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Cellulose: A comprehensive review of its properties and applications

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ABSTRACT

Cellulose is a complex carbohydrate and a fundamental structural element in plant cell walls, consisting of long chains of glucose molecules that form a rigid framework providing strength and support to plants. As the most prevalent natural polymer, cellulose is an ideal candidate for producing environmentally friendly and economically viable polymeric products, traditionally made from petroleum-based synthetic polymers. It is the most abundant renewable material in the biosphere, cost-effective, non-toxic, and biodegradable. Cellulose's physical and chemical properties – such as its insolubility in water, semi-crystalline structure, high tensile strength, biodegradability, and chemical reactivity – make it an incredibly versatile material. Recent studies have demonstrated its promising applications in various industries, including biofuels, bioplastics, and eco-conscious packaging. Specifically, cellulose acetate has emerged as a widely used derivative due to its biodegradable nature and versatility in applications like 3D printing, medical supplies, and environmentally friendly packaging. However, challenges related to extraction costs, property variability, and competition with synthetic materials still exist. Future research will aim to overcome these barriers by enhancing the properties of cellulose, improving processing technologies, and exploring nanocellulose and genetically modified plants as key areas for innovation. Innovations in cellulose recycling and the use of agricultural waste for biofuels are expected to further drive its integration into circular economy models, fostering environmental benefits and reducing overall impact.

1. Introduction

Cellulose is a complex polysaccharide and the primary structural component of plant cell walls. It is the most abundant organic polymer on Earth [1,2], making up a significant part of the dry weight of plants, especially in wood, cotton, and other fibrous plant materials. As a biopolymer, cellulose plays a crucial role in providing structural integrity and rigidity to plants, helping them maintain their shape and resist mechanical stress [3].

Cellulose can be derived from a range of sources, including plants, bacteria, and algae [4]. Cellulose was used in paper manufacturing in China by Cai Lun around 105 AD, but it wasn't until 1838 that it was isolated and identified as a substance by the French chemist Anselme Payen, who determined its chemical formula ($C_6H_{10}O_5$) [5].

In recent years, cellulose has gained more interest due to its biocompatibility, biodegradability, economic value, high mechanical properties, large surface area, nontoxicity, and renewability, making it an environmentally friendly alternative to synthetic materials in many applications [6,7]. However, its high crystallinity also renders it insoluble in water and many organic solvents due to the presence of intramolecular and intermolecular hydrogen bonds [8–10].

As shown in Fig. 1, cellulose is made up of long chains of β-D-glucose molecules connected by β(1→4) glycosidic bonds, with hydroxyl groups at the C2, C3, and C6 positions [6,11]. Its chemical formula is $(C_6H_{10}O_5)_n$, with the C4-OH group acting as the non-reducing end and the C1-OH group as the terminating end [12]. These individual glucose units are called cellobiose, and the polymer chain can be very long, consisting of hundreds to thousands of glucose units [13]. Four different types of cellulose crystallinity have been identified and are classified as Type I, II, III, and IV. The structure of cellulose is highly ordered, with each glucose unit rotated 180 degrees relative to the previous one, allowing the formation of a linear, straight chain [1,12]. These long chains are aligned in parallel to each other, forming microfibrils, which are bundles of cellulose molecules held together by hydrogen bonds. These microfibrils are organized into larger structures and contribute to cellulose's high strength and rigidity [14].

The crystalline regions of cellulose are highly ordered, providing significant tensile strength, while the amorphous regions (less ordered) allow some flexibility. The structure of cellulose is stabilized by hydrogen bonds between adjacent cellulose molecules, which helps

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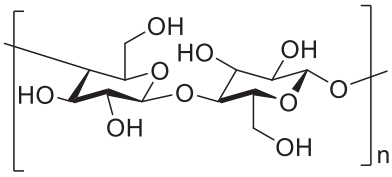


Fig. 1. Chemical structure of cellulose.

form strong, rigid fibers that contribute to cellulose's mechanical strength [15].

Cellulose is semi-crystalline, meaning it contains both crystalline and amorphous regions. The crystalline regions, where the cellulose chains are tightly packed, give it its strength and resistance to degradation, while the amorphous regions, which are less organized, allow for easier chemical modification and interaction with solvents. This unique structure gives cellulose a combination of mechanical strength and chemical stability, making it a highly versatile and useful material in both natural and industrial applications [16].

Cellulose is the primary component of lignocellulosic plant cell walls, Fig. 2. Hemicellulose, lignin, and other carbohydrate polymers, as well as pectin, protein, wax, ash, tannins, and inorganic salts, are components of a gel matrix embedded with cellulose, which exists in lignocellulosic materials [17,18].

In nature, plant cells are composed of two walls: the primary and the secondary walls and by the middle lamella. The primary wall contains hemicellulose, pectins, and proteins; on the other hand, the secondary wall contains the same constituents but is richer in cellulose and also contains lignin. Cellulose combines with hemicellulose and lignin to form various elongated cells with a central channel called the lumen, responsible for the transportation of nutrients and water [19–21].

Natural fibers are composed of a variety of organic compounds, primarily cellulose, hemicellulose, lignin, proteins, and other minor components [22].

These fibers are low-cost, lightweight, renewable, and readily available materials, with cellulose-based fibers being abundant sources of biomass on the planet. They come in various forms depending on the plant source, such as bamboo, cotton, flax, hemp, jute, ramie, sisal, and hold significant economic importance in certain countries [18,20,23]. The exact composition of these fibers varies depending on the source, age, species, climatic conditions, influencing their properties such as strength, flexibility, moisture absorption, and biodegradability. Understanding the chemical composition of natural fibers is crucial for optimizing their processing and expanding their applications across industries such as textiles, construction, and bioplastics [14,20,24].

Cotton, the purest form of cellulose, is hydrophilic, highly elastic, flexible, and exhibits high elongation at break. It is the dominant natural fiber in the textile industry, with an annual global production of around

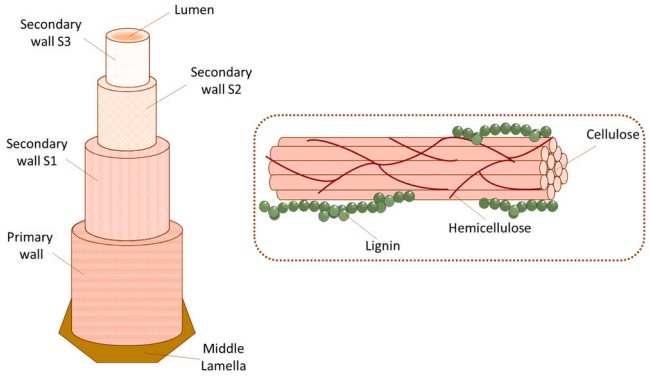


Fig. 2. Schematic representation of the plant cell wall, illustrating its various components, adapted from ref. [20].

25 million tons. Cotton fibers are composed of 90 % cellulose, making them lightweight, soft, and highly absorbent. In comparison, wood contains 40–50 % cellulose, and dried hemp contains approximately 57 % [25,26]. Other plants, such as bamboo, hemp, and flax, also have high cellulose content. Table 1 provides an overview of the chemical composition of some commonly used natural fibers.

Despite cellulose's well-established role in various industries, significant challenges remain regarding the efficient use of cellulose and its derivatives, such as cellulose acetate, in emerging technologies. These challenges involve optimizing their properties for specific applications, as well as exploring environmentally friendly and cost-effective production and modification methods. Additionally, while cellulose-based materials show great promise in sectors like bioplastics, pharmaceuticals, and eco-conscious packaging, there is still a limited understanding of their full range of properties and applications. Addressing these challenges, the current work aims to bridge the gaps in understanding the fundamental properties of cellulose, explore its diverse applications, and offer insights into how cellulose derivatives can stimulate innovation across various industries.

Given these challenges, this review seeks to bridge the existing knowledge gaps in understanding the fundamental properties of cellulose. By examining its chemical, physical, and mechanical traits, we aim to identify the barriers hindering its broader industrial adoption, particularly in emerging fields such as bioplastics, biofuels, and eco-friendly packaging. Furthermore, we will explore how cellulose derivatives, including cellulose acetate, can foster technological innovation and help address key sustainability issues in today's world.

This study aims to provide a comparative analysis of cellulose derivatives, emphasizing their mechanical properties, biodegradability, and industrial feasibility. It also examines the increasing significance of cellulose-based materials in the circular economy and sustainable development. Additionally, we will explore both current industrial applications and emerging trends that could transform global industries.

2. Properties of cellulose

Cellulose is a versatile biopolymer with a wide range of physical, chemical, and optical properties that make it suitable for various applications across multiple industries.

2.1. Physical properties

Cellulose is insoluble in water due to its crystalline structure and strong hydrogen bonds between chains, which prevent water molecules from breaking them apart. It is semi-crystalline, with ordered (crystalline) regions providing mechanical strength and resistance to degradation, while disordered (amorphous) regions are more accessible for modifications [16]. The crystalline structure gives cellulose high tensile strength, making it resistant to hydrolysis and ideal for plant structural integrity. The thermal stability of cellulose exhibits a single peak at 355 °C [2]. Its fibrous structure offers both rigidity and some flexibility, balancing strength and growth. Cellulose is also opaque in fiber or film form, making it suitable for paper and other opaque materials.

2.2. Chemical properties

Cellulose is highly reactive due to its hydroxyl (-OH) groups, allowing for chemical modifications like cellulose acetate, carboxymethyl cellulose and methylcellulose, for example. The irreversible reaction always occurs at the hydroxyl group on C2, while the reversible reaction primarily occurs at the hydroxyl group on C6 [1,33]. It can be broken down by acid hydrolysis, which cleaves the β(1→4) glycosidic bonds between glucose units, producing glucose or bioethanol [34]. Cellulose is biodegradable, easily degraded by microorganisms, making it environmentally friendly compared to synthetic polymers. It is chemically stable under normal conditions but can degrade under

Table 1
Some natural fibers' chemical composition.

Fiber	Cellulose (wt%)	Hemicellulose (wt%)	Lignin (wt%)	Pectin (wt%)	Wax (wt%)	Ref.
Bamboo	22.8–65	16–43.8	5–31	1–5	–	[14,16,19,20,22,27,28]
Banana	60–67.6	10–24	5–17.5	4	–	[14,19,24,27,29,30]
Cotton	80–95	3–20	< 2	0.1–6.0	0.6	[14,22,24,27,30,31]
Flax	61–82	10–21	1–8	1.8–2.3	1.5–1.7	[14,19,22,24,27,31,32]
Hemp	57–81	7.9–23	2.5–13	0.5–0.9	0.8	[14,19,20,22,24,27,31,32]
Jute	59–73.2	12–22.1	5–16	0.2–0.5	0.5	[14,19,20,22,24,27,31,32]
PALF	66.2–83	12–24	4.28–12.7	4	–	[14,19,24,27,30]
Ramie	61.85–91	3–16.7	0.5–9.06	1.9	0.3	[14,19,20,24,27]
Sisal	47–78	10–38.2	7–14	0.5–10	2	[14,19,20,22,24,27,31]

extreme conditions, particularly in acidic or alkaline environments. Cellulose reacts with alkalis, especially sodium hydroxide, which increases its reactivity. Although not highly flammable, cellulose can combust at high temperatures [35–37].

2.3. Optical properties

Cellulose can be transparent in thin films or fibers, especially in regenerated forms like cellophane, due to the alignment of its fibers. Its polar nature, caused by hydroxyl groups, allows it to interact with polar substances, enabling it to form gels, absorb water, and interact with other chemicals [38–40]. The optical properties of cellulose are known to be especially responsive to environmental factors such as humidity, pH, temperature, and more, making it highly suitable for luminescent sensing applications [41,42].

3. Potential applications

Cellulose materials and their derivatives are increasingly being used in various applications, including the medical and pharmaceutical industry, such as wound dressings, drug delivery, and tablet binders; the paper and pulp industry; biofuels; and bioplastics. They are also being explored in other industries like textiles, adhesives, coatings, food, and biodegradable products [2,7,13,43].

Cellulose can be combined with other materials, primarily biopolymers, to form a variety of composites with diverse applications in everyday life. Its abundance, biodegradability, and renewability make it an ideal choice for producing environmentally friendly materials [44].

Cellulose has a wide range of applications across various industries due to its unique properties. These applications demonstrate cellulose's versatility and importance, particularly in the push for more sustainable practices. Some key applications include biofuels, bioplastics, construction, cosmetics and personal care (such as lotions, creams, and shampoos, where it functions as a thickener, stabilizer, and emulsifier), the food industry, nanocellulose, the paper and pulp industry, pharmaceuticals (in tablet and capsule formulation as a binder and filler), sustainable packaging, and textiles (including cotton, linen, and rayon) [45–47].

Thanks to its unique properties, cellulose is used across numerous industries, highlighting its versatility and crucial role in promoting eco-friendly practices. Key applications include biofuels, bioplastics, construction, cosmetics (e.g., lotions, creams, shampoos as a thickener, stabilizer, and emulsifier), the food industry, nanocellulose, paper and pulp, pharmaceuticals (as a binder and filler in tablet and capsule formulation), eco-conscious packaging, and textiles (e.g., cotton, linen, rayon) [45–47].

4. Cellulose derivatives

The following table (Table 2) provides an overview of various cellulose derivatives, highlighting their key characteristics and common applications across different industries [4,48–50].

One of the most widely used cellulose derivatives is cellulose acetate, which is formed by esterifying cellulose with acetic acid or acetic anhydride. This versatile material is commonly used in the production of photographic films, coatings, and fibers for textiles and clothing.

4.1. Cellulose acetate

Cellulose acetate (CA) is one of the most important cellulose derivatives due to its wide range of applications and versatile properties [51]. First synthesized in 1865 by Schutzenberger, CA is a thermoplastic polymer known for its biodegradability [4].

In addition, it is an important regenerated cellulose fiber used in the textile industry, produced by acetylating cellulose with acetic anhydride or acetic acid, in the presence of sulfuric acid [52]. The structure of CA is shown in Fig. 3.

CA is a natural polymer that is biodegradable, environmentally benign, nontoxic, and offers design versatility [53–55]. Also, CA, a soft and flexible fiber, typically breaks down over a period of months to a few years, with the rate of degradation decreasing as the degree of substitution (DS) increases, according to the following order: triacetate, diacetate, and monoacetate (the number of acetyl groups substituting the hydroxyl groups on the glucosidic units of cellulose) [56,57].

It exhibits a wide range of degrees of substitution (DS) due to its strong solubility in common solvents and their molecular weights. CA with a DS greater than 0.8 is soluble in acetic acid; when the DS ranges from 2.0 to 2.5, CA dissolves in acetone, dioxane and methyl acetate. More highly acetylated forms of CA are soluble in dichloromethane [55].

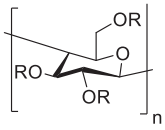
CA is one of the most widely used polymeric materials for preparing membranes using the phase inversion technique [58]. Fig. 4 presents the physical properties of CA [59].

It is a semi-synthetic polymer with a variety of applications due to its favourable properties, as shown in Fig. 5. Here are some key points about CA: (1) It is more environmentally friendly than many synthetic plastics; (2) it can create flexible, strong films, making it ideal for various coating and packaging applications; (3) it exhibits good thermal stability, allowing it to withstand higher temperatures during processing; (4) it can be produced in a transparent form, making it suitable for applications that require visibility [49,60,61].

CA has a wide range of applications across various industries due to its unique properties, as shown in Fig. 6. Here are some key applications: (1) increasingly explored as a material for 3D printing due to its good mechanical properties; (2) used in coatings for various surfaces, including wood, metal, and paper, providing protection and enhancing appearance; (3) found in medical supplies, such as surgical sutures and membranes, due to its biocompatibility; (4) employed in biodegradable films and food packaging, offering an eco-friendly alternative to conventional plastics; (5) historically used in photographic and X-ray films due to its stability and transparency; (6) commonly used in filter tips for cigarettes, helping to reduce the inhalation of harmful substances; (7) used as a fiber in clothing and upholstery, known for its silk-like feel and often blended with other fibers [62–71].

Overall, cellulose acetate is a versatile and environmentally friendly

Table 2
Classification and chemical structure of cellulose derivatives.

Derivative		Description
Carboxymethyl Cellulose	R = H or CH_2COOH	A water-soluble cellulose derivative commonly used as a thickener, stabilizer, and emulsifier in various products, including food, pharmaceuticals, cosmetics, and paper.
Carboxymethyl Hydroxyethylcellulose	R = H or CH_2CH_2OH, CH_2COOH	A derivative used in personal care products, pharmaceuticals, and food products, known for its ability to increase viscosity and stabilize emulsions.
Cellulose Acetate	R = H or $COCH_3$	Formed by esterifying cellulose with acetic acid or acetic anhydride. It is used in the production of photographic films, coatings, and fibers for textiles and clothing.
Cellulose Nitrate	R = H or NO_2	Formed by nitrating cellulose, primarily used in the production of explosives and the creation of films and coatings, although it has been largely replaced by other materials in certain applications.
Ethyl cellulose	R = H or CH_2CH_3	A non-water-soluble cellulose derivative commonly used in pharmaceutical coatings, adhesives, and as a binder in tablet formulations, as well as a thickening agent in the food industry.
Hydroxyethyl cellulose	R = H or CH_2CH_2OH	A water-soluble derivative used in personal care products (such as shampoos and lotions), pharmaceuticals, and as a thickening agent in paints and coatings.
Hydroxypropyl Methylcellulose	R = H or CH_3 or $CH_2CH(OH)CH_3$	Used in pharmaceuticals as a binder and controlled-release agent for tablets, as well as in construction materials like cement and plaster, and in cosmetics.
Methylcellulose	R = H or CH_3	A derivative created by reacting cellulose with methyl groups, commonly used as a thickener in food products, a binder and stabilizer in pharmaceuticals, and for its water retention properties in construction materials like cement.

alternative to many traditional materials, with a wide range of potential applications. Ongoing research may uncover new uses in biomedicine, packaging, and other fields, especially as technology advances [61].

5. Circular economy of cellulose

The circular economy of cellulose is a regenerative model that aims to maximize the value of cellulose, one of the most abundant natural

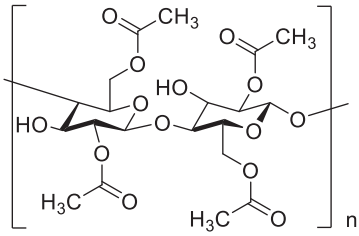


Fig. 3. Chemical structure of cellulose acetate.

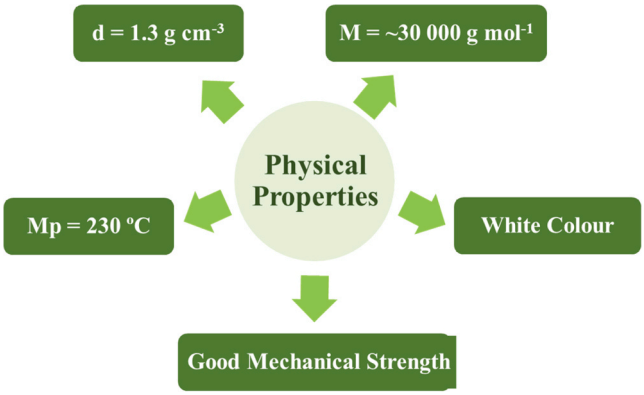


Fig. 4. Physical properties of CA.

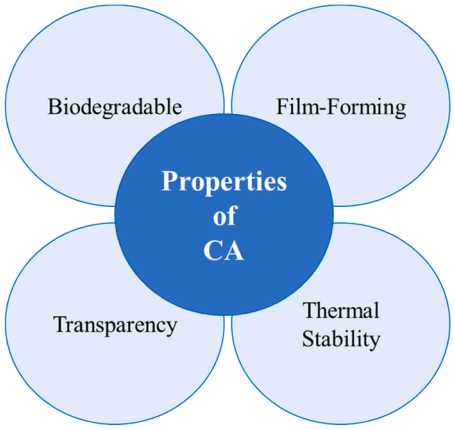


Fig. 5. Key properties of cellulase acetate (CA).

resources, by ensuring its continuous use and regeneration [72]. The core idea is to create a closed-loop system where materials are constantly made, maintained, repaired, reused, redistributed, and recycled, minimizing waste and the depletion of natural resources, as shown in Fig. 7 [73]. This approach emphasizes the responsible use of cellulose-based materials, promoting a system in which products made from cellulose can be repurposed, maintained, repaired, or biodegraded rather than contributing to waste [13].

The cycle begins with make, where cellulose-based products such as paper, textiles, and packaging are initially created. In the circular economy, manufacturing focuses on producing durable, high-quality products that are designed to last and can be easily reused or recycled at the end of their life. This ensures that the materials can fit seamlessly into the cycle, contributing to a more efficient system [49,74].

Once products are made, the next step is maintain. Proper maintenance is essential to extend the life of cellulose products. Instead of discarding damaged items, maintenance practices such as proper care, cleaning, and storage help preserve their condition, allowing them to

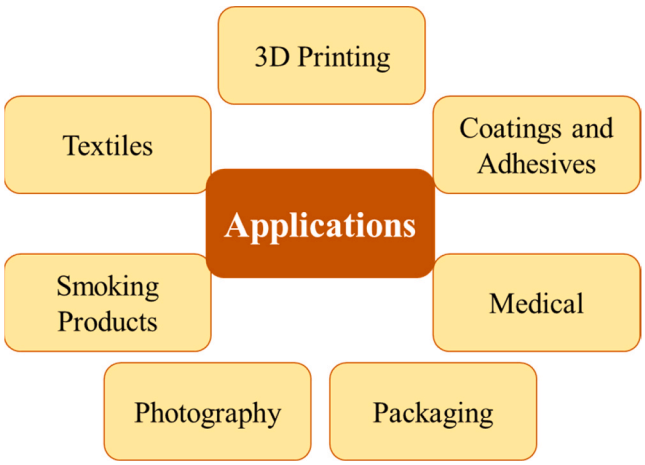


Fig. 6. Applications of cellulose acetate.

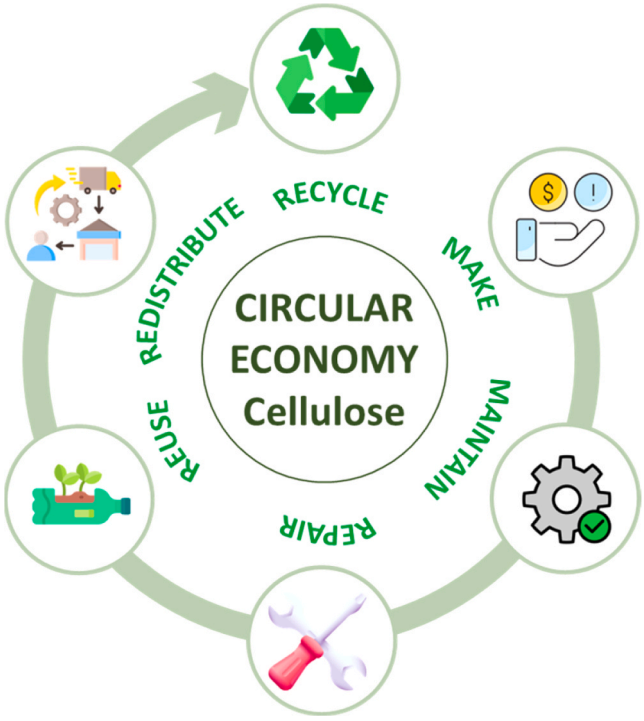


Fig. 7. Circular economy of cellulose.

continue to be useful for a longer period before any repairs are needed or before they are recycled.

If products become damaged despite maintenance, repair becomes crucial. Techniques such as mending fabrics, gluing paper, or fixing other cellulose-based materials give products a second life. Repair not only prolongs the life of products but also helps reduce waste and the need for new resources, contributing to a more resource-efficient economy.

As products are repaired and maintained, they can be reused in different ways. Reuse involves giving products or materials a second life, either in their original form or by repurposing them for new uses. For example, packaging can be reused for different items, textiles can be worn longer, and paper can be repurposed for crafts or other purposes. Reusing products minimizes waste and maximizes the value of materials, reducing the demand for new resources.

Another key aspect of the circular economy is redistribute. This step involves circulating cellulose products to new users or markets, often through second-hand sales, donations, or reprocessing. Redistribution promotes resource sharing and ensures that products and materials are utilized more efficiently, further extending their life and value.

Finally, when products can no longer be reused or repaired, they enter the recycling phase. At this stage, cellulose-based materials are collected, cleaned, and processed to create new products. Recycling reduces the need for virgin raw materials, lowers waste, and ensures that valuable resources are kept within the economy, contributing to a more regenerative system.

By following these steps – make, maintain, repair, reuse, redistribute, and recycle – the circular economy of cellulose promotes a continuous cycle that reduces waste, conserves resources, and minimizes environmental impact. This closed-loop approach ensures that cellulose materials remain in circulation for as long as possible, supporting a more efficient, resource-conserving and regenerative economy [75].

6. Future of cellulose

The future of cellulose looks promising, especially with the increasing global focus on sustainability and eco-friendly materials. Cellulose, derived from a variety of sources, can be reassembled into diverse bulk materials, such as aerogels, fibers, films, hydrogels, and membranes. Additionally, it can be combined with other materials to form composites, expanding its potential applications [7].

Emerging applications of cellulose - especially in competing with plastics for primary packaging, textiles, and other value-added materials - face challenges related to property variability, long-term durability, and high production costs. Despite these hurdles, innovations in processing methods, material design, and functionalization are expected to enhance its performance and versatility [76]. However, further research is needed to develop more efficient functionalization techniques to improve cellulose's properties for specific applications, particularly in the realm of high-performance materials.

Cellulose fits well into the circular economy model, where materials are reused, recycled, or composted. Its biodegradability and renewability make it an excellent candidate for reducing environmental impact. Despite its potential, several challenges persist, including high extraction and processing costs, raw material variability, and competition with synthetic alternatives. Technological limitations particularly in nanocellulose production, also hinder its widespread commercialization. For example, methods for scaling up nanocellulose production and improving its properties for use in industrial applications remain areas that need significant development. Addressing these gaps will require continued innovation in processing technologies and sustainable sourcing practices.

Overcoming these barriers will require continued innovation in processing technologies, sustainable sourcing practices, and the development of cost-effective, high-performance cellulose-based materials. Increasing the recycling of cellulose-based products and converting cellulose from agricultural waste and other biomass into biofuels could reduce waste, promote resource efficiency, and decrease dependence on fossil fuels [77,78]. When sourced sustainably, cellulose also contributes to carbon sequestration, helping mitigate climate change and enhance energy sustainability [79]. Furthermore, advancements in biotechnology could enable the development of genetically modified plants that produce higher yields of cellulose or forms that are more easily digested by microorganisms, potentially boosting biofuel production.

The development of nanocellulose, derived from cellulose at the nanoscale, is an exciting area of research. Its strength, lightweight properties, and biodegradability make it suitable for use in composites, electronics, and advanced materials [80]. Advances in biotechnology may also lead to genetically modified plants that produce higher yields of cellulose or more easily digestible forms, potentially improving biofuel production and other cellulose-based applications [48]. Cellulose-derived materials are also gaining attention in biodegradable coatings and films, particularly those that are both renewable and

appeal to environmentally conscious consumers [7]. The future outlook for cellulose will thus be shaped by breakthroughs in biotechnology, new production techniques, and functionalization strategies that enhance its use in emerging technologies.

In summary, the future of cellulose is driven by technological innovation, sustainability goals, and growing consumer demand for environmentally friendly products. Research trends and opportunities span a wide range of industries, including bioplastics, biofuels, pharmaceuticals, and electronics. Innovations in production methods, material properties, and functionalization will continue to unlock new applications for cellulose, positioning it as a critical material in the transition to a more sustainable and eco-friendly future.

7. Conclusions

Cellulose, linear chains of β-D-glucose units connected by β(1→4) glycosidic bonds, is the most abundant organic polymer on Earth and a critical component of plant cell walls. It serves a fundamental role in providing structural integrity and is crucial for the growth and sustainability of plants.

In addition, cellulose is a renewable and biodegradable material, making it a prime candidate for applications aimed at reducing environmental impact. It is abundant in plant biomass, especially in materials like cotton (90 % cellulose), wood (40–50 %), and hemp (57 %). As the global demand for eco-friendly alternatives increases, cellulose offers an environmentally responsible solution across various sectors, from packaging and bioplastics to biofuels and medical applications. Cellulose can be transformed into various forms, such as nanocellulose, fibers, films, and hydrogels, increasing its versatility across industries ranging from packaging and bioplastics to biofuels and medical applications or sustainable textiles. This transformation into different forms further enhances its application potential, contributing to its growing importance in technological innovations and green alternatives.

Cellulose is a highly recyclable material, making it a valuable component in the circular economy. As a natural polymer, it can be reused in various applications, helping to minimize waste and reduce environmental impact. Its recyclability, combined with its renewability, makes cellulose a key material for a resource-efficient future. Additionally, cellulose, which is broken down by many microorganisms, is a major component of natural fibers, contributing to their ease of recycling and environmental sustainability.

CRediT authorship contribution statement

Elina Marinho: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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