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Perspective

Nature-Derived Polymers for Next-Generation Sustainable Electronics

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ABSTRACT

The rapid growth of modern electronic technologies has led to a significant increase in electronic waste, posing major environmental and sustainability challenges. Most conventional electronic devices rely on petroleum-based polymers that are non-biodegradable and environmentally persistent, creating an urgent need for sustainable material alternatives. Natural polymers derived from renewable biomass have emerged as promising candidates for next-generation sustainable electronics due to their biodegradability, biocompatibility, abundance, and low environmental impact. This perspective highlights recent progress in natural polymer-based electronic materials, including polysaccharide-based polymers, protein-based polymers, and natural polymer nanocomposites. Their applications in flexible and wearable electronics, transient electronics, and sustainable sensing devices are discussed. Key strategies such as molecular engineering, nanocomposite design, and green processing methods are explored to improve electrical performance and stability. Major challenges, including limited conductivity, moisture sensitivity, thermal stability, and device integration, are also addressed, along with future opportunities for developing fully biodegradable and environmentally friendly electronic systems.

Keywords: Biodegradable electronics; Biopolymer nanocomposites; Flexible electronics; Green electronics; Natural polymers; Sustainable electronics; Transient electronics; Wearable sensors

1. Introduction

The rapid advancement of electronic technologies has profoundly transformed modern society, enabling innovations in communication, healthcare, environmental monitoring, and intelligent systems [1],[2],[3]. The proliferation of consumer electronics, wearable devices, and smart sensing platforms has significantly increased the global demand for electronic materials and components. In most conventional electronic systems, petroleum-derived synthetic polymers are widely used as substrates, encapsulation layers, dielectric materials, and structural components because of their excellent mechanical stability, chemical resistance, and ease of large-scale fabrication [4],[5]. However, the continuous growth of electronic device production has led to an alarming rise in electronic waste (e-waste), which has become one of the fastest-growing waste streams worldwide [6],[7]. The improper disposal and accumulation of non-degradable electronic materials pose serious environmental and ecological challenges, including soil and water contamination and the release of toxic substances during degradation processes. Consequently, the development of environmentally sustainable materials for electronic applications has become a critical priority for researchers and policymakers seeking to reduce the ecological footprint of modern electronic technologies.

Despite the remarkable progress achieved in electronic device engineering, the materials used in most electronic systems remain largely dependent on non-renewable, petroleum-based polymers that are inherently non-biodegradable and environmentally persistent [8],[9],[10]. These synthetic polymers, such as polyimide, polyethylene terephthalate, and other engineering plastics, provide excellent thermal and mechanical properties but contribute significantly to long-term environmental pollution after disposal. Furthermore, the increasing integration of flexible and wearable electronic devices has intensified the need for materials that are not only mechanically compliant but also environmentally benign. Conventional polymers typically require energy-intensive processing methods and generate substantial carbon emissions during their production lifecycle. Additionally, their long degradation times make recycling and waste management increasingly difficult [11],[12],[13]. These challenges highlight the urgent need to develop alternative materials that combine desirable electronic functionality with sustainability, renewability, and eco-friendly disposal pathways. In this context, natural polymers derived from biomass have emerged as highly promising candidates due to their inherent biodegradability, biocompatibility, and abundant availability [14],[15],[16]. Materials such as cellulose, chitosan, starch, silk fibroin, and gelatin possess unique chemical structures and functional groups that enable tunable physical properties and compatibility with advanced nanomaterials. However, despite their significant potential, several challenges remain in achieving the electrical performance, environmental stability, and large-scale processability required for next-generation electronic devices. As shown in Figure 1, natural biomass sources can be converted into functional polymers and further integrated into electronic device components for sustainable electronics.

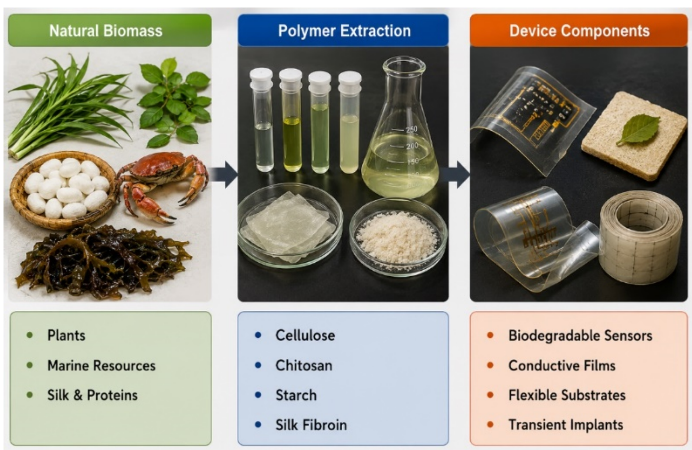

Figure 1: *Schematic illustration of natural biomass sources converted into functional polymers and integrated into electronic device components for sustainable electronics.*

