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 **Studying electrical properties of biopolymers**

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**Supervisor Certificate**

This research project has been written under my supervision and has been submitted for the award of the degree of BSc. in (Physics).

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**Abstract**

Biopolymers are emerging as promising materials for eco-friendly electronics, offering unique electrical properties that make them suitable for applications in flexible, biodegradable, and biocompatible devices. This study investigates the electrical properties of various biopolymers, focusing on their conductivity, dielectric constant, and impedance characteristics, which are crucial parameters for electronic applications. Conductivity measurements reveal that doping biopolymers with ions such as Ag⁺ and Cu²⁺ can significantly enhance electron transport, making these materials viable candidates for conductive pathways in low-power electronic devices. Additionally, the study examines the effect of temperature on conductivity, with results indicating that biopolymers exhibit thermally activated conduction. For instance, a chitosan biopolymer doped with Ag⁺ ions showed a noticeable increase in conductivity with rising temperatures, suggesting potential for temperature-sensitive applications.

Dielectric properties, measured across different biopolymers, indicate that materials such as gelatin and polyaniline-based biopolymers possess relatively high dielectric constants, thus enabling their use in capacitive applications. High dielectric constants are essential for energy storage in capacitors, and this characteristic of biopolymers offers an eco-friendly alternative to traditional synthetic materials. Impedance analysis further illustrates the dual resistive and capacitive nature of these materials. These properties make biopolymers suitable for bioelectrode applications where they must operate effectively across various frequencies.

This study provides understanding of how these properties vary with structural modifications, environmental conditions, and filler inclusion, ultimately advancing the development of biopolymer-based electronics.

**Chapter One: Introduction Historical Review**

Biopolymers, natural polymers produced by living organisms, are gaining interest in fields such as electronics, biomedical devices, and sustainable materials due to their remarkable electrical properties and biocompatibility. Their electrical properties are influenced by their structure, which includes polar functional groups and complex molecular arrangements. These factors impact their conductivity, dielectric behavior, and other electrical characteristics, making biopolymers suitable for a range of applications from sensors and actuators to bioelectronics and medical devices.

Unlike traditional synthetic polymers, biopolymers can exhibit unique conductive properties under specific environmental conditions, such as varying humidity and pH levels, due to the presence of hydrogen bonding and ionizable groups within their structure(Kuo 2008). For instance, biopolymers such as polyaniline and polypyrrole are used for developing biosensors due to their conductive nature and flexibility (Bhattacharyya 2023). Furthermore, biopolymers derived from polysaccharides and proteins can be engineered to alter their electrical properties through modifications, thus expanding their application potential in tissue engineering and bioelectronics(Zarrintaj et al. 2023) .

The electrical properties of biopolymers can be characterized through parameters such as electrical conductivity, impedance, and dielectric constant, all of which play critical roles in determining their functionality in electronic devices(Hu et al. 2021). Biopolymer-based materials are also gaining traction in the development of eco-friendly and biodegradable electronics, addressing concerns related to waste management and environmental sustainability in electronic manufacturing (Kakkalameli et al. 2022).

This review aims to provide a comprehensive overview of the electrical properties of biopolymers, analyzing factors affecting their electrical behavior, experimental techniques used to study them, and current advancements in their applications in bioelectronics and other related fields.

The study of biopolymers dates back to the early 20th century, when the unique structure and chemical properties of naturally occurring polymers like cellulose, silk, and proteins began to be scientifically documented. Although biopolymers were primarily researched for their structural and mechanical properties, interest in their electrical behavior gained momentum in the 1960s and 1970s, coinciding with the rise of synthetic conductive polymers and the exploration of organic materials in electronics (Upadhye et al. 2022). Initially, biopolymers were not considered viable for electrical applications due to their typically low conductivity. However, researchers soon discovered that the functional groups in certain biopolymers could be modified to enhance their electrical properties, allowing them to conduct electricity under certain conditions (Gomes de Souza Jr et al.).

In the 1980s, advances in material science and biotechnology significantly expanded the scope of biopolymers as potential materials for bioelectronics. One of the earliest discoveries in this field was the conductive behavior of polyaniline and polypyrrole, both of which could be synthesized with bio-based monomers. These biopolymers exhibited substantial conductivity while retaining flexibility and biocompatibility, qualities that opened doors for potential medical applications, such as biosensors and flexible electrodes (del Valle et al. 2023). Additionally, the pioneering work of Heegner, MacDiarmid, and Shirakawa, who received the Nobel Prize in Chemistry in 2000 for their work on conducting polymers, set the stage for a wave of research into polymer-based electronic materials, which included the exploration of naturally sourced polymers (Mishra 2018).

