Advances in Bioresearch
Adv. Biores., Vol 16 (6) November 2025: 320-301
©2025 Society of Education, India
Print ISSN 0976-4585; Online ISSN 2277-1573
Journal's URL:http://www.soeagra.com/abr.html
CODEN: ABRDC3
DOI: 10.15515/abr.0976-4585.16.6.320330

Advances in Bioresearch

REVIEW ARTICLE

Advances In Cellulose Extraction from Agro-Waste: A Focus on Corn Cob

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ABSTRACT
Cellulose, the most abundant natural polymer on Earth, is renewable, biodegradable, and non-toxic, making it a cornerstone in sustainable materials science. The world generates an estimated 180 billion tons of cellulose annually in nature, making it the most abundant biopolymer on Earth. This review presents a focused overview of recent advances in cellulose extraction from agro-waste, with particular emphasis on corn cobs. It examines the potential of corn cob as a rich, underutilized source of cellulose and evaluates various extraction methods, including chemical, mechanical, and green techniques. Special attention is given to extraction yield and the purity of cellulose obtained, as these are critical factors in determining the suitability of cellulose for further applications.The review also highlights the potential of cellulose derived from corn cob for use in sustainable packaging and related fields. For instance, alkaline extraction methods have achieved cellulose yields of up to 38.18% (w/w) from corn cobs. Ultrasound-assisted alkali extraction has resulted in yields of 0.445 g of cellulose per gram of corn cob. Furthermore, the production of nanocrystalline cellulose (NCC) from corn cobs has yielded crystallinities ranging from 50.07% to 65.33%. Despite promising developments, challenges such as process optimization, cost-effectiveness, and scalability persist. Future research should prioritize eco-friendly, high-yield extraction methods and explore innovative applications of purified cellulose to advance sustainable material solutions.

***Keywords** : Cellulose, Biopolymers, Nanocellulose, Sustainability, Biomedical Applications, Packaging, Extraction Methods*

Received 24.08.2025 Revised 12.10.2023 Accepted 23.11.2025

How to cite this article:
Abhijna S, Chaitradeepa G, KN Hanumantharaju, Poornima D, Madhusudhan N and Chennapa G. Advances in Cellulose Extraction from Agro Waste: A Focus on Corn Cob. Adv. Biores. Vol 16 [6] November 2025. 320-330

INTRODUCTION

Background and Significance

The global shift toward sustainable and eco-friendly materials has intensified the search for alternatives to conventional synthetic packaging, which contributes significantly to environmental pollution. Biopolymers, particularly those derived from polysaccharides like cellulose and starch, have emerged as promising candidates due to their biodegradability, renewability, and non-toxicity. Cellulose, the most abundant natural polymer, and starch, a widely available carbohydrate, offer unique properties that make them ideal for developing innovative packaging solutions. Recent advancements in edible films, coatings, and biodegradable packaging materials have demonstrated the potential of these biopolymers to enhance food shelf life, reduce waste, and minimize environmental impact. However, despite their potential, challenges such as scalability, mechanical strength, and cost-effectiveness remain, creating a gap in the commercialization of cellulose-based biopolymers. This review explores the integration of cellulose with other polysaccharides like starch to address these limitations and unlock their full potential in sustainable packaging.