Despite the rapid progress in biodegradable and bio-derived electronic materials, several important research gaps remain in the current literature [17],[18]. Existing reviews often focus on specific material classes, individual device applications, or general biodegradable electronics without providing a comprehensive perspective on the integration of nature-derived polymers, nanocomposite engineering, and sustainable device design strategies for next-generation electronics. In particular, limited attention has been given to correlating the molecular properties of natural polymers with their electrical functionality, environmental stability and scalable fabrication approaches required for practical electronic applications [19]. Furthermore, emerging opportunities involving artificial intelligence-assisted material discovery, transient electronics, and circular electronic design have not been systematically discussed in the context of natural polymer-based electronics. Therefore, this critical review provides a comprehensive and forward-looking overview of nature-derived polymers for sustainable electronics by critically discussing material platforms, nanocomposite strategies, green processing approaches, and emerging device applications. In addition, this review highlights key performance limitations, identifies current technological bottlenecks, and outlines future research directions that may accelerate the development of fully biodegradable and environmentally responsible electronic system.

2. Natural Polymer Platforms for Electronics

Natural polymers derived from renewable biological resources have emerged as promising materials for the development of sustainable electronic devices. Unlike conventional petroleum-based polymers, natural polymers offer intrinsic advantages such as biodegradability, biocompatibility, low toxicity, and environmental sustainability. Their molecular structures typically contain abundant functional groups (e.g., hydroxyl, amino, and carboxyl groups), which enable strong intermolecular interactions, chemical tunability, and compatibility with a wide range of nanomaterials. These characteristics make natural polymers attractive platforms for flexible, biodegradable, and biointegrated electronics. In recent years, significant research efforts have focused on exploiting different classes of natural polymers to fabricate substrates, dielectric layers, sensing elements, and encapsulation materials for next-generation electronic systems. Among these materials, polysaccharide-based polymers, protein-based polymers and natural polymer nanocomposites have received particular attention due to their structural diversity and functional versatility, as mentioned in Figure 2. The following sections discuss these major material classes and highlight their emerging applications in sustainable electronic technologies.

2.1. Polysaccharide-Based Polymers

Polysaccharides represent one of the most abundant classes of natural polymers and are widely distributed in plants, microorganisms, and marine organisms [20],[21]. These macromolecules consist of carbohydrate units connected through glycosidic linkages, forming structurally diverse polymers with tunable mechanical, chemical, and interfacial properties. Owing to their natural abundance, biodegradability, and excellent film-forming ability, polysaccharide-based materials have emerged as promising candidates for sustainable electronic systems. Among them, cellulose, chitosan, starch, and alginate have been extensively explored for applications in flexible electronics, dielectric layers, and sensing platforms.

Cellulose is the most abundant biopolymer on Earth and has attracted considerable interest as a sustainable substrate for electronic devices [22],[23],[24]. Composed of linear β-(1→4) linked glucose units, cellulose forms highly ordered crystalline domains through strong hydrogen-bonding networks, resulting in excellent mechanical strength, flexibility, and chemical stability. Cellulose can be processed into films, nanopaper, and nanofiber networks that function as flexible substrates for printed electronics and wearable devices. In addition, cellulose derivatives such as cellulose acetate and carboxymethyl cellulose exhibit favourable dielectric properties and can be processed using environmentally friendly solution-based techniques. Chitosan, derived from the deacetylation of chitin found in crustacean shells, is another important polysaccharide for electronic applications [25]. Its intrinsic biocompatibility, biodegradability, and reactive amino groups enable facile chemical modification and functionalization.

Chitosan has been widely utilised as a dielectric layer in organic field-effect transistors and as a functional matrix for biosensors [26],[27]. The incorporation of conductive nanomaterials such as graphene or metal nanoparticles further enhances electrical conductivity and sensing performance. Starch and alginate also provide attractive platforms for biodegradable electronics [28],[29]. Modified starch materials can be processed into flexible films serving as substrates or encapsulation layers, while alginate hydrogels, formed through ionic crosslinking, offer soft and biocompatible interfaces for wearable sensors and bioelectronic devices. Collectively, polysaccharide-based materials provide versatile and sustainable building blocks for next-generation, environmentally friendly electronic technologies.

