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Polypyrrole-Based Materials for 6G Networks: Applications and Sustainability Across Emerging Fields

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Abstract

Polypyrrole (PPy) is a conductive polymer that has gained significant attention for its potential in advanced materials for 6G networks. This study explores how (PPy)--based materials contribute to the development of 6G technologies, focusing on their uses, advantages, and sustainability. Due to their flexibility, conductivity, and environmental stability, these composites have a lot of potential for use in 6G networks, especially in applications like energy storage, flexible antennas, Electromagnetic Interference (EMI) shielding, and Internet of Things (IoT) sensors. The material's energy efficiency, recyclability, and tunability make it an essential part of sustainable 6G infrastructure. This study also investigates how PPy synthesis affects the environment and how it might reduce e-waste and support environmentally friendly communication networks. The potential of PPy in next-generation communication systems by emphasizing improvements in material performance and sustainability is also highlighted.

Keywords: Polypyrrole, 6G technology, Sustainable, Advanced materials.

1 | Introduction

The advent of Sixth-Generation (6G) communication networks marks a transformative leap in digital connectivity, aiming to enable unprecedented capabilities such as real-time holographic transmission, Ultra-Reliable Low-Latency Communications (URLLC), and pervasive intelligence powered by Artificial Intelligence (AI) and Machine Learning (ML). This evolution builds upon the foundation laid by 5G. Still, it

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extends its boundaries by targeting data rates exceeding 1 Tbps, sub-millisecond latencies, and the seamless integration of advanced sensing, computing, and communication technologies. However, achieving these ambitious goals necessitates innovations not only in architecture and software but also at the fundamental level of materials. In this context, next-generation materials play a crucial role in shaping the performance, reliability, and sustainability of future communication systems. Among various candidates, conductive polymers have gained significant attention due to their tunable electrical and mechanical properties, and among them, polypyrrole (PPy) stands out as particularly promising. PPy-based materials exhibit a unique combination of high conductivity, mechanical flexibility, and environmental stability, making them highly suitable for 6G-enabled technologies such as flexible antennas, Electromagnetic Interference (EMI) shielding, and energy storage devices. Moreover, their lightweight nature and ease of processing enhance their compatibility with emerging device architectures, including wearable electronics and Reconfigurable Intelligent Surfaces (RIS), which are expected to become central components of the 6G ecosystem. This article explores the multifaceted role of PPy-based materials in 6G applications and their contribution to sustainable technological development. The integration of PPy into various device platforms not only improves technical performance but also supports environmentally responsible innovation. With increasing attention being paid to reducing the carbon footprint and material waste in electronics, the recyclability and low environmental impact of PPy composites offer a pathway toward green 6G networks.

Furthermore, the tunability of PPy's properties through doping and nanocomposite formation allows for custom-designed solutions tailored to specific use cases within the 6G framework. As the world moves toward an era of hyper-connectivity, the strategic development and deployment of advanced materials such as PPy are indispensable. This paper seeks to highlight the synergy between material science and next-generation communications, focusing on how PPy-based technologies can facilitate not only high-performance applications but also long-term sustainability in digital infrastructure.

The transition from 5G to 6G represents a revolutionary step forward in wireless communication, emphasizing enhanced latency, speed, and capacity, and the direct integration of AI and ML into network infrastructure. 6G intends to enable ultra-low latency, real-time responsiveness, and huge data transfer for advanced applications like holographic communication and Extended Reality (XR), whereas 5G concentrates on improved mobile broadband and the Internet of Things (IoT) [1]. All the benefits of 6G come with the need for different material requirements specified for various applications. Advanced materials and their enhancement are vital in addressing the high demands for the performance of 6G [2]. For ultra-low latency communication and high-frequency signal transmission in the Terahertz (THZ) range (over 100 GHz), materials like graphene, CNTs, and metamaterials, as well as conductive polymers like PPy, are essential. These materials make it easier to create flexible antennas, wearable technology, and RIS, all of which are essential for upcoming 6G applications, including autonomous systems, smart cities, and Extended Reality (XR) [3]. Advanced materials offer energy-efficient designs, leading to lower power consumption, which is very important for the network's sustainability. Materials that have advanced EMI shielding offer reliable communication and the reduction of device dimensions for compact and high-performance systems. Integrating these materials into 6G technologies is an open challenge in achieving the capacity, speed, and reliability needed [4]. This article's goal is to investigate how materials based on PPy may improve the functionality of 6G technologies while highlighting the importance of sustainability. PPy-based composites offer unique properties like high conductivity, flexibility, and tunable performance, making them suitable for applications like flexible antennas, energy-efficient devices, and wearable devices. This study also intends to investigate how these materials contribute to minimizing the environmental effects of 6G infrastructure by enhancing energy efficiency and supporting sustainable production processes.