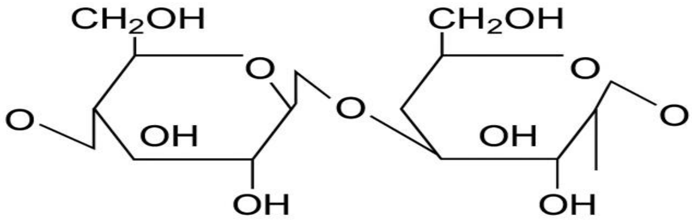

Figure 1: Molecular structure of cellulose

Objective And Scope

The primary objective of this review is to explore the development and application of cellulose-based biopolymers in sustainable packaging, with a particular focus on their integration with other polysaccharides such as starch. This review aims to evaluate the physical, mechanical, and antimicrobial properties of cellulose and starch-based packaging materials while highlighting recent advancements in edible films, coatings, and biodegradable packaging. Additionally, it seeks to identify gaps in current research, including challenges related to scalability, cost-effectiveness, and performance optimization. Furthermore, the review proposes future directions for the commercialization of cellulose-based biopolymers in the packaging industry, emphasizing their potential for sustainable and practical applications. This review focuses on the use of cellulose and starch as primary polysaccharides for developing sustainable packaging materials. It explores the role of cellulose and starch in creating edible films, coatings, and biodegradable packaging, [1,2,3,4,5]. The review also examines the synergistic effects of combining cellulose with starch to enhance mechanical strength, barrier properties, and biodegradability [6,7,8]. Additionally, it discusses innovative applications such as heat-induced edible paper, electrostatic spray coatings, and antimicrobial packaging using plant-based extracts[7]. Furthermore, the review identifies key challenges, including scalability, cost, and performance optimization, that must be addressed to bridge the gap between research and commercialization [9]. Cellulose is the focal point of this review due to its abundance, renewability, and versatility in packaging applications. However, several challenges remain in scaling up its use. High production costs and energy-intensive processes hinder the industrial feasibility of cellulose-based packaging [9,5]. While cellulose is biodegradable, its mechanical strength and barrier properties often require enhancement through blending with other polysaccharides like starch [8]. The cost-effectiveness of these materials also remains a significant barrier, as their production is typically more expensive than synthetic alternatives [6,7]. Additionally, there is limited research on the synergistic effects of combining cellulose with starch and other polysaccharides to optimize their performance and functionality [4]. By addressing these gaps, this review aims to provide a comprehensive understanding of cellulose-based biopolymers and their potential to drive sustainable innovations in packaging, paving the way for greener, more cost-effective solutions.

EXTRACTION AND PURIFICATION

Extraction and purification of cellulose involve isolating cellulose from lignocellulosic biomass by removing non-cellulosic components like hemicellulose and lignin. Common extraction methods include chemical, mechanical, and green techniques. These methods aim to obtain high-purity cellulose suitable for further applications.

Alkaline Treatment Of Cellulose

Alkaline treatment is a widely used method to modify the structural and mechanical properties of cellulose by removing impurities such as lignin and hemicellulose while increasing crystallinity and accessibility. Alkaline treatment enhances the mechanical strength of bacterial cellulose by increasing hydrogen bonding and fibril alignment [11]. Similarly, optimized alkaline treatment parameters for apple pomace-derived cellulose, showing that controlled NaOH concentration and temperature improve cellulose purity and nanocrystal yield [12]. Additionally, the alkaline pretreatment alters cellulose accessibility by disrupting the hydrogen-bonding network, thereby increasing enzymatic digestibility [10]. These studies collectively indicate that alkaline treatment is a crucial step in cellulose processing, improving its suitability for applications in biocomposites, nanocellulose production, and biofuel conversion .

Acid Hydrolysis of Cellulose

Acid hydrolysis is a key chemical method for breaking down cellulose into glucose and other fermentable sugars by cleaving β-1,4-glycosidic bonds under acidic conditions. The mechanisms of acid hydrolysis, highlighting how factors such as acid concentration, temperature, and reaction time influence cellulose degradation [14]. Further demonstrated that the presence of hemicellulose and lignin can hinder hydrolysis efficiency by physically blocking cellulose accessibility or forming inhibitory byproducts [15]. In the context of bioethanol production, the optimized dilute-acid hydrolysis for sugarcane bagasse, showing that controlled sulfuric acid concentrations and moderate temperatures maximize glucose yield while minimizing degradation products like furfural [13].

Microwave-Assited Extraction Of Cellulose

Microwave-assisted extraction (MAE) is an efficient and rapid method for isolating cellulose from lignocellulosic biomass, offering advantages such as reduced processing time and enhanced yield compared to conventional techniques. The successful extraction of cellulose from corn husk (*Zea mays L*) using MAE, highlighting its effectiveness in breaking down lignin and hemicellulose while preserving cellulose integrity [17]. Similarly, the optimized MAE for corncob cellulose extraction, showing that microwave-assisted chemical treatments significantly improve fiber separation and purity while minimizing energy consumption [16]. These studies indicate that MAE is a promising green technology for cellulose extraction, with potential applications in biodegradable materials, food packaging, and nanocomposites.

Ultrasound-Assisted Extraction of Cellulose

Ultrasound-assisted extraction (UAE) is an emerging green technique for isolating cellulose from lignocellulosic biomass, leveraging cavitation effects to enhance efficiency and reduce processing time. The ultrasonic treatment significantly improves cellulose extraction from corn husk, leading to high-purity cellulose suitable for bionanocomposites with enhanced drug adsorption capabilities [18]. Earlier studies showed that ultrasound effectively disrupts the lignocellulosic matrix, increasing hemicellulose extractability while preserving cellulose structure [19]. The ultrasonic pretreatment modifies the physicochemical properties of corn biomass, improving enzymatic digestibility and thermal stability. [20]. These studies collectively suggest that UAE is a sustainable and efficient method for cellulose extraction, with applications in pharmaceuticals, biocomposites, and biorefineries .

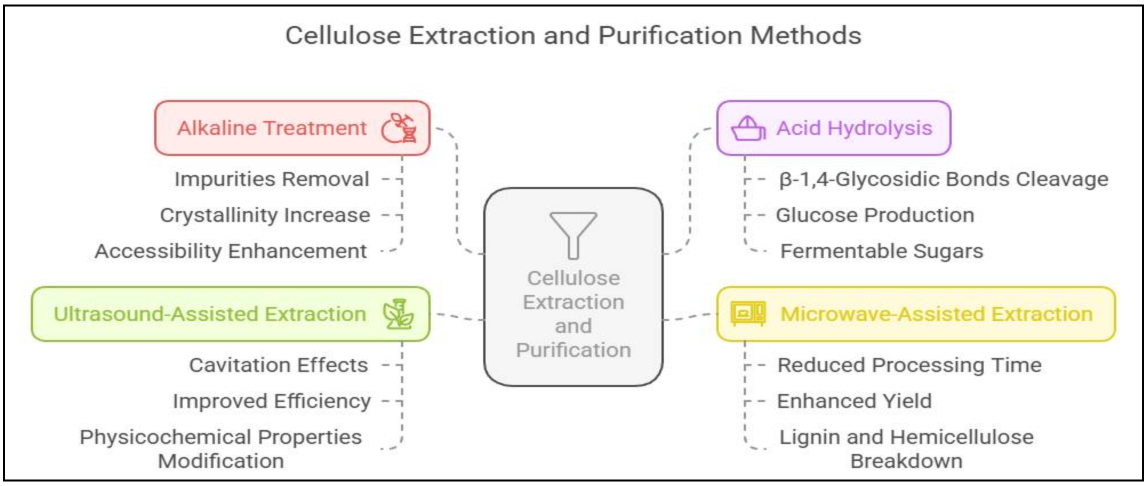

Figure 2: Methods for extraction of cellulose

YIELD AND PURITY OF CELLULOSE

Processing of cellulose typically involves a sequence of pre-treatment, extraction, and post-treatment steps to enhance yield and purity. Pre-treatment helps break down lignin and hemicellulose, while post-treatment refines the cellulose for targeted applications. A multi-approach strategy combining chemical, mechanical, and green methods is often used to optimize efficiency and sustainability.

Pretreatment Of Cellulose

Pretreatment is a crucial step in cellulose processing, enhancing its accessibility for hydrolysis or nanomaterial production by disrupting the rigid lignocellulosic structure. The relationship between cellulose structure and pretreatment efficiency, emphasizing that mechanical, chemical, and thermal methods significantly influence subsequent hydrolysis yields [22]. The cellulose nanocrystal (CNC) and nanofiber (CNF) production, highlighting that pretreatment methods—such as acid hydrolysis, enzymatic treatment, and mechanical fibrillation—directly impact the morphology and properties of nanocellulose. Additionally, the use of imidazolium-based ionic liquids (ILs) for cellulose pretreatment, demonstrating their ability to efficiently dissolve cellulose while minimizing degradation, offering a greener alternative to traditional solvents [21]. These studies collectively underscore the importance of selecting appropriate pretreatment techniques to optimize cellulose processing for applications in biofuels, nanocomposites, and biomaterials.

Post Treatment of Cellulose

Post-treatment processes play a significant role in modifying the structural and functional properties of cellulose-based materials. The impact of fermentation conditions and post-treatment methods, such as drying and chemical purification, on the porosity of bacterial cellulose membranes, demonstrating that optimized post-treatments can enhance membrane permeability and mechanical strength [24]. The studies show the effect of post-treatment and concentration of cotton linter cellulose nanocrystals (CNCs) on agar-based nanocomposite films, revealing that post-treatment methods, including acid hydrolysis and homogenization, improve the dispersion of CNCs and enhance the films' mechanical and barrier properties [23]. These studies highlight the importance of post-treatment strategies in tailoring cellulose materials for applications in biomedical membranes, food packaging, and nanocomposites .

Multi Step Approaches for Extraction of Cellulose

The production and modification of cellulose can be significantly enhanced through systematic optimization approaches. An integrated method for optimizing cellulose mercerization, demonstrating that controlled NaOH concentration and treatment duration can precisely modify cellulose crystallinity and reactivity while minimizing chemical waste [25]. For bacterial cellulose production, the multivariable linear regression to identify optimal culture conditions, showing that parameters like pH, temperature, and nutrient concentration critically influence yield and quality [26]. The applied response surface methodology to optimize cellulose extraction from hybrid agricultural wastes, reveals that pretreatment time and temperature significantly affect cellulose purity and yield. These studies collectively demonstrate that statistical and computational optimization methods are powerful tools for improving cellulose processing efficiency and tailoring material properties for specific applications.

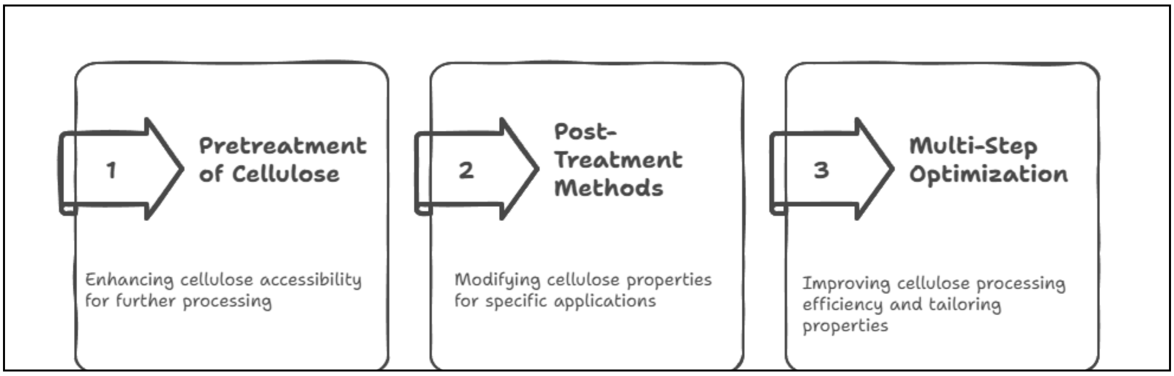

Figure 3: Yield and Purity of cellulose

PROPERTIES OF CELLULOSE BASED BIOPOLYMERS

The properties of cellulose play a vital role in determining its performance and end-use applications. Mechanical strength, thermal stability, biodegradability, and barrier properties are key factors that influence its effectiveness in various fields. These attributes make cellulose a strong candidate for sustainable material development.

Mechanical Properties of Cellulose

Cellulose and its derivatives possess excellent mechanical properties, including high tensile strength, flexibility, and stiffness, making them valuable for biopolymer composites, packaging, and biomedical applications. Bacterial cellulose (BC) exhibits particularly high tensile strength due to its highly crystalline structure, often exceeding plant-based cellulose. Similarly, cellulose nanocrystals (CNCs) and nanofibers (CNFs) serve as effective reinforcing agents in composites, enhancing durability. Flexibility is another key characteristic, especially in CNFs, which feature long, flexible fibers with high aspect ratios. This property makes them suitable for flexible packaging and wearable electronics [27]. Additionally, chemically modified cellulose, such as hydroxyethyl cellulose-based hydrogels, demonstrates improved stiffness and elasticity, enabling applications in biomedical fields . The tunable mechanical properties of cellulose make it a sustainable alternative to synthetic polymers in various industries [27]

Table1: Mechanical Properties of cellulose based biopolymers

Property	Range	Materials	References
Tensile Strength (MPa)	20–300	Nanocellulose films, Cellophane	[28]
Elastic Modulus (GPa)	2–100	Cellulose nanocrystals (CNCs), Bacterial Cellulose	[29]
Elongation at Break (%)	3–20	Cellulose Nanofibrils (CNFs), Methylcellulose	[30]
Toughness (MJ/m^3)	0.5–10	Cellulose composites	[31]

Thermal Stability Of Cellulose

Cellulose exhibits thermal decomposition between 200-400°C, with stability influenced by crystallinity and processing methods. A two-stage degradation process: initial breakdown of amorphous regions followed by crystalline decomposition [32]. Higher crystallinity improves thermal resistance, making cellulose suitable for moderate-heat application. Chemical modifications and nanocomposites enhance thermal performance. The halloysite nanotube incorporation boosts stability by creating heat barriers [33].The cellulose films' value in heat-resistant food packaging, while esterification/etherification further improves heat resistance [34,35]. These properties, combined with renewability, position cellulose as an eco-friendly material for demanding thermal applications.

Table 2: Thermal Stability of Cellulose Based Biopolymers

Property	Range	Materials	References
Decomposition Temperature (°C)	250–400	Cellulose nanocrystals (CNCs), Cellulose acetate	[36]
Glass Transition Temperature (°C)	100–250	Cellulose derivatives (e.g., ethylcellulose)	[37]
Thermal Conductivity (W/m·K)	0.1–0.4	Nanocellulose-based aerogels	[38]

Biodegradeability And Biocompatability of Cellulose

Cellulose's natural biodegradability enables microbial breakdown into harmless byproducts, the degradation rates controllable through crystallinity adjustments and modifications. This tunable decomposition makes it ideal for eco-friendly packaging and agricultural products. The material's excellent biocompatibility also supports medical uses like wound care and tissue engineering, where modified cellulose enhances cell interaction . Its dual functionality as both an environmental and biomedical solution highlights cellulose's role as a sustainable alternative to synthetic polymers [39]

Table 3: Biodegradability of Cellulose

Condition	Degradation Time	References
Composting	1–3 months	[40]
Soil Environment	2–6 months	[41]
Aqueous Environment	3–12 months	[42]
Landfill	6 months – 2 years	[43]

Table 4: Biocompatibility of Cellulose Based Biopolymers

Property	Description	Applications	References
Cytotoxicity	Non-toxic	Wound dressings, Drug delivery	[44]
Immunogenicity	Low	Tissue engineering, Implants	[45]
Cell Adhesion	High	Regenerative medicine	[46]
Degradation Byproducts	Non-harmful	Biodegradable medical scaffolds	[47]

Barrier Properties of Cellulose

Cellulose nanomaterials (CNMs) and derivatives offer exceptional barrier and mechanical properties for eco-friendly packaging, though moisture sensitivity remains a challenge for CNMs. Solutions include polymer composites and multilayer structures to maintain oxygen barrier performance [48]. Cellophane and modified celluloses like MC and HPC provide strong oxygen barriers, with nanocellulose reinforcement enhancing their strength [49]. Film properties can be tuned via molecular weight and plasticizers, balancing flexibility and barrier effectiveness [50]. CNF-based nanocomposites with biopolymers (e.g., starch, chitosan) improve rigidity, oxygen/moisture barriers, and antimicrobial activity - reducing food oxidation by 23% and inhibiting bacterial growth [51]. These innovations position cellulose materials as key players in sustainable active packaging solutions.

Table5: Barrier Properties of Cellulose Based Biopolymers

Property	Range	Materials	References
Oxygen Permeability ($cm^3·\mu m/m^2·day·atm$)	0.01–5	Cellophane, Nanