501204t>
- [67] Tadesse, M. G., Ahmmed, A. S., & Lübben, J. F. (2024). Review on Conductive Polymer Composites for Supercapacitor Applications. *Journal of Composites Science*, 8(2).
- [68] Matsui, I. (2005). Nanoparticles for Electronic Device Applications: A Brief Review. *JOURNAL OF CHEMICAL ENGINEERING OF JAPAN*, 38(8), 535-546. <https://doi.org/10.1252/jcej.38.535>
- [69] Shi, Y., Peng, L., Ding, Y., Zhao, Y., & Yu, G. (2015). Nanostructured conductive polymers for advanced energy storage [10.1039/C5CS00362H]. *Chemical Society Reviews*, 44(19), 6684-6696. <https://doi.org/10.1039/C5CS00362H>
- [70] Pan, X., Yang, P., Guo, Y., Zhao, K., xi, B., Lin, F., & Xiong, S. (2021). Electrochemical and Nanomechanical Properties of TiO<sub>2</sub> Ceramic Filler Li-Ion Composite Gel Polymer Electrolytes for Li Metal Batteries. *Advanced Materials Interfaces*, 8. <https://doi.org/10.1002/admi.202100669>
- [71] Khan, M., Ding, X., Zhao, H., Wang, Y., Zhang, N., Chen, X., & Xu, J. (2022). SiO<sub>2</sub>-Based Lithium-Ion Battery Anode Materials: A Brief Review. *Journal of Electronic Materials*, 51(7), 3379-3390. <https://doi.org/10.1007/s11664-022-09628-1>
- [72] Ding, L., Li, D., Du, F., Zhang, D., Zhang, S., Xu, R., & Wu, T. (2022). Fabrication of Nano-Al<sub>2</sub>O<sub>3</sub> in-Situ Coating Lithium-Ion Battery Separator Based on Synchronous Biaxial Stretching Mechanism of  $\beta$ -Crystal Polypropylene. *Industrial & Engineering Chemistry Research*, 61(30), 11034-11045. <https://doi.org/10.1021/acs.iecr.2c01673>
- [73] Chen, J. H., Li, W. Z., Wang, D. Z., Yang, S. X., Wen, J. G., & Ren, Z. F. (2002). Electrochemical characterization of carbon nanotubes as electrode in electrochemical double-layer capacitors. *Carbon*, 40(8), 1193-1197. [https://doi.org/https://doi.org/10.1016/S0008-6223\(01\)00266-4](https://doi.org/https://doi.org/10.1016/S0008-6223(01)00266-4)
- [74] Shi, Y., Lin, M., Jiang, X., & Liang, S. (2015). Recent Advances in FePt Nanoparticles for Biomedicine. *Journal of Nanomaterials*, 2015(1), 467873. <https://doi.org/https://doi.org/10.1155/2015/467873>
- [75] Zhang, H.-w., Liu, Y., & Sun, S.-h. (2010). Synthesis and assembly of magnetic nanoparticles for information and energy storage applications. *Frontiers of Physics in China*, 5(4), 347-356. <https://doi.org/10.1007/s11467-010-0104-9>
- [76] Zheng, W., Hu, L., Lee, L. Y. S., & Wong, K.-Y. (2016). Copper nanoparticles/polyaniline/graphene composite as a highly sensitive electrochemical glucose sensor. *Journal of Electroanalytical Chemistry*, 781, 155-160. <https://doi.org/https://doi.org/10.1016/j.jelechem.2016.08.004>

- [77] Osuna, V. A.-O., Vega-Rios, A. A.-O., Zaragoza-Contreras, E. A.-O. X., Estrada-Moreno, I. A.-O. X., & Dominguez, R. B. Progress of Polyaniline Glucose Sensors for Diabetes Mellitus Management Utilizing Enzymatic and Non-Enzymatic Detection. LID - 10.3390/bios12030137 [doi] LID - 137. (2079-6374 (Electronic)).
- [78] Zare, E. N., Agarwal, T., Zarepour, A., Pinelli, F., Zarrabi, A., Rossi, F., Ashrafizadeh, M., Maleki, A., Shahbazi, M.-A., Maiti, T. K., Varma, R. S., Tay, F. R., Hamblin, M. R., Mattoli, V., & Makvandi, P. (2021). Electroconductive multi-functional polypyrrole composites for biomedical applications. *Applied Materials Today*, 24, 101117. <https://doi.org/https://doi.org/10.1016/j.apmt.2021.101117>
- [79] Balint, R., Cassidy, N. J., & Cartmell, S. H. (2014). Conductive polymers: Towards a smart biomaterial for tissue engineering. *Acta Biomaterialia*, 10(6), 2341-2353. <https://doi.org/https://doi.org/10.1016/j.actbio.2014.02.015>
- [80] Serafin, A., Culebras, M., Oliveira, J. M., Koffler, J., & Collins, M. N. (2023). 3D printable electroconductive gelatin-hyaluronic acid materials containing polypyrrole nanoparticles for electroactive tissue engineering. *Advanced Composites and Hybrid Materials*, 6(3), 109. <https://doi.org/10.1007/s42114-023-00665-w>
- [81] Ong, C., Lim, J. Z. Z., Ng, C. T., Li, J. J., Yung, L. Y. L., & Bay, B. H. (2013). Silver Nanoparticles in Cancer: Therapeutic Efficacy and Toxicity. *Current Medicinal Chemistry*, 20(6), 772-781. <https://doi.org/http://dx.doi.org/10.2174/0929867311320060003>
- [82] Wei, L., Lu, J., Xu, H., Patel, A., Chen, Z.-S., & Chen, G. (2015). Silver nanoparticles: synthesis, properties, and therapeutic applications. *Drug Discovery Today*, 20(5), 595-601. <https://doi.org/https://doi.org/10.1016/j.drudis.2014.11.014>
- [83] Asyraf, M., Anwar, M., Sheng, L. M., & Danquah, M. K. (2017). Recent Development of Nanomaterial-Doped Conductive Polymers. *JOM*, 69(12), 2515-2523. <https://doi.org/10.1007/s11837-017-2628-8>
- [84] Xu, H., & Zhang, Y. (2019). A Review on Conducting Polymers and Nanopolymer Composite Coatings for Steel Corrosion Protection. *Coatings*, 9(12).
- [85] Ali, A., Shah, T., Ullah, R., Zhou, P., Guo, M., Ovais, M., Tan, Z., & Rui, Y. (2021). Review on Recent Progress in Magnetic Nanoparticles: Synthesis, Characterization, and Diverse Applications [Review]. *Frontiers in Chemistry*, 9. <https://doi.org/10.3389/fchem.2021.629054>