2 | Method

This study reviews recent research on PPy composites for applications in 6G technologies, such as flexible antennas, EMI shielding, and energy storage. Conductivity and flexibility were analyzed for their relevance to communication devices as key material properties. Moreover, environmental impact and recyclability were examined based on sustainable methods.

2.1|Polypyrrole as an Advanced Material

PPy is well-known for its exceptional combination of mechanical flexibility, electrical conductivity, and environmental resilience, which are essential for high-frequency signal transmission and integration into wearable devices and flexible antennas [5]. Its chemical structure, resulting from the polymerization of pyrrole monomers, contributes to its impressive electrical characteristics. Its tunable properties and lightweight design align with 6G's focus on energy efficiency and sustainability [6]. Additionally, PPy composites enhance energy storage capabilities, making them ideal for low-power 6G devices [7].

The table below shows the chemical and physical properties of PPy.

Table 1. Chemical and physical properties of polypyrrole.

Property	Description	Reference
Electrical Conductivity	High electrical conductivity, often exceeding 10 S/cm; tunable through doping with various species.	[5], [6]
Mechanical Flexibility	Maintains flexibility, enabling integration into flexible and wearable devices.	[5]
Environmental Stability	Significant resistance to oxidation and degradation, enhancing longevity in various environments.	[6]
Processability	Syntheses can be made through methods like chemical and electrochemical polymerization and in versatile forms (films, fibers, composites).	[6]
Thermal Properties	Reasonable thermal stability, with decomposition temperatures typically above 200°C.	[7]
Biocompatibility	Certain formulations are biocompatible, expanding applications in biomedical fields.	[5]
Electromagnetic Shielding	Effective in shielding against Electromagnetic Interference, enhancing reliability in communication systems.	[5]
Tunable Properties	Properties, especially electrical conductivity, can be adjusted through doping and synthesis conditions.	[5], [6]

As mentioned, enhancing the properties of materials is very important in achieving high-performance demands. To improve its functioning, PPy composites are created by blending PPy with different materials, like fillers and nanoparticles [6]. This method enhances qualities like mechanical strength, thermal stability, and electrical conductivity. For instance, introducing graphene can considerably raise conductivity, whereas metal nanoparticles can enhance EMI protection [8], [9]. These composites are particularly interesting for applications in electronics and communication systems since their improved features make them appropriate for sensors, flexible electronics, and energy storage devices.

2.2|Applications of PPy-Based Materials in 6G

With the rising demand for sophisticated functions in next-generation communication systems, PPy-based materials are becoming essential elements in 6G networks. This section delves into the various applications of PPy composites, showcasing their versatility and effectiveness across several domains critical to 6G technology, as seen in *Fig. 1*.

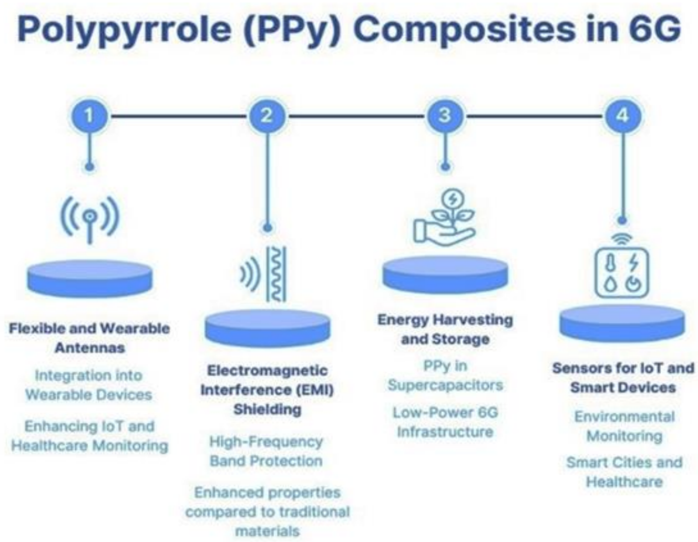

Fig. 1. Applications of polypyrrole in 6G technology.

2.2.1 | Flexible and wearable antennas

PPy composites offer the design of flexible, conformable antennae that are suitable for wearable applications. Their flexibility allows the integration into clothing and accessories, making them suitable for health monitoring devices and the IoT. Ehteshami et al. [10] experimented on a circularly polarized flexible polymer/composite microstrip antenna, demonstrating its effectiveness in wearable applications. Furthermore, research by [11] highlights progress in conductive polymer antennas based on free-standing PPy and PEDOT, showcasing their potential for high-performance and lightweight antenna designs. These advancements position PPy composites as a key enabler in the evolution of flexible antennas for 6G networks.

2.2.2 | Electromagnetic interference shielding

EMI is a significant concern for the reliability of 6G systems, which operate in high-frequency bands [12]. PPy composites have shown impressive EMI shielding qualities, which are essential to protecting devices from external interference and maintaining stable signal transmission in 6G networks [13]. Due to their excellent electrical conductivity and lightweight nature, PPy-based materials can attenuate electromagnetic waves across various frequency ranges, making them ideal for shielding sensitive components in 6G infrastructure. Compared to traditional materials like metals and carbon-based composites, PPy composites offer several advantages. While metals provide robust EMI protection, they are typically heavy and inflexible, making them less suitable for applications such as wearable electronics and flexible devices. On the other side, PPy composites, which can be processed into thin films or coatings, deliver comparable Shielding Effectiveness (SE) while offering enhanced flexibility and reduced weight. For instance, PPy/Ti3C2Tx composites have demonstrated SE values of up to 71.4 dB in the THz frequency range, a key spectrum for 6G communications [14]. Additionally, PPy-barium hexaferrite composites have been found to improve shielding properties via both absorption and reflection, further enhancing their suitability for high-frequency EMI protection [15].

2.2.3 | Energy harvesting and storage

PPy has emerged as a promising material for supercapacitors and energy-harvesting devices. PPy is ideal for powering low-energy 6G components like sensors and IoT devices due to its high capacitance and rapid charge/discharge rates. PPy-based composites demonstrate enhanced energy density and charge retention when coupled with elements like graphene or CNTs [14]. Additionally, by offering environmentally appropriate energy storage options, these composites help achieve sustainability goals and are in line with the long-term aims of lowering energy consumption and e-waste [15].

2.2.4 | Sensors for IoT and smart devices

PPy--based sensors are increasingly integrated into IoT systems due to their flexibility and conductivity, making them ideal for real-time data collection in smart cities and healthcare applications. In smart cities, PPy sensors monitor air quality, temperature, and pollutants, helping in sustainable urban management [16]. In healthcare, they make continuous monitoring of patient vitals possible, improving outcomes through real-time adjustments in treatment [17].

2.3 | Sustainability in PPy Applications

2.3.1 | Environmental impact of polypyrrole synthesis

PPy synthesis can have environmental impacts depending on the methods and chemicals used. According to [18], the development of PPy-based nanomaterials presents a sustainable approach by reducing the use of toxic chemicals in synthesis processes. Their study emphasizes the potential of PPy composites in environmental sustainability applications, such as reducing pollution and waste management, particularly through more eco-friendly synthesis routes. The innovative strategies they discuss, including green chemistry approaches, aim to minimize environmental harm while still producing high-performance PPy materials for various applications. PPy materials must undergo a Lifecycle Assessment (LCA) to be evaluated for environmental sustainability from synthesis to disposal. [19] state that there are advantages and disadvantages to synthesizing PPy via polymerization techniques. Although PPy-based materials have prospective uses in environmental protection and photocatalysis, issues with their energy-intensive production methods and usage of dangerous chemicals can compromise the sustainability of their entire lifecycle. To improve PPy's environmental performance throughout its lifecycle, changes, including using greener polymerization methods and lowering harmful byproducts, are advised.

2.3.2 | PPy in reducing energy consumption

PPy-based materials play a critical role in enhancing energy efficiency, particularly in the realm of communication devices. According to [20], PPy can be doped and engineered to reduce energy consumption in electrochemical systems significantly. This principle translates well to communication technologies, where PPy composites help lower power requirements in devices by improving conductivity and energy storage capabilities. For ultra-low-power communication systems, such as those used in IoT and 6G, PPy’s high conductivity and flexibility allow it to power sensors and antennas efficiently, ensuring long-lasting performance with minimal energy input. These features make PPy especially valuable in 6G and IoT networks, where energy efficiency is crucial for ensuring sustainability and operational longevity in billions of interconnected devices.

2.3.3 | Recycling and end-of-life considerations

Recycling and end-of-life considerations for PPy and composite materials are increasingly important in the context of sustainability for 6G infrastructure. As [21] highlights, recycling technologies for carbon fiber composites—often combined with PPy in various applications—allow for the recovery and reuse of valuable materials from end-of-life devices. Similarly, designing PPy-based materials for recyclability in communication systems, such as antennas and sensors, can enhance the sustainability of 6G networks by reducing waste and supporting circular economies. This approach aligns with the goal of minimizing the environmental footprint while ensuring the efficient recovery of materials used in high-tech applications.

3 | Results

Several critical points must be addressed to ensure the practical application and sustainability of Ppy composites. *Fig 2* shows the critical points. Improving PPy's long-term stability in practical applications and expanding production for broad adoption in communication devices are two important areas of focus [1]. Additionally, there are advantages and disadvantages to integrating PPy with advanced nanomaterials like graphene and CNTs, especially when it comes to compatibility and adjusting material properties to maximize performance while controlling costs [3]. Furthermore, the creation of standardized techniques to evaluate the sustainability of materials based on PPy is essential [18]. For PPy composites to be widely used in the next generation of communication technologies, their recyclability, environmental impact, and general eco-friendliness must be assessed [18]-[21].

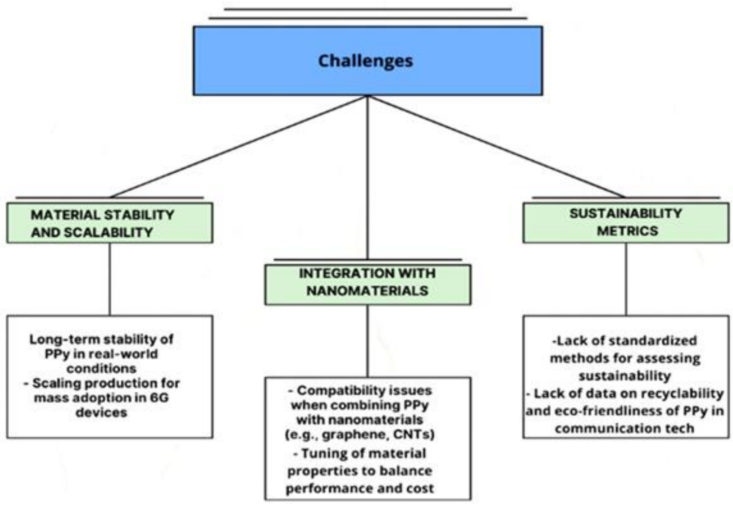

Fig. 2. Challenges to address for practical solutions.

4 | Conclusion

PPy-based materials represent a highly promising class of functional materials tailored for the demanding requirements of 6G communication systems. Their unique combination of electrical conductivity, mechanical flexibility, and environmental resilience positions them as valuable candidates for use in next-generation technologies such as flexible and wearable antennas, energy-efficient EMI shielding, supercapacitors, and IoT-based sensors. In addition to their performance-related advantages, PPy composites contribute to the broader goal of sustainable innovation through environmentally friendly synthesis processes, energy-saving functionalities, and potential recyclability. The integration of PPy into communication devices helps reduce power consumption and enhances material efficiency, thus addressing two of the most pressing challenges in modern network design: scalability and sustainability. However, further research is necessary to overcome remaining challenges, such as improving long-term stability, cost-effective large-scale production, and LCAs for greener disposal. The continued development of PPy nanocomposites with tailored properties can further optimize their use in ultra-fast, intelligent, and low-energy 6G systems. Ultimately, PPy-based materials bridge the gap between high-performance technology and ecological responsibility, supporting the creation of smarter, greener, and more connected global communication networks.

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Author Contribution

Conceptualization, A.Q.; methodology, A.Q.; data maintenance, F.B.; validation, F.B.; investigation, D.A.J.; writing- creating the initial design, A.Q.; writing - reviewing and editing, F.B.; visualization, A.Q.; project management, A.Q. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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