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Wood-Derived Cellulose Materials for Future Electronic Applications

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Bachelor's thesis

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The continuous growth of electronic waste has increased the need to develop more environmentally friendly alternatives to fossil-based materials in the electronics industry. Wood-derived cellulose possesses several promising properties, including biodegradability, renewability, good mechanical durability, and extensive possibilities for physical and chemical modification. However, the wider industrial adoption of cellulose-based materials in electronics is limited by factors such as moisture sensitivity, high production costs, and the complexity of controlling the cellulose structure.

This thesis examines the use of wood-derived cellulose materials in future electronics and electronic applications. The study discusses the properties and limitations of different cellulose materials and their suitability for flexible electronics, particularly in biodegradable substrates, energy storage devices, optoelectronic devices, and sensors. In addition, the thesis analyzes the potential of wood-derived cellulose materials from the perspectives of circular economy and sustainable development in Finland. Finland's extensive forest resources, together with its strong expertise in forest industry and research, provide excellent opportunities for the development of cellulose-based electronics.

Based on the study, wood-derived cellulose materials demonstrate significant potential in future electronics, especially in the development of biodegradable, flexible, and lightweight devices. In particular, nanocellulose has attracted considerable interest due to its large specific surface area and exceptional mechanical properties. The utilization of cellulose-based materials could reduce the environmental impact of electronics and decrease the amount of electronic waste while promoting the development of more sustainable electronic solutions.

Keywords: wood-derived cellulose, flexible electronics, biodegradable electronics, forest industry

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Elektroniikkajätteen määrän jatkuva kasvu on lisännyt tarvetta kehittää elektroniikkateollisuuteen ympäristöystävällisempiä vaihtoehtoja fossiilipohjaisille materiaaleille. Puupohjaisella selluloosalla on useita lupaavia ominaisuuksia, kuten biohajoavuus, uusiutuvuus, hyvä mekaaninen kestävyys sekä laajat fysikaaliset ja kemialliset muokkausmahdollisuudet. Selluloosapohjaisten materiaalien laajempaa teollista käyttöönottoa elektroniikassa rajoittavat kuitenkin muun muassa kosteusherkkyys, tuotannon korkeat kustannukset sekä selluloosan monimutkaisen rakenteen hallinta.

Tässä tutkielmassa tarkastellaan puupohjaisten selluloosamateriaalien käyttöä tulevaisuuden elektroniikassa ja elektronisissa sovelluksissa. Työssä käsitellään eri selluloosatyyppien ominaisuuksia, rajoitteita ja niiden soveltuvuutta joustavassa elektroniikassa, erityisesti biohajoavissa alustoissa, energiavarastoinnissa, optoelektronisissa laitteissa ja sensoreissa. Lisäksi työssä analysoidaan puupohjaisten selluloosamateriaalien mahdollisuuksia kiertotalouden ja kestävän kehityksen näkökulmasta Suomessa. Suomen laajat metsävarat sekä metsäteollisuuden ja tutkimuksen vahva osaaminen tarjoavat erinomaiset edellytykset selluloosapohjaisen elektroniikan kehittämiselle.

Tutkimuksen perusteella voidaan todeta, että puupohjaisilla selluloosamateriaaleilla on merkittävää potentiaalia tulevaisuuden elektroniikassa erityisesti biohajoavien, joustavien ja kevyiden laitteiden kehityksessä. Erityisesti nanoselluloosa on herättänyt kiinnostusta sen suuren ominaispinta-alan ja poikkeuksellisten mekaanisten ominaisuuksien ansiosta. Selluloosapohjaisten materiaalien hyödyntäminen voisi tulevaisuudessa vähentää elektroniikan ympäristökuormitusta ja pienentää elektroniikkajätteen määrää sekä edistää kestävän kehityksen mukaisten elektroniikkaratkaisujen kehittämistä.

Avainsanat: puupohjainen selluloosa, joustava elektroniikka, biohajoava elektroniikka, metsäteollisuus

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1 Introduction

The increasing use of electronics has generated a vast amount of electrical and electronic waste (e-waste). Only a small portion of this waste is recyclable, and it often contains plastics derived from non-renewable fossil fuels as well as heavy metals [1]. In 2022, 62 million tonnes of e-waste were generated, but only 22.3% of this amount was officially documented as properly collected and recycled [2]. E-waste is expected to continue increasing, which has driven growing demand for biodegradable, flexible, lightweight, and multifunctional electronic devices.

Wood-derived cellulose is a versatile natural polymer and the most abundant polymer on Earth. Cellulose consists of long, ordered molecular chains that are bound together by hydrogen bonds. These strong hydrogen bonds make cellulose structurally stable and poorly soluble in water and most used solvents [3]. The biodegradability, mechanical strength, and chemical tunability of cellulose make it a promising material for the development of more environmentally friendly next-generation electronics. In addition, cellulose can be processed into various derived materials, including nanocellulose, which exhibits excellent mechanical properties.