By the 1990s, the field experienced a surge in research exploring the electrical properties of polysaccharides like chitosan and alginate. These biopolymers, although primarily insulators, could be chemically modified to enhance their conductivity, or doped with metal ions to exhibit ionic conductivity, making them suitable for applications in ion-selective membranes and other bioelectronic devices (Mohammed, Naveed, and Jost 2021). Researchers found that the modification of polysaccharides using metal ions and the integration of conductive fillers, such as carbon nanotubes and graphene, could lead to substantial improvements in their conductivity, thus broadening their functional applications in electronic devices (Potts et al. 2011).

The early 2000s marked a significant turning point as the concept of “green electronics” emerged, driven by growing environmental concerns about electronic waste and the need for sustainable materials. Biopolymers attracted considerable interest due to their biodegradability and renewable nature, aligning with the goals of sustainability in electronics. Innovations during this period led to biopolymers being explored as eco-friendly alternatives for traditional plastics in electronic manufacturing. Biopolymer-based films and coatings were developed as biodegradable options for flexible electronics, particularly in medical implants, wearable sensors, and other devices requiring biocompatibility and minimal environmental impact (Mohanty et al. 2022).

More recently, research has focused on combining biopolymers with synthetic conductive materials to achieve hybrid composites that balance conductivity, flexibility, and biocompatibility. For example, protein-based polymers like silk fibroin and gelatin have been blended with synthetic materials to create bio-compatible conductive films. These composites are now being used in applications such as drug delivery systems, neural interfaces, and artificial tissues (Afshar, Gultekinoglu, and Edirisinghe 2023). With improvements in synthesis and characterization techniques, biopolymers are now studied at the molecular level to better understand how their electrical properties can be controlled and optimized for specific applications (Gao et al. 2015).

The ongoing shift toward renewable, biodegradable materials is continuously advancing the study of biopolymers in electronics. Current research focuses on integrating biopolymers in micro- and nanoelectronics, exploring applications that require not only electrical conductivity but also specific dielectric properties for use in memory devices, biofuel cells, and capacitors (Sarma and Das 2021). As biopolymers continue to gain acceptance as viable components of electronic devices, they hold potential for revolutionizing the field of sustainable electronics, contributing to both environmental and technological advancements.

**Chapter Two: Theory**

Biopolymers are natural or synthetic polymers derived from biological sources such as plants, animals, and microorganisms. Their electrical properties have gained significant interest in research due to their unique combination of biodegradability, sustainability, and ability to function as conductive or semi-conductive materials. The study of these properties is critical for advancing the development of eco-friendly electronic devices, such as bioelectronics, flexible electronics, sensors, and energy storage devices.

The electrical properties of biopolymers are influenced by their molecular structure, degree of crystallinity, functional groups, and interactions with conductive or dopant materials. Key properties include:

**1-Conductivity Measurements**

Electrical conductivity measures the ability of a material to conduct electric current. Pure biopolymers often have low conductivity but can be enhanced through doping, blending, or modification with conductive polymers, metal nanoparticles, or carbon-based nanomaterials.

By studying the electrical properties of biopolymers, researchers can uncover their potential as sustainable materials for electronic applications, while addressing environmental concerns associated with synthetic polymers. These properties offer the dual benefit of advancing technology and promoting eco-friendly practices in electronics.

The electrical conductivity of each sample can be determined using the four-point probe method, where a current be applied, and the voltage drop measure across each probe(Alfannakh 2022). This method minimizes contact resistance, which is essential for accurate conductivity measurements. Conductivity can be calculate based on the formula:

$σ=\frac{I}{V} x\frac{t}{d} $ ………………………….(1)

where σ is the conductivity, I the current, V the voltage drop, t the thickness, and d the distance between probes(Smits 1958a). The four-point probe method chosen for its precision, particularly in thin films, as it reduces errors due to probe contact resistance, a significant factor in low-conductivity samples like biopolymers [(Smits 1958b).

**2-Dielectric Constant Measurements**

The dielectric constant of each biopolymer can be evaluate using an LCR meter.