2.2. Protein-Based Polymers

Protein-based polymers represent another important class of natural materials for sustainable electronic applications [30],[31]. Proteins consist of amino acid building blocks linked through peptide bonds, forming hierarchical structures with diverse mechanical and functional properties. Due to their inherent biocompatibility, biodegradability, and mechanical flexibility, protein-based materials have attracted significant interest for biointegrated electronic systems. Among them, silk fibroin, gelatin, and collagen have been widely investigated for applications in wearable electronics, bioelectronics, and implantable sensing devices.

Silk fibroin, derived from silkworm cocoons, is one of the most promising protein-based materials for electronic applications [32],[33]. It exhibits excellent mechanical strength, optical transparency, and biodegradability, along with outstanding biocompatibility. Silk fibroin can be processed into thin films through simple solution-based methods and has been widely used as flexible substrates, dielectric layers, and structural materials in transient electronic devices. These properties enable the development of electronic systems that can safely degrade after completing their function. In addition, silk can be integrated with conductive nanomaterials to form hybrid materials for biosensing platforms and flexible circuits. Gelatin, obtained from the partial hydrolysis of collagen, is another widely utilised protein polymer [34]. It forms flexible films and hydrogels with tunable mechanical properties, making it suitable for wearable sensors and soft electronic devices. The presence of amino and carboxyl functional groups enables chemical modification and incorporation of conductive nanomaterials, improving electrical conductivity and sensing performance. Collagen, the most abundant structural protein in the human body, also provides an attractive platform for sustainable electronics [35],[36]. Its excellent biocompatibility and ability to form porous scaffolds or hydrogels make it particularly suitable for implantable sensors, tissue-interfacing electronics, and biosensing systems.

2.3. Biopolymer Nanocomposites

Natural polymers offer many advantages for sustainable electronics; however, their intrinsically low electrical conductivity limits their direct application in devices requiring efficient charge transport [37],[38]. To address this challenge, significant research efforts have focused on the development of biopolymer nanocomposites, where natural polymers are combined with conductive nanomaterials. This strategy enables the integration of the flexibility, biodegradability, and environmental compatibility of

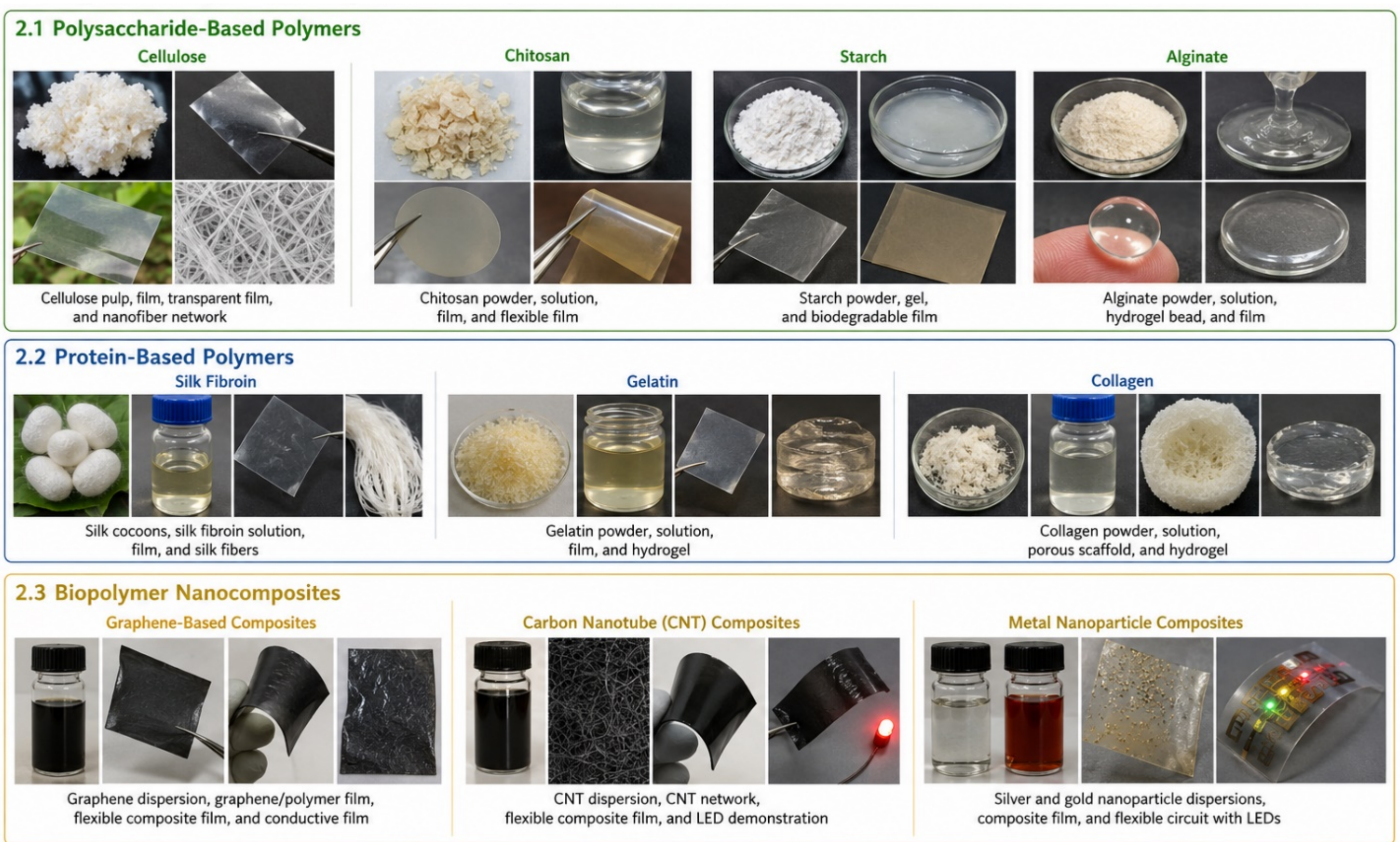

Figure 2: *Representative natural polymer platforms for sustainable electronics, including polysaccharide-based polymers (cellulose, chitosan, starch, and alginate), protein-based polymers (silk fibroin, gelatin, and collagen), and biopolymer nanocomposites integrated with graphene, carbon nanotubes (CNTs), and metal nanoparticles. The figure highlights real material forms, processing characteristics, and their potential applications in flexible, biodegradable, wearable, and biointegrated electronic devices.*

natural polymers with the excellent electrical properties of advanced nanomaterials. Graphene is one of the most widely used conductive nanomaterials in biopolymer composites [39],[40]. Owing to its exceptional electrical conductivity, large surface area, and mechanical strength, graphene can significantly enhance the electrical performance of natural polymer matrices. Strong interfacial interactions between graphene sheets and polymer chains contribute to improved mechanical stability and conductivity, enabling applications in flexible sensors, wearable electronics, and biodegradable conductive films. Carbon nanotubes (CNTs) are also extensively employed due to their high aspect ratio and outstanding electrical properties [41],[42]. When incorporated into natural polymer matrices, CNTs form interconnected conductive pathways that dramatically improve charge transport. Such composites have been explored for strain sensors, gas sensors, and flexible electronic circuits.

Metal nanoparticles, including silver and gold, further enhance conductivity and sensing performance through catalytic and electron transfer effects [43],[44]. Overall, natural polymer–nanomaterial composites provide a promising pathway toward high-performance, environmentally friendly electronic systems.

3. Emerging Device Applications

The integration of natural polymers into electronic materials has opened new opportunities for the development of sustainable and environmentally friendly electronic systems [37],[45],[46]. In recent years, increasing attention has been directed toward designing devices that are not only high-performing but also biodegradable, biocompatible, and environmentally responsible. Natural polymers offer unique advantages for these applications due to their mechanical flexibility, chemical functionality, and compatibility with solution-based fabrication techniques, as shown in Figure 3. Moreover, their ability to form thin films, hydrogels, and nanostructured composites enables the fabrication of lightweight and flexible electronic platforms. As a result, natural polymer-based materials are increasingly being explored in several emerging device applications, including flexible and wearable electronics, transient electronics, and sustainable sensing technologies. These developments represent important steps toward the realisation of next-generation green electronics that can minimise environmental impact while maintaining functional performance.

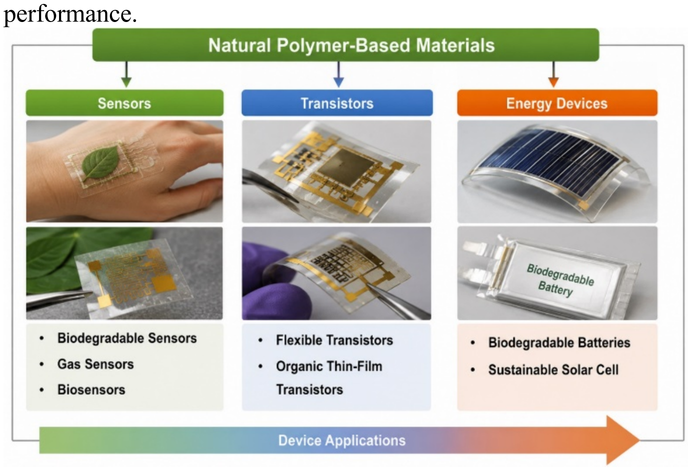

Figure 3: *Device applications of natural polymer-based materials for sustainable electronics, including sensors, transistors and energy devices such as biodegradable batteries and solar cells.*

3.1. Flexible and Wearable Electronics

Flexible and wearable electronics have emerged as a major technological direction in modern electronic systems [2],[47],[48]. These devices are designed to conform to curved surfaces, human skin, or soft biological tissues while maintaining stable electrical performance under mechanical deformation. Traditional electronic materials are generally rigid and brittle, limiting their use in flexible platforms. In contrast, natural polymers possess intrinsic flexibility, low elastic modulus, and excellent film-forming capability, making them attractive materials for mechanically compliant electronic devices.

Natural polymer-based materials have been widely explored as substrates and functional components in flexible electronics [37]. Polymers such as cellulose, silk fibroin, and gelatin can be processed into thin, lightweight films that provide mechanical support while maintaining bendability. When combined with conductive nanomaterials, including graphene, carbon nanotubes, and metallic nanostructures, these materials enable the fabrication of flexible electronic circuits and sensing elements. Such hybrid systems can withstand repeated bending, stretching, and mechanical deformation without significant performance degradation.

Biodegradable sensors represent one of the most promising applications of natural polymer-based flexible electronics [49],[50]. These devices can detect physical, chemical, or biological signals while reducing environmental impact after disposal. Natural polymer substrates support conductive sensing layers capable of responding to stimuli such as gases, humidity, temperature, or mechanical strain, making them suitable for environmental monitoring and disposable healthcare devices.

Another rapidly developing area is skin-like electronics. Natural polymers such as silk fibroin and gelatin exhibit softness and biocompatibility similar to human skin, enabling intimate contact with the body [51],[52]. Flexible electronic patches based on these materials have been developed to monitor physiological signals, including heart rate, body temperature, and motion. Such systems provide promising opportunities for continuous, non-invasive health monitoring and next-generation wearable technologies.

3.2. Transient Electronics

Transient electronics represent a rapidly growing field that focuses on electronic devices designed to physically disappear or degrade after completing their intended function [53],[54]. Unlike conventional electronic systems that persist in the environment for long periods, transient electronics are engineered to dissolve in water or biological fluids, thereby eliminating electronic waste and enabling new biomedical applications. Natural polymers are particularly attractive materials for transient electronics because of their inherent biodegradability and environmentally friendly degradation pathways.

Natural polymer-based transient electronic devices can be fabricated using materials such as cellulose, silk fibroin, and chitosan, which gradually degrade under specific environmental conditions [55],[56]. These materials can serve as substrates, dielectric layers, or encapsulation materials for electronic circuits that are designed to operate for a predetermined period before dissolving. By carefully controlling the thickness, crystallinity, and chemical modification of the polymer matrix, researchers can tune the degradation rate of these materials to match the desired device lifetime.

One of the most important applications of transient electronics is in the field of biomedical implants. Temporary electronic implants can be used to monitor physiological signals, deliver therapeutic stimulation, or assist in tissue healing following surgery [57]. After the required monitoring or treatment period, the device gradually degrades inside the body, eliminating the need for surgical removal. Natural polymer substrates provide excellent biocompatibility and minimise adverse immune responses, making them ideal materials for such implantable electronic systems.

Environmental monitoring is another promising application area for transient electronics [53],[58]. In many cases, electronic sensors are deployed in natural environments such as forests, oceans, or agricultural fields to monitor environmental conditions. However, retrieving these devices after use can be difficult or impractical, leading to the accumulation of electronic waste. Transient electronics fabricated from biodegradable polymers offer a sustainable alternative, as they can naturally degrade after completing their monitoring tasks. Such systems can be used for temporary environmental sensing, disaster monitoring, or agricultural data collection without leaving long-term electronic debris.

3.3. Sustainable Sensors

Among the various applications of natural polymer electronics, sustainable sensing technologies have received significant research attention. Sensors play a critical role in modern electronic systems by enabling the detection and monitoring of environmental, chemical, and biological signals [59],[60],[61]. However, the widespread deployment of sensing devices has raised concerns regarding material sustainability and electronic waste generation. Natural polymer-based sensing platforms offer a promising solution by combining high sensitivity with environmental compatibility.

Natural polymer composites have been extensively investigated as sensing materials due to their ability to interact with analyte molecules through functional chemical groups [50],[62]. Polymers such as chitosan, cellulose, and gelatin contain abundant hydroxyl, amino, and carboxyl groups that can form interactions with various chemical species. These interactions can induce changes in electrical conductivity, capacitance, or optical properties, which can be detected as sensor signals. Gas sensors based on natural polymer composites have demonstrated considerable potential for environmental monitoring and industrial safety applications [63]. By incorporating conductive nanomaterials such as graphene or carbon nanotubes into natural polymer matrices, researchers have developed highly sensitive gas sensors capable of detecting pollutants such as ammonia, nitrogen dioxide, and volatile organic compounds [64],[65]. The polymer matrix provides a flexible and biodegradable support structure, while the conductive nanomaterials enable efficient electrical signal transduction. Humidity sensors represent another important category of sustainable sensing devices [66]. Many natural polymers exhibit strong interactions with water molecules due to their hydrophilic functional groups [67]. These interactions lead to measurable changes in electrical resistance, capacitance, or dielectric properties when exposed to varying humidity levels. As a result, natural polymer-based humidity sensors have been widely investigated for applications in environmental monitoring, smart packaging, and wearable electronics. Biosensors based on natural polymers are also gaining increasing importance in healthcare and biomedical diagnostics [68]. Natural polymers provide a biocompatible environment for immobilising enzymes, antibodies, or other biomolecules that can selectively detect biological analytes. These sensing platforms can be used for monitoring glucose levels, detecting pathogens, or analysing biomarkers in bodily fluids. The combination of biocompatibility, flexibility, and biodegradability makes natural polymer-based biosensors particularly attractive for next-generation medical diagnostics and wearable health monitoring systems.

Overall, the development of emerging device applications based on natural polymer materials represents a major step toward sustainable electronic technologies. Flexible and wearable electronics, transient electronic systems, and sustainable sensing platforms demonstrate how natural polymers can be integrated into functional electronic devices while reducing environmental impact. Continued research in this area is expected to further enhance device performance, expand application possibilities, and accelerate the transition toward environmentally responsible electronic systems.

4. Comparing Cocrystals Protonated through Acidic Stimulation

The successful implementation of natural polymers in sustainable electronic devices requires careful material design and engineering strategies. Although natural polymers possess attractive properties such as biodegradability, flexibility, and biocompatibility, their direct use in electronic devices is often limited by challenges, including low electrical conductivity, poor moisture stability, and limited thermal resistance [37]. To overcome these limitations and enhance device performance, several design strategies have been developed. These strategies focus on modifying the molecular structure of natural polymers, integrating them with functional nanomaterials, and employing environmentally friendly fabrication methods. Among the most important approaches are molecular engineering, nanocomposite design, and green processing techniques. Together, these strategies provide a comprehensive framework for developing high-performance natural polymer-based electronic materials.

4.1. Molecular Engineering

Molecular engineering plays a critical role in tailoring the structural and functional properties of natural polymers for electronic applications [38],[69]. Natural polymers typically contain reactive functional groups such as hydroxyl, amino, and carboxyl groups, which provide opportunities for chemical modification. By introducing new functional groups or altering the polymer network structure, researchers can significantly improve the electrical, mechanical, and chemical properties of these materials.

Functionalization is one of the most widely used molecular engineering strategies [69]. Through chemical modification, functional molecules or conductive groups can be attached to the polymer backbone, enabling enhanced interactions with analyte molecules or conductive nanomaterials [70]. For example, functionalized cellulose and chitosan derivatives have been used to improve the sensitivity of gas sensors and biosensors. Functionalization can also improve interfacial compatibility between natural polymers and conductive fillers, leading to improved electrical performance in composite materials.

Crosslinking is another important strategy for improving the stability and mechanical strength of natural polymer networks. Crosslinking involves forming chemical or physical bonds between polymer chains, which enhances the structural integrity of the material [71]. This approach can improve thermal stability, reduce water solubility, and increase the durability of polymer films used in electronic devices. For example, crosslinked gelatin or chitosan hydrogels have been widely used in flexible electronics and bioelectronic interfaces due to their improved mechanical properties and stability under environmental conditions [42].

4.2. Nanocomposite Design

Nanocomposite engineering has emerged as a powerful approach for enhancing the electrical functionality of natural polymer materials [72],[73]. Since most natural polymers are electrically insulating, the incorporation of conductive nanomaterials is essential for enabling electronic device operation.

Nanocomposite design involves dispersing conductive fillers within a natural polymer matrix to create hybrid materials with improved electrical conductivity and sensing performance. Common conductive fillers include graphene, carbon nanotubes, metal nanoparticles, and conductive polymers [74],[75],[76]. These nanomaterials provide efficient pathways for electron transport, allowing the composite material to exhibit significantly improved electrical conductivity. In addition, the high surface area of nanomaterials facilitates strong interactions with gas molecules, biomolecules, or environmental stimuli, which enhances the sensitivity of sensing devices. The performance of nanocomposite materials depends strongly on factors such as filler dispersion, interfacial bonding, and the formation of conductive networks within the polymer matrix [77],[78]. Uniform dispersion of nanomaterials within the polymer is essential to achieve consistent electrical properties and mechanical stability. Researchers often employ surface modification techniques or polymer functionalization to improve compatibility between the polymer matrix and conductive fillers. As a result, natural polymer nanocomposites have demonstrated excellent performance in applications such as gas sensors, strain sensors, flexible electronics, and wearable sensing devices.

4.3. Green Processing

In addition to material design, fabrication techniques play a crucial role in determining the sustainability and scalability of natural polymer electronics. Green processing methods aim to minimise environmental impact by reducing energy consumption, eliminating toxic solvents, and enabling low-temperature fabrication processes [79],[80]. Natural polymers are particularly well-suited for green processing because they can often be dissolved or dispersed in water or other environmentally benign solvents.

Table 1
Key Design Strategies for Natural Polymer-Based Sustainable Electronics

Strategy	Key Methods	Purpose	Example Applications
Molecular Engineering	Functionalization, Crosslinking	Improve chemical stability, mechanical strength, and interfacial interactions.	Flexible electronics, biosensors, dielectric layers
Nanocomposite Design	Incorporation of graphene, carbon nanotubes and metal nanoparticles	Enhance electrical conductivity and sensing performance	Gas sensors, strain sensors and wearable devices
Green Processing	Printing electronics, solution processing	Enable scalable, low-cost, and environmentally friendly fabrication	Printed sensors, flexible circuits, biodegradable electronics

Printing electronics is one of the most promising fabrication strategies for natural polymer-based devices [45],[81]. Techniques such as inkjet printing, screen printing, and roll-to-roll printing allow the direct deposition of functional materials onto flexible substrates. These methods enable large-area device fabrication while minimising material waste and processing complexity. Natural polymer inks containing conductive nanomaterials can be printed to form electronic circuits, sensors, or electrode structures for various applications. Solution processing is another widely used technique for fabricating natural polymer electronic materials [82]. Many natural polymers can be processed from aqueous solutions, allowing thin films or coatings to be formed through methods such as spin coating, drop casting, or dip coating. These techniques are relatively simple, cost-effective, and compatible with flexible substrates. Furthermore, solution-based fabrication enables easy integration of nanomaterials and functional additives, which can enhance the performance of the resulting electronic devices.

Overall, the combination of molecular engineering, nanocomposite design, and green processing strategies provides a comprehensive approach to developing high-performance natural polymer-based electronics. By carefully optimising these design strategies, researchers can overcome the inherent limitations of natural polymers while preserving their environmental advantages, as mentioned in Table 1. Continued progress in these areas is expected to accelerate the development of sustainable electronic technologies capable of addressing both performance and environmental challenges.

5. Key Challenges

Despite significant progress in natural polymer-based sustainable electronics, several critical challenges continue to limit their large-scale commercialisation and practical implementation in advanced electronic systems. One of the major limitations is the inherently low electrical conductivity of most natural polymers. Materials such as cellulose, chitosan, starch, and protein-based polymers are electrically insulating because they lack extended conjugated electron transport pathways. Although the incorporation of conductive nanomaterials, including graphene, carbon nanotubes, conductive polymers, and metal nanoparticles, can significantly improve electrical conductivity, achieving homogeneous dispersion and stable conductive networks within the polymer matrix remains challenging. Agglomeration of nanofillers, poor interfacial compatibility, and inconsistent electrical pathways can result in reduced device performance, signal instability, and limited reproducibility.

Mechanical stability is another important concern, particularly for flexible and wearable electronic devices subjected to repeated bending, stretching, and deformation. Many natural polymers exhibit relatively weak mechanical strength, low fracture resistance, and structural degradation under cyclic mechanical loading. In addition, environmental exposure to humidity and temperature fluctuations can further weaken polymer structures due to water absorption and swelling effects. These issues may lead to cracking, delamination, or degradation of conductive interfaces during long-term operation. Therefore, improving the mechanical robustness and fatigue resistance of natural polymer composites remains essential for reliable device performance.

Scalability and large-scale manufacturing also represent major challenges for the practical adoption of natural polymer electronics. Although laboratory-scale fabrication methods such as solution casting, spin coating, and printing techniques have demonstrated promising results, translating these approaches to industrial-scale manufacturing remains difficult. Variations in natural biomass sources, purification processes, molecular structure, and material consistency can lead to batch-to-batch variability and inconsistent device performance. Furthermore, many natural polymers require additional chemical modification, crosslinking, or nanocomposite engineering to achieve suitable electronic functionality, which can increase processing complexity and production cost. The compatibility of natural polymers with existing semiconductor manufacturing infrastructure also remains limited in many cases.

Long-term operational reliability is another critical issue for sustainable electronic systems based on natural polymers. Compared with conventional engineering polymers, natural polymer materials often exhibit lower thermal stability, higher moisture sensitivity, and accelerated degradation under environmental stress conditions such as heat, ultraviolet radiation, and oxidation. These factors can significantly affect the electrical stability, sensing accuracy, and lifetime of electronic devices during prolonged use. In biodegradable and transient electronics, balancing controlled degradation behaviour with sufficient operational lifetime remains particularly challenging. Achieving stable performance while maintaining environmental degradability requires careful optimisation of polymer chemistry, encapsulation strategies, and device architecture.

Addressing these challenges will require interdisciplinary efforts involving materials science, nanotechnology, chemical engineering, and device physics. Future research should focus on developing highly conductive bio-derived materials, improving interfacial engineering, enhancing environmental stability, and establishing scalable green manufacturing methods capable of supporting commercial production of sustainable electronic devices.

6. Future Opportunities

Despite these challenges, natural polymer-based electronics represent an exciting and rapidly evolving research field with significant potential for future technological development. Continued advances in materials science, nanotechnology, and sustainable manufacturing are expected to enable new solutions that overcome current limitations and unlock the full potential of natural polymer platforms. Several promising research directions have emerged that could significantly accelerate the development of sustainable electronic technologies, including bio-derived conductive polymers, artificial intelligence-assisted material discovery, fully biodegradable electronic systems, and circular electronic design strategies, as mentioned in Figure 4.

Figure 4: *Future roadmap for natural polymer-based sustainable electronics. Current challenges, including low electrical conductivity, moisture instability, limited thermal stability, and device integration issues, can be addressed through emerging solutions such as bio-derived conductive polymers, artificial intelligence-assisted materials discovery, and circular electronic design, ultimately enabling next-generation sustainable electronic technologies.*

Several promising research directions are emerging to advance natural polymer–based sustainable electronics. One key approach involves the development of bio-derived conductive polymers that combine the environmental advantages of natural materials with the electrical functionality required for electronic devices. Introducing conjugated structures or conductive pathways through chemical modification and hybrid material design can significantly improve charge transport. For example, integrating natural polymers with intrinsically conductive polymers or bio-inspired conductive molecules may produce materials that retain biodegradability while exhibiting enhanced electrical performance for sensors, flexible electronics, and energy devices.

- Artificial intelligence and machine learning are also becoming valuable tools for accelerating the discovery and optimisation of natural polymer materials. By analysing large datasets related to polymer structures, nanocomposite formulations, and device performance, AI-driven models can predict promising material combinations and processing strategies. This approach can significantly reduce experimental time and enable the rapid development of high-performance sustainable electronic materials.
- Another important direction is the development of fully biodegradable electronic systems. Achieving this goal requires environmentally friendly alternatives for all device components, including electrodes, semiconductors, and energy storage materials. Such systems could enable transient medical implants, disposable sensors, and eco-friendly electronic platforms.
- In addition, the concept of circular electronics emphasises recyclability, renewable materials, and closed-loop manufacturing. Natural polymers are well-suited for this approach due to their renewable origin and natural degradability, supporting the development of environmentally responsible electronic technologies.

7. Conclusion

Natural polymer-based materials have emerged as highly promising candidates for next-generation sustainable electronic technologies due to their biodegradability, biocompatibility, renewability, and low environmental impact. This review highlights the significant progress achieved in the development of nature-derived polymers such as cellulose, chitosan, starch, alginate, silk fibroin, gelatin, and collagen for applications in flexible electronics, wearable devices, transient electronics, and sustainable sensing systems. The integration of these polymers with conductive nanomaterials, including graphene, carbon nanotubes, and metal nanoparticles, has substantially improved their electrical performance, mechanical flexibility, and sensing capabilities, enabling environmentally friendly alternatives to conventional petroleum-based electronic materials. In addition, advances in molecular engineering, nanocomposite design, and green fabrication methods have demonstrated strong potential for enhancing device functionality and scalability. However, several challenges, including low intrinsic conductivity, moisture sensitivity, limited thermal and mechanical stability, scalability issues, and long-term operational reliability, still restrict large-scale practical implementation. Future research should therefore focus on developing bio-derived conductive materials, improving interfacial engineering and environmental stability, establishing scalable green manufacturing strategies, and designing fully biodegradable electronic systems with controlled degradation behaviour. Furthermore, emerging approaches such as artificial intelligence-assisted material discovery and circular electronic manufacturing may accelerate the development of high-performance and commercially viable sustainable electronics. Overall, continued interdisciplinary research combining materials science, nanotechnology, chemistry, and device engineering is expected to play a crucial role in advancing nature-derived polymers toward environmentally responsible next-generation electronic technologies.

Declaration

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Author Contribution Statement: A. N. and A. U. equally work on this paper.

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