In Finland, the use of wood-derived cellulose materials in electronics has gained increasing interest as a replacement for fossil-based raw materials. This supports Finland’s goals for sustainable development and the circular economy. Finland has extensive forest resources and a well-developed forest industry, providing a strong foundation for the utilization of cellulose-based materials. Furthermore, the use of forest industry side streams improves material efficiency and reduces waste generation. However, challenges remain, particularly regarding the cost-efficiency of production.

This thesis examines the use of wood-derived cellulose materials in electronics and electronic applications. The aim is to present their key properties and limitations affecting their mechanical performance, electrical conductivity, and processability. Finally, the use of cellulose-based materials in Finland is discussed, and their future potential in the field of electronics is evaluated. This thesis has utilized the AI-based ChatGPT application for structuring the text and improving language quality, and Anara AI has been used to support the review of source materials.

2 Wood-Derived Materials

2.1 Overview of Cellulose

Cellulose is the most abundant biopolymer on the earth [1]. It is mainly obtained from wood and is derived from plant cell walls [4]. The wood cell wall nanostructure primarily consists of three biopolymers, which are cellulose, hemicellulose and lignin [3]. As shown in Figure 1, plant cells consist a primary wall and a secondary wall, while adjacent cells are joined by the middle lamella [5]. The centre of the cell wall is called the lumen. The primary wall contains hemicellulose, proteins, and pectins, whereas the secondary wall contains the same components but also includes lignin and a higher amount of cellulose [5].

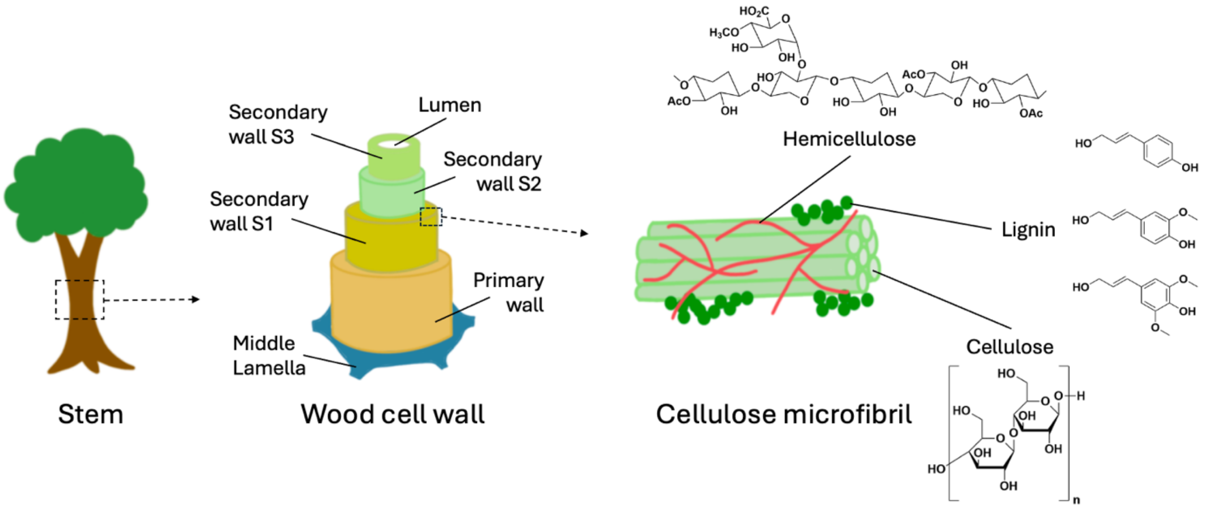

Figure 1. Hierarchical structure of wood. [5,6]

Cellulose can be used to produce cellulose derivatives, which include cellulose acetate (CA), cellulose acetate propionate (CAP), cellulose acetate butyrate (CAB), cellulose carbamate (CC), Carboxymethyl cellulose (CMC), methyl cellulose (MC), hydroxyethyl cellulose (HEC), cellulose xanthate (CX), cellulose octanoate, cellulose palmitate [7], and hydroxypropyl methyl cellulose (HPMC) [8].

2.1.1 Cellulose

Cellulose is a polysaccharide composed of long linear chains of glucose molecules. The repeating unit of cellulose is glucose ($C_6H_{12}O_6$), and the glucose units are linked by glycosidic bonds. In these bonds, each glucose molecule links to the next one in the chain. [1] These bonds give the cellulose chain rigidity and strength. The two main structural components of a cellulose fiber are crystalline cellulose and amorphous cellulose. [9] Cellulose is primarily derived from plant cell walls, and it is biodegradable. Cellulose is the most abundant natural polymer on the earth, and a significant source of cellulose is wood. Between different types of wood, cellulose content is different [10].

The cellulose chain length depends on the number of glucose units in the chain, referred to as the degree of polymerization (DP) [1]. Wood-derived cellulose typically has DP of 10 000 [3]. The significant physical and mechanical properties of cellulose derive from its long molecular chains. These chains interact with each other through hydrogen bonds and van der Waals forces by forming microfibrils, which are organized into crystalline and amorphous regions. The DP of wood-derived cellulose is significantly reduced to 800-1500 after industrial processing such as pulping and bleaching. [1]

2.1.2 Nanocellulose

Nanocellulose is sustainable and renewable nanomaterial from cellulose. Nanocellulose is obtained by assembling cellulose molecules into parallel stacks. Its combines desired properties of cellulose and nanomaterials. These properties of cellulose include chemical modifiability, biodegradability, and high abundance on Earth. Nanomaterials have properties such as strong mechanical strength and large specific surface area.[1] Nanocellulose average diameter is a few nanometres and length range from 1–100 nm. These materials are used in a different application such as electronic devices and applications in films and sheets. The properties of these materials include sustainability, chemical stability and recyclability. [11,12]

Nanocellulose can be divided into three main categories its structural features: cellulose nanofibrils (CNFs), cellulose nanocrystals (CNCs), and bacterial nanocellulose (BC) [12]. Nanocellulose is divided into these categories based on its extraction methods, size, shape and its cellulose source. CNFs are produced by mechanically breaking up cellulose fibers, separating them from cellulose microfibrils. The fibers used can be either modified (chemically, solvent-treated, or enzymatically) or unmodified. CNFs average size is 5–100 nm. CNCs is primarily derived from plants or other cellulosic biomass. Nanocrystals can be extracted via acid hydrolysis of the cellulosic material using strong acid. In acid hydrolysis, the temperature and acid-cellulosic fiber ratio must be carefully controlled to ensure successful extraction. CNCs average size is 1–20 nm. [11] BC is produced by aerobic bacteria with a 3D micro and nanoporous network structure. This structure provides many important properties such as high purity and crystallinity, and high thermal and mechanical stability. BC average size is 20–100 nm. [10,11]

2.1.3 Cellulose acetate (CA)

Cellulose acetate is a biodegradable natural polymer which is cellulose derivative. It is produced by esterifying cellulose with acetic acid [13]. In the reaction, the hydroxyl groups of cellulose are replaced by acetyl groups. This significantly affects the properties of cellulose, such as processability, thermal properties, and transparency. Cellulose acetate can be used in a wide range of applications due to its versatility and cost-effectiveness. In certain applications, its higher solubility in solvents compared to cellulose is considered an advantageous property. [8]

2.2 Hemisellulose

Hemicellulose is a complex polysaccharide which consist of many different monosaccharide units, making it more structurally diverse and complex than cellulose. These unit are connected to each other by different types of glucose bonds, such as β-1,3- and β-1,4-glucosidic bonds. Hemicellulose form either long-chain or branched polysaccharide structures due to glucose bonds. Hemicellulose and lignin interact with each other, forming an extensive cross-linked network. This network is formed as a result of lignification, during which covalent bonds in lignin cross-link with hemicellulose molecules [4]

Hemicellulose consists of, among other things, xylose, glucose, arabinose, galactose, mannose and galacturonic acid. Structures, concentrations and compositions of hemicellulose vary between different wood species. [6] In hardwood, the DP ranging from

150 to 200, whereas in softwoods it is between 70 and 130. Hemicellulose derived from plant cell walls, where it functions as a structural support material. The irregular and amorphous structure of hemicellulose makes it highly prone to degradation when exposed to heat or acidic conditions. [9]

2.3 Lignin

Lignin is a complex biopolymer derived from plant cell walls. Its chemical structure is more complicated than cellulose and hemicellulose. It is a structural component in the cell wall where it interacts with cellulose and hemicellulose [4]. Lignin is highly branched [4], high-molecular-weight amorphous polymer [9], and it has been shown to form covalent cross-links with many polysaccharides [4].

There are two ways to separate lignin from its source. The first method is the hydrolysis of polysaccharides, and the second method is decomposition of lignin into soluble components. These processes modify the chemical functional groups and properties of lignin. Many factors affect the mechanical properties of lignin, including the DP, temperature, chemical structure, moisture and molecular weight. It can also improve the material’s stretchability and flexibility when it is connected with other polymers. [14]

2.4 Advantages and Limitations

Wood-derived cellulose offers versatile properties that can be utilized in many different applications. Its abundance makes it a cheaper alternative to materials such as plastic, glass, and silicon [1]. The biodegradability, low toxicity, and renewability of cellulose make it an environmentally friendly material [5,13]. Cellulose can also be extracted on an industrial scale, and cellulose-based materials can be produced using low cost methods [1].

Cellulose has a unique structure that improves its good mechanical properties and large surface area [5]. Because of its light weight, the use of this material can reduce the overall weight of products [1]. The structure of cellulose contains both crystalline and amorphous regions. The crystalline regions offer significant tensile strength, and the amorphous regions provide flexibility to material. Hydrogen bonds between adjacent cellulose molecules give more mechanical strength to cellulose [5]. In addition, cellulose is easy to process, which makes it a good choice for various applications [15].

Although cellulose has many good properties, there are also limitations and challenges to its use that need to be considered. Different types of wood contains different amounts of cellulose, which directly affects the amount of cellulose available for use [4]. In addition, challenges have been reported in the controlling structure and surface chemistry of cellulose, which can affect its processing and mechanical properties [1]. The ductile and semicrystalline structure of cellulose complicates or prevents its solubility in of most commonly used solvents. Furthermore, unmodified cellulose can absorb large amounts of water without dissolving. Various methods are required to break down or modify its structure, which may include chemical, physical, or biological methods. Unmodified cellulose cannot be processed in the same way as synthetic polymers for example, controlling the process temperature must be different. [7] Finally, it is challenging to manufacture an electronic device made entirely of cellulose, because cellulose lacks the necessary electrical conductivity. For this reason, cellulose must be combined with other functional materials to achieve electrical conductivity [1].

2.5 Cellulose Extraction and Pre-Treatment Methods

Many techniques have been developed for extracting cellulose from wood, and pretreatment plays an important role in this process. After pretreatment, the material can be further processed into desired product. Cellulose is typically obtained by removing hemicellulose, lignin and other low-molecular-weight compounds from biomass. The methods used may include physical, chemical, biological and physicochemical methods. Table 1 outlines the advantages, disadvantages, and costs of these various methods. However, traditional pretreatment methods are environmentally harmful, which is why more environmentally friendly alternatives have been developed.[16]

Table 1. Various pretreatment and extraction methods for isolating cellulose from wood. [17]

Pretreatment and extraction methods	Advantages	Disadvantages
Physical	Processes are simple and versatile. They reduce particle size and increase surface area.	High energy consumption due to pressure and temperature requirements.
Chemical	Generally high yields. Effectively breaks down lignin and facilitates cellulose extraction.	Acid and alkali treatments have significant environmental impacts. Green solvents can be considerably more expensive.
Biological	Potentially selective and greener degradation of lignin at low pressure and temperature.	Time-consuming process. High cost associated with enzymes or biocatalysts.
Physicochemical	High degree of delignification. Enables extraction of hemicellulose and modified cellulose.	High energy consumption due to extreme temperature and pressure conditions. Less environmentally friendly.

Traditional pretreatment methods are effective for cellulose isolation, but the solvents and processing conditions used make them environmentally harmful. These traditional solvents are acidic or alkaline, with acidic treatments being more commonly used. More environmentally friendly solvent has been developed, such as deep eutectic solvent (DESs), ionic liquid (ILs), and organo-solvent [18]. These solvents are characterized by high efficiency, low toxicity, easy recycling, biodegradability, good stability and low environmental impact. Organic solvents can be used for dissolving cellulose derivatives as well as as swelling agents for the cellulose structure, where they penetrate the fiber structure and disrupt hydrogen bonds. However, the high viscosity of ILs reduces their processability and efficiency. Lower viscosity improves the solution’s ability to access the wood matrix, thereby accelerating lignin removal. Nevertheless, the use of ILs is limited by high production and purification costs, making their industrial-scale impractical. DESs, on the other hand, suffer from limited thermal and electrochemical stability as well as high hygroscopicity. [16,18]

3 Cellulose Materials in Electronics

Cellulose offers useful properties for next-generation biodegradable electronics. Its chemical processability, biodegradability, mechanical strength, and renewability are noteworthy. For example, cellulose-based flexible materials have evolved from simple biodegradable substrates into more integrated and multifunctional electronic substrates [19]. In addition, the potential for industrial production is supported by the low cost and abundant availability of cellulose. The properties of cellulose can be enhanced through chemical and mechanical processes, resulting in improved properties for various electronic applications. [15]

The demand for biodegradable electronics is constantly increasing. To address this, there is a desire to develop biodegradable materials, for example from cellulose. Generally, the materials used in electronics can be divided into three different types, which are mechanical supporting substrate, functional or active component, and adhesive or encapsulant. Mechanical supporting substrate is used as a passive component. A conductor, a semiconductor, or a dielectric material can be used as a functional or active component. In cellulose-based electronics, these roles can potentially be fulfilled by modified cellulose materials. Cellulose is naturally an electrical insulator, but its properties can be modified by adding conductive materials (e.g., conductive polymers, graphite, and nanoparticles), enabling its use in electronic applications. [1]

One advantage of cellulose in electronic applications is that it can be modified to impart desired properties, for example, nanocellulose can be extracted from cellulose, offering a high specific surface area that enables high absorption capacity [9]. In addition, various cellulose derivatives can be used to obtain the desired properties. Cellulose also has good mechanical properties, including lightweight, high toughness, and flexibility, making it suitable for flexible and wearable electronics [3]. Furthermore, cellulose is an environmentally friendly choice for electronics because, under certain conditions, it can be broken down into non-toxic molecules at the end of its life cycle. [1]

The use of cellulose in electronics also presents a few challenges that must be considered before it can be widely adopted on an industrial scale. First, cellulose is sensitive to high temperatures. For this reason, it is not suitable for high-temperature applications. Chemical modification of cellulose can either improve or impair its heat resistance and stability [3]. Secondly, its long-term stability still needs improvement. The key characteristics of electronic devices, such as electrical conductivity, performance management, durability, and biocompatibility must be verifiable in various operating environments [19].

Finally, a key challenge is the moisture sensitivity of cellulose-based materials, meaning they may absorb water and swell. However, water is an essential component of cellulose materials, so it would make sense to utilize it. Water can help increase the toughness and strength of cellulose fibers and facilitate better chemical reactions [20]. Overall, these properties and limitations must be considered when evaluating different applications of cellulose in electronics.

Transparent wood (TW) is an example of the use of wood-derived cellulose in electronic applications. It is a composite material produced by removing or modifying lignin in wood and impregnating the remaining cellulose structure with a transparent polymer. The transparent polymer must have the same refractive index as cellulose so that the difference in refractive index between the air and the cell wall can be rectified. The mechanical properties of TW typically include a tensile strength of up to 500 MPa and an optical transmittance of up to 90%. So, it combines excellent optical and mechanical properties, making it a promising alternative for plastic substrates used in flexible displays, sensors and wearable devices. TW's flexibility enables it use in flexible electronic devices and allows for customized designs. [21]

TW has also been studied for solar cells, thermal energy storage, and energy-efficient technologies. It has a low thermal conductivity of about 0.2 W/m·K, significantly lower than that of indium tin oxide (ITO) glass, which is roughly five times higher. This improves thermal insulation by reducing heat transfer through the material, which can help maintain temperature stability in electronic devices. In addition, TW exhibits superior mechanical properties compared to natural wood, including higher tensile strength, toughness, and stiffness. However, challenges such as high hydrophilicity, chemical consumption during processing, and permeability remain. These issues have been mitigated, for example, using hydrophobic coatings. [22]

4 Applications of Wood-Derived Cellulose in Electronics

Research into the use of wood-derived cellulose has expanded from basic electronic components to more advanced functional devices and systems [1]. Wood-derived cellulose is being investigated for use in flexible sensors, energy storage devices, dielectric materials, additive manufacturing, biodegradable substrates, and optoelectronic devices. These applications aim to provide more sustainable alternatives to conventional fossil-based materials and non-recyclable electronic materials while maintaining the performance required for electronic applications.

4.1 Flexible Sensors

The demand for flexible sensors has increased in recent years. Their use is being studied especially in wearable devices, health monitoring, and human–computer interaction. Sensors are often required to possess stretchability, compressibility, flexibility, and the ability to convert mechanical, biological, and chemical stimuli into electrical signals. Accordingly, they are primarily classified into pressure-strain sensors, chemical coupling sensors, and ion–electronic sensors [15]. Wood-based cellulose could provide an alternative to the soft materials traditionally used in these applications. A major challenge with conventional materials is their ability to simultaneously offer high performance, biocompatibility, and durability. Cellulose possesses significant mechanical performance as well as broad chemical tunability. [19]

4.1.1 Strain Sensor Based on a Conductive Regenerated Cellulose Film

Cellulose can be used to manufacture a conductive regenerated cellulose-based film (CRC film) with stable conductivity. It is produced by encapsulating silver nanowires (AgNWs) between a regenerated cellulose film and poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) nanolayers. Due to its properties, it can be used in the fabrication of flexible hybrid films with stable electrical conductivity. The sensor was assembled by placing a cellulose film between two CRC films. CRC film can be used to produce a strain sensor, as shown in Figure 2. The sensor is flexible, highly transparent, and exhibits excellent responsiveness to signals such as bending and pressing. It remains highly sensitive to mechanical stimuli even after 30 days of exposure to relative humidity levels as high as 90%. [23]

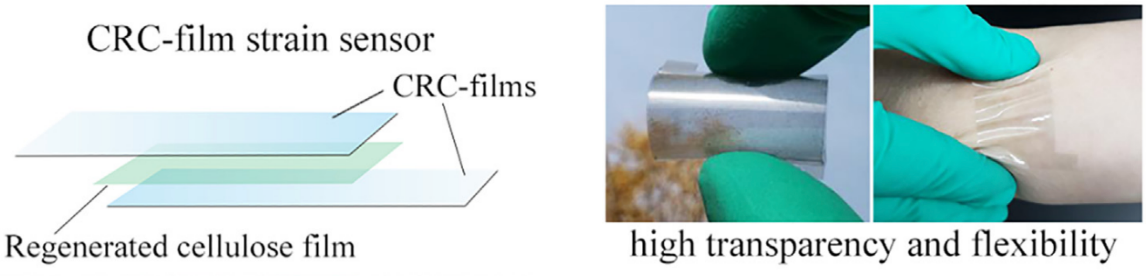

Figure 2. Transparent and flexible CRC-film strain sensor. Image reproduced with permission from [23]. Copyright 2019, Elsevier.

4.1.2 Nanocellulose-Based Hydrogel Sensors

Nanocellulose-based hydrogels can be used in various typer of sensors, including physical sensors, biosensors and chemical sensors. These sensors convert external stimuli detect in the environment into electrical signals or other signal formats, depending on the quantity being measured, such as pressure or strain [12]. Hydrogel is a water-insoluble polymer with a three-dimensional network structure. Nanocellulose-based hydrogel sensors are physically or chemically cross-linked with nanocellulose and functional polymers. It forms a three-dimensional network structure for hydrogel. [12,24]

Physical sensors are mainly used to measure pressure, strain, and temperature. With a sensor, a mechanical change can be converted into an electrical signal. Through the mechanical change, the capacitance or resistance of a material changes, which can be used to determine the magnitude of the change or pressure. Such sensors could be especially utilized in wearable devices and flexible electronics, for example electronic skins (e-skin). [12]

Nanocellulose-based hydrogels combine the high mechanical strength, chemical stability, and processability of nanocellulose with the flexibility and reactivity of the hydrogel matrices. There are also several challenges using nanocellulose-based hydrogels, which are the long-term durability and stability under varying environmental conditions. Secondly, hydrogel sensors need to be made more multifunctional, rather than limited to a single measurement function. For example, a multifunctional sensor could measure humidity, temperature, gases or pH all at the same time. This will enable more reliable and accurate monitoring. Finally, there is the issue of traditional nanocellulose extraction and purification methods, which are time-consuming and complex. More efficient and sustainable solutions need to be found to replace these. [12]

4.2 Energy Storage Devices

The physical and chemical properties of cellulose, combined with its porous, hierarchical pore structure, make it a good material for use in the construction of flexible electrochemical energy storage devices. It can form three-dimensional pore channels that provide many interfaces for charge storage. Cellulose's abundant hydroxyl groups enable efficient transport of ions and electrons and better electrolyte absorption[15]. These properties can be utilized, for example, in supercapacitors and batteries [10,15]. In particular, nanocellulose is a promising option for energy storage applications due to its excellent mechanical and electrochemical properties [10].

Wood-derived cellulose can be used in various roles of flexible energy storage devices. Such roles include electrolyte reservoir, substrate materials, separators, and binders. Additionally, conductive electrodes can be produced from cellulose by carbonizing it, resulting in a highly electrically conductive carbon material [10]. Other conductive electrodes can also be produced in which cellulose is combined with conductive nanoparticles for example. [15]

A supercapacitor is an energy storage device characterized by a long cycle life and high-power density [15]. The use of cellulose-based materials in supercapacitors enables their application in flexible and wearable electronic devices. Cellulose is typically used as a substrate that can be coated with conductive materials such as graphite or conductive polymers. Supercapacitors fabricated using such coated structures have demonstrated high capacitance as well as good mechanical durability. [10]

Supercapacitors made from cellulose paper offer the potential for low raw material costs and structures that are both stable and mechanically flexible. The utilization of cellulose has also been widely studied in flexible batteries. Nanocellulose can be used to produce paper-like structures onto which battery electrode materials can be integrated. In this case, nanocellulose acts as a supporting substrate, enabling the fabrication of paper batteries with low cost, good performance, and flexibility. [10]

Paper batteries can also be fabricated from nanocellulose using a heterogeneous nanofiber mat structure (h-nanomats), in which all battery components are integrated into a single unified structure through a filtration process. This structure enables uniform current distribution and good flexibility. In this configuration, nanocellulose serves as a binder, substrate, and insulating layer between the cathode and anode. However, a key challenge is the high proportion of cellulose in the structure, which may reduce current density. [10]

4.3 Dielectric and Insulating Applications

Cellulose’s insulating properties have been utilized in electronic components for many years. With the advancement of nanotechnology, it has been possible to develop nanocellulose-based materials with significantly improved properties. The use of these materials has expanded to applications in microelectronics, including energy storage, field-effect transistors (FETs), and radio transmission. [25]

Nanocellulose materials can be used as a substrate or dielectric layer in FETs. The fabricated films can be made thin and smooth, which reduces the operating voltage of FET devices and improves their sensitivity. Additionally, cellulose-based materials are well suited for use as insulating layers in various electrodes and capacitors due to their good film-forming properties. In energy technology applications, an important feature is the ability to modify the properties of cellulose-based materials, either through chemical modification or by incorporating insulating materials into them. [25]

Although cellulose and nanocellulose have desirable properties for dielectric applications, their dielectric properties still need to be improved. Attention should be paid to compatibility with other material. In addition, hygroscopicity must be addressed, and the flexibility of cellulose-based composites should be improved. Reducing hygroscopicity can enhance the material’s lifetime as well as its dielectric properties. Improved compatibility can reduce dielectric loss and improve both energy storage density and lifetime. Furthermore, chemical modification of nanocellulose may lead to the formation of larger particles that can aggregate. These larger particles can cause film roughness and create pores, which weaken its dielectric breakdown strength. [25]

4.4 Additive Manufacturing

Additive manufacturing (AM) also known as 3D printing is a process in which three-dimensional structures are built usually layer by layer using digital modes. The most used techniques are fused filament fabrication, direct ink writing and digital light processing. Large-scale extrusion-based AM can be up to approximately 200 times faster than traditional 3D printing. In polymer-based AM, interlayers adhesion strongly influences service life and mechanical strength. [26]

Wood-derived cellulose nanomaterials (CNMs) are particularly well-suited for AM due to their renewability, high aspect ratio, and low density. CNMs can be used in various AM techniques as well as in various electronic applications. However, a challenge is aggregation in the polymer resin, i.e., the tendency to adhere to each other and form clumps, as well as poor compatibility with hydrophobic and thermoplastic polymers.

Cellulose nanofibers (CNFs) and cellulose nanocrystals (CNCs), for example, are used in AM. CNFs have been combined with a conductive polymer to produce conductive foams suitable for printing. Conductive foams can be used to manufacture pressure sensors with excellent shape recovery and pressure sensitivity. CNCs can be used to improve the electrical properties of composites by adding them to the polymer resin. This gives the composite better capacitance and dielectric constant, which are utilized in flexible electronics, such as in dielectric layers or printed capacitors. [26]

4.5 Cellulose Substrates

Substrates made from cellulose meet criteria for biodegradable electronics. These criteria include, for example, biodegradability, mechanical durability, renewability, affordability, and chemical stability. By chemically modifying cellulose or adjusting the structure and composition of a cellulose-based film, it is possible to produce substrates with different mechanical properties or levels of transparency. Their transparency can range from opaque to translucent and their haziness from hazy to clear. Their properties can also range from rigid to soft and foldable. [1]

Opaque and hazy cellulose paper can be produced that is suitable for use in transistors and generators. This cellulose paper is often produced using a papermaking process in which the cellulose fibers are randomly interconnected. On the other hand, transparent and hazy cellulose film can be used in thin solar cells and touch screens. The film is typically made from microscale cellulose fibers, as well as nanocellulose or molecular cellulose. However, one challenge is the high surface roughness, which would need to be smoothed out for use in electronic applications. Transparent and clear cellulose film is ideal for transistors, e-skins, recyclable or disposable solar cells, and touchscreens. These cellulose films are often made from nanocellulose, molecular cellulose or cellulose derivatives. However, all of the above-mentioned substrates still require further research and development compared to conventional materials used in electronics, such as glass, plastics, and silicon. [1]

4.5.1 Biodegradable Printed Circuit Boards

Cellulose is an alternative material for printed circuit boards due to its useful electrical and mechanical properties. It can be used to produce a biodegradable and renewable substrate that could replace traditionally used substrates and reduce electronic waste. Traditionally used substrates are flexible polyimide (PI) or stiff fibre glass (FR-4) substrate. For example, substrates can be made from cellulose acetate or CNF. Cellulose acetate can be used to produce flexible sheets that can be further processed with other biopolymers to achieve better moisture resistance and mechanical strength. CNF can be used to cast transparent, rigid films that can withstand component mounting and manufacturing processes. [13]

4.6 Optoelectronic Devices

The demand for energy-efficient displays, fast communication, and rapid integration and conversion of information into suitable formats is driving the need for more flexible, lightweight, thinner, and multifunctional optoelectronic devices. Optoelectronic devices convert electrical energy into light and vice versa by utilizing the photoelectric properties of semiconductors. These characteristics can be applied in wearable electronics, flexible displays, photodetectors, and flexible lighting. [19]

Cellulose-based composite structures improve the mechanical properties of displays, thereby enhancing foldability and touch sensitivity. The functional groups of cellulose and its hierarchical structure enable bonding with conductive nanomaterials through hydrogen bonding and self-assembly. This results in improved optoelectronic and mechanical stability as well as enhanced conductivity, making cellulose suitable for applications such as flexible diodes, bendable displays, and solar cells. [19]

Cellulose can be used as a substrate in perovskite solar cells (PSCs), replacing traditionally used glass and synthetic polymers (PET/PEN). It is a more environmentally friendly and cost-effective alternative. In addition, it offers better solvent resistance and lower thermal expansion compared to commonly used synthetic polymers. Synthetic polymers typically have a thermal expansion coefficient of 12–122 ppm K^{-1}, whereas cellulose can achieve very low values, down to approximately 0.1 ppm K^{-1}. However, cellulose often requires treatment such as coatings, plasticizers, or cross-linking to make it more suitable for PSC processing. As shown in Figure 2, a cellulose-based PSC can be constructed using an NIP structure. [7]

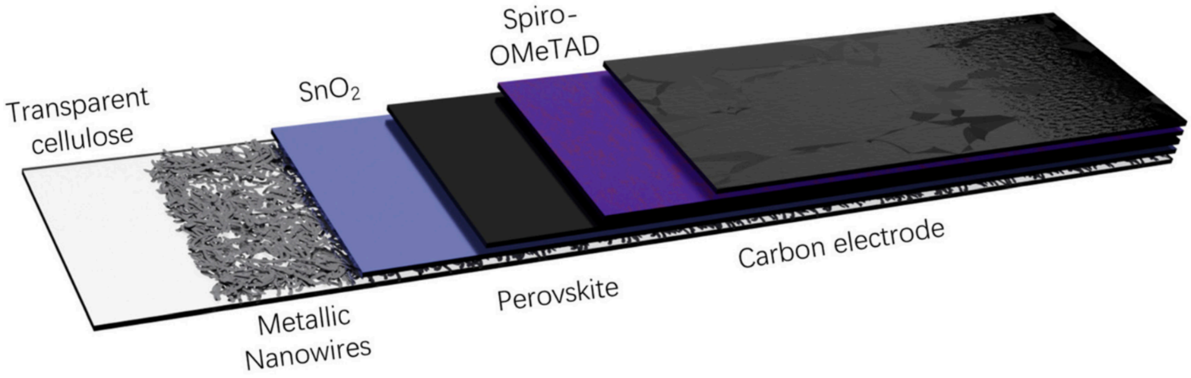

Figure 3. Cellulose-substrate in a PSC. Modified from Valdez García et al. [7]. Copyright 2026, published by Royal Society of Chemistry.

In this structure, the n-type semiconductor is located above the perovskite layer, while the p-type semiconductor is below it. The use of cellulose in PSC production could be scaled up if issues related to moisture sensitivity and oxygen permeability are addressed, for example through surface treatments. [7]

5 Use of Wood-Derived Cellulose in Electronics in Finland

Wood-derived cellulose offers Finland an opportunity to replace the use of fossil-based raw materials in the electronics industry. Its renewability and biodegradability provide solutions to growing sustainability challenges and help reduce the environmental impact of electronic products. In Finland, cellulose has been developed into materials that can replace plastics in electronics, such as transparent films and composite structures for device casing [27]. In this way, cellulose can be used to produce higher value-added products.

Finland's strong position is based on its abundant forest resources and advanced forest industry. More than 75% of the country's land area is covered by forests, and the annual growth of forests is approximately 103 million cubic meters [28]. As a result, there is increasing interest in utilizing the potential of wood-based raw materials as part of electronic products. In addition, major forest industry companies and research institutions in Finland collaborate closely to develop new cellulose-based innovations. According to the Finnish Forest Industries Federation, demand for forest industry products is expected to grow significantly in the coming decades, making such development work economically viable [27].

The utilization of forest industry side streams is a key element in advancing the circular economy in Finland. Side streams refer to material flows generated during production alongside the main product, and their formation cannot be entirely avoided [29]. In 2023, as much as 95% of these side streams were utilized [27]. Their use improves material efficiency and reduces waste generation. Through industrial symbiosis, side streams can also be utilized in the processes of partner companies, ensuring that raw materials are used as efficiently as possible [25].

The use of cellulose has been studied particularly in the field of nanotechnology. Nanocellulose has been used to produce electrically conductive films, which have been tested in flexible displays. Nanocellulose paper, in turn, has been developed into flexible electrodes and sensors. However, a key challenge remains the cost-efficiency of production, which needs to be improved to enable wider adoption of these materials [27].

In the future, wood-based cellulose materials could replace plastics in the electronics, especially in the development of biodegradable and flexible devices. Finland has strong potential to advance this development due to its abundant forest resources, long-standing expertise in the forest industry, and active research environment. As a result, wood-based cellulose can be developed into materials with significant potential in international markets. [27]

6 Conclusions

The use of cellulose derived from wood in future electronics is being studied increasingly. Due to its biodegradability, abundance, and flexibility, it offers promising properties for flexible and wearable electronics. Thanks to its modifiability, its range of applications is broad, and cellulose can be utilized in various electronic components in many ways. In the future, wood-based cellulose could replace the use of synthetic plastics in electronic structures, for example. However, there are still challenges related to its large-scale industrial adoption that need to be solved.

In electronics, the use of wood-derived cellulose is not limited merely to replacing traditionally used materials. It can also add functionality to devices, such as flexibility, lightness, and recyclability. In particular, the utilization of nanocellulose is currently attracting significant interest. Its unique properties, such as a large surface area, light weight, and high strength, enable the development of even lighter and stronger materials for various electronic applications. Wood-derived cellulose materials can be used in many different electronic components. Their use has been tested in flexible substrates, sensors, energy storage devices, and optoelectronic systems. Promising results have been achieved from the use of cellulose materials in flexible substrates.

Although wood-based cellulose has many beneficial and unique properties, its use also involves certain challenges. The most significant challenges are moisture sensitivity, limited heat resistance, and the environmental and cost-related challenges of pretreatment. Production must become cost-effective for cellulose materials to be adopted on a larger scale. In addition, cellulose extraction and pretreatment methods need to shift toward more environmentally friendly alternatives, although alternative methods have fortunately already emerged. Solving these challenges requires further research and technological development. These advances could improve production scalability and material performance.

Finland has strong potential in the utilization and research of wood-derived cellulose. Finland’s strong position is based on its abundant forest resources, advanced forest industry, and growing research activities. These create opportunities to develop flexible and biodegradable devices in the future. Furthermore, utilizing side streams from the forest industry promotes the circular economy and reduces waste generation. However, this also requires strong cooperation between research and industry in Finland, as well as sufficient financial investment in new innovations.

In the future, the popularity of cellulose-based electronic solutions is expected to increase as the transition toward more sustainable and environmentally friendly electronics continues. The modification possibilities of wood-based cellulose, together with nanotechnology and the development of various composite materials, could enable better stability, durability, and conductivity when needed. Combining cellulose with different functional materials, such as conductive polymers, nanoparticles, or graphite, further expands its application possibilities. In addition, the development of manufacturing technologies, such as the use of additive manufacturing, will certainly expand the application areas of cellulose materials considerably.

Wood-derived cellulose could replace traditionally used fossil-based materials, such as plastics, in electronics. However, its wider adoption still involves economic and technical challenges. With continued research and technological development, these challenges can be solved. This could make it possible to manufacture more environmentally friendly, long-lasting, and flexible electronic solutions in the future.

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