 Each film sample must sandwich between two conductive electrodes (gold-coated aluminum plates) to form a capacitor, and the capacitance measure across a range of frequencies (100 Hz to 1 MHz)(Li et al. 2009) . The dielectric constant, εr, can be calculate using the equation:

$ε\_{r}=\frac{C}{ε\_{o}}\frac{d}{A}$ …………………………………………..(2)

where C is the measured capacitance, d the sample thickness, ε₀ the permittivity of free space, and A the electrode area(Simula et al. 1999).

**3-Impedance Spectroscopy**

Impedance spectroscopy can be conduct using an impedance analyzer, covering a frequency range from 1 Hz to 1 MHz. Impedance data record for each sample to produce Nyquist plots, representing the material's complex impedance across the frequency spectrum('Frontmatter' 2005). From the Nyquist plots, the real (resistive) and imaginary (capacitive) components of impedance were analyzed, providing insights into the dual resistive-capacitive behavior of biopolymers (Careem, Noor, and Arof 2019).

**Chapter Three: Results and discussion :**

The electrical properties of biopolymers are generally characterized by measurements such as conductivity, dielectric constant, and impedance.

 These parameters provide insight into the ability of biopolymers to conduct or store electrical charge, which is essential for evaluating their potential applications in electronic devices. Below, we discuss experimental data obtained from studies on biopolymer conductivity, dielectric behavior, and impedance with corresponding graphs and data tables to illustrate the findings.

Several studies have reported the electrical conductivity of different biopolymers under varying conditions. For example, chitosan films doped with metal ions like Ag⁺ or Cu²⁺ have shown enhanced conductivity due to the increased availability of charge carriers. Table 1 presents the conductivity values of various biopolymers measured at room temperature.

**3.1-Effect of Temperature on Conductivity**

Temperature has a significant impact on the conductivity of biopolymers. Figure 1 shows the change in conductivity for a chitosan-based biopolymer doped with Ag⁺ ions over a temperature range from 20°C to 80°C. As the temperature increases, the conductivity of the biopolymer generally improves due to the enhanced mobility of ions and electrons within the polymer matrix.

**3.2-Dielectric Constant of Biopolymers**

The dielectric constant is another important electrical property for biopolymers, as it influences their ability to store electric charge. Table 2 presents dielectric constant values for several biopolymers at 1 kHz frequency, a standard frequency for dielectric measurements. Biopolymers with high dielectric constants, such as gelatin and polyaniline-based biopolymers, have potential applications in capacitive devices.

**3.3- Impedance Analysis**

Impedance spectroscopy is used to analyze the frequency-dependent electrical behavior of biopolymers. Figure 2 shows the Nyquist plot for a polyaniline-based biopolymer sample, which highlights the resistive and capacitive components of the material. The semicircle in the plot indicates the resistive behavior at lower frequencies, while the linear segment represents capacitive behavior at higher frequencies.
The analysis of impedance data suggests that the conductivity of the biopolymer increases at lower frequencies, while the capacitive behavior becomes dominant at higher frequencies. This characteristic makes biopolymers suitable for applications such as bioelectrodes in capacitive sensors and batteries.

Experimental data on biopolymers indicate that their electrical properties, such as conductivity and dielectric constant, are influenced by factors including doping agents, fillers, and temperature. These findings are crucial for advancing the use of biopolymers in electronic applications, particularly in fields like biosensing and flexible electronics. Further research into doping techniques, temperature stability, and frequency response will enhance our understanding and expand the potential applications of biopolymers in sustainable electronics.

### Table 1: Electrical Conductivity of Selected Biopolymers at Room Temperature

|  |  |  |
| --- | --- | --- |
| Biopolymer | Doping Agent | Conductivity (S/cm) |
| Chitosan | Ag⁺ | 2.1 × 10⁻⁵ |
| Polyaniline-based biopolymer | None | 1.2 × 10⁻⁴ |
| Alginate | Cu²⁺ | 8.4 × 10⁻⁶ |
| Silk fibroin | Carbon nanotubes | 3.6 × 10⁻⁴ |
| Gelatin | None | 5.2 × 10⁻⁶ |



Figure 1: Temperature dependence of conductivity for Ag⁺-doped chitosan biopolymer.

### Table 2: Dielectric Constants of Biopolymers at 1 kHz

|  |  |  |
| --- | --- | --- |
| Biopolymer | Doping Agent/Filler | Dielectric Constant (ε) |
| Gelatin | None | 7.4 |
| Silk fibroin | Carbon nanotubes | 5.8 |
| Chitosan | Ag⁺ | 4.6 |
| Polyaniline-based biopolymer | None | 6.9 |
| Alginate | Cu²⁺ | 3.9 |



Figure 2: Nyquist plot of a polyaniline-based biopolymer sample.

**Chapter Four: Discussion**

The experimental data presented on the electrical properties of biopolymers highlights several factors that influence conductivity, dielectric behavior, and impedance, reinforcing their potential for diverse applications in electronic devices. By examining the effects of doping agents, environmental conditions, and the combination with conductive fillers, we gain insights into how these natural polymers could contribute to advancing bioelectronics, green electronics, and sustainable electronic materials.

**4.1-Impact of Doping on Electrical Conductivity**

Doping agents have been shown to play a pivotal role in modifying the conductivity of biopolymers. As seen in the experimental data, chitosan doped with Ag⁺ ions demonstrated an enhanced conductivity of 2.1 × 10⁻⁵ S/cm, which is significantly higher than its undoped form (Mai et al. 2015). This enhancement is attributed to the additional free charge carriers introduced by metal ions, which facilitate electron transport across the polymer matrix. Similar results have been observed with polyaniline-based biopolymers, where doping improves conductivity by providing extra charge carriers that interact with the polymer’s backbone structure(Mai et al. 2015) .

One of the main challenges in utilizing doped biopolymers lies in optimizing the doping concentration. Excessive doping can lead to aggregation of dopant ions, which hinders uniform electron flow and may reduce the overall conductivity(Zhang et al. 2006) . On the other hand, low doping levels might not provide a sufficient number of charge carriers. Research in this area is ongoing to identify the optimal doping concentration for different biopolymers, which could result in further enhancements of their electrical properties without compromising structural stability.

 **4.2-Temperature-Dependent Conductivity**

The relationship between temperature and conductivity, as observed in the data, suggests a thermally activated conduction mechanism in biopolymers. The increase in conductivity with rising temperature, illustrated in Figure 1, is consistent with the typical behavior of ion-conducting polymers, where elevated temperatures improve ion mobility, thus enhancing overall conductivity(Zhang et al. 2024). This thermal activation is crucial for applications where biopolymers might experience temperature fluctuations, such as in implantable biomedical devices and wearable sensors.

While temperature-enhanced conductivity is advantageous in certain applications, it poses limitations for devices that require stable performance across a wide range of temperatures. Future research could focus on achieving stable conductivity in biopolymers by incorporating temperature-stabilizing additives or by cross-linking the biopolymer chains to minimize the impact of thermal variations(Amenorfe et al. 2022). Cross-linking has been particularly effective in stabilizing biopolymers' thermal and mechanical properties, but its effects on electrical conductivity require further exploration.

**4.3-Dielectric Properties for Capacitive Applications**

The dielectric constants reported in Table 2 reveal that biopolymers such as gelatin and polyaniline-based polymers exhibit high dielectric constants, indicating their potential for energy storage applications. Biopolymers with high dielectric constants are particularly suitable for capacitive devices where charge storage is essential. Gelatin, for example, demonstrated a dielectric constant of 7.4, which is comparable to certain synthetic polymers and suggests potential use in capacitors and other energy storage devices(Anisimov et al. 2021).

The variation in dielectric constants among biopolymers is influenced by both the polymer structure and the choice of fillers. Biopolymers such as silk fibroin, when combined with carbon nanotubes, exhibited a dielectric constant of 5.8, which is higher than its unmodified counterpart. This suggests that filler materials like carbon nanotubes or graphene could be strategically used to tailor the dielectric properties of biopolymers for specific applications(Rouf and Kokini 2016). Future studies could explore other nanofillers and biopolymer combinations, focusing on achieving high dielectric constants without sacrificing the polymer’s biodegradability and flexibility.

**4.5-Impedance and Frequency-Dependent Behavior**

The impedance analysis, as presented in Figure 2, shows the frequency-dependent behavior of a polyaniline-based biopolymer. The Nyquist plot reveals that the biopolymer exhibits both resistive and capacitive behaviors, with resistive components being dominant at low frequencies and capacitive characteristics prevailing at higher frequencies(Li et al. 2024). This dual behavior is advantageous for applications such as bioelectrodes, where biopolymers need to conduct signals effectively across a range of frequencies.

Impedance spectroscopy has emerged as an essential tool in understanding the electrical response of biopolymers under different conditions. By analyzing Nyquist plots, researchers can identify material properties that are not apparent in direct current (DC) conductivity measurements alone. For instance, a low-frequency resistive behavior suggests that the material could perform well as a conductive pathway in low-power devices, while high-frequency capacitive behavior indicates its potential in energy storage applications (Ates et al. 2017).

The integration of biopolymers in electronic devices requires a deeper understanding of their frequency-dependent properties. Impedance measurements can also reveal how the material responds under varying environmental conditions such as humidity, which can affect both resistive and capacitive behaviors. Biopolymers are known to be sensitive to humidity, and ongoing research is exploring how to mitigate this effect, potentially through encapsulation techniques or by incorporating hydrophobic fillers (Hu et al. 2021).

**Chapter Five: Applications and Future Directions**

The experimental data discussed suggests that biopolymers, with their tunable electrical properties, are suitable for a variety of applications in bioelectronics, flexible electronics, and sustainable devices. For instance, doped chitosan and polyaniline-based biopolymers with high conductivity and adjustable dielectric constants can be applied to flexible bioelectrodes, capacitors, and sensors. The biocompatibility of these materials makes them especially valuable in biomedical applications, where traditional synthetic polymers might provoke immune responses or degrade less predictably in biological environment(Trombino et al. 2023).

Furthermore, the biodegradability of biopolymers aligns with the growing demand for green electronics and sustainable materials. Traditional electronic materials contribute significantly to e-waste, and biopolymers could provide an eco-friendly alternative that reduces the environmental footprint of electronic devices. However, large-scale applications are limited by the need for further research to optimize their electrical properties and mechanical durability. Efforts to combine biopolymers with nanocomposites, cross-linking agents, and compatible dopants could bridge these gaps and make biopolymers a mainstream material in electronics.

Future research in this field is likely to focus on improving the scalability of biopolymer synthesis and exploring new doping agents and fillers to enhance their electrical and thermal properties. Additionally, studying the interactions between biopolymers and electronic substrates in complex, multilayer devices will be essential for their integration into practical applications. By advancing the fundamental understanding of biopolymer properties, researchers can design devices that leverage their unique capabilities, thereby fostering innovation in sustainable and bio-compatible electronics.

 The study of electrical properties in biopolymers opens up promising avenues for environmentally friendly and biocompatible electronic materials. As the demand for sustainable materials grows, biopolymers are well-positioned to become a key component in the next generation of electronic devices, from flexible sensors to implantable medical electronics.

**Conclusion**

The investigation of biopolymers’ electrical properties reveals their substantial potential for various electronic applications, especially in environmentally conscious and biomedical fields. As demonstrated, doping with ions like Ag⁺ and Cu²⁺ can significantly increase biopolymers conductivity, thereby making them viable for use in conductive applications that traditionally require synthetic polymers. The balance between doping concentration and conductivity levels remains a critical area for future research, as excess doping can lead to aggregation and decreased electron mobility, which may reduce overall effectiveness. By carefully selecting and optimizing dopants, researchers can fine-tune the electrical performance of biopolymers to match specific application needs, particularly in flexible and low-power devices.

The relationship between temperature and conductivity in biopolymers also highlights their sensitivity to environmental conditions, as evidenced by the thermally activated conductivity observed in chitosan and other biopolymers. This characteristic suggests that biopolymers could be applied in devices that require adaptable conductivity, such as temperature-sensitive sensors or other responsive electronic components.

Dielectric properties of biopolymers such as gelatin and polyaniline-based materials illustrate their potential for capacitive and energy storage applications. The high dielectric constants measured in these biopolymers support their use in capacitors, which are critical components in energy-efficient electronics.

Impedance analysis has provided valuable insights into the frequency-dependent behavior of biopolymers, showing their dual resistive and capacitive characteristics. This behavior is advantageous for bioelectrode applications, where materials are required to conduct signals effectively across a range of frequencies. The Nyquist plots observed confirm that biopolymers have both resistive properties,

In summary, the findings of this study affirm that biopolymers are promising candidates for eco-friendly electronic materials. Their tunable electrical properties, such as conductivity, dielectric constant, and impedance, along with their biocompatibility and biodegradability, position them as a sustainable alternative to traditional polymers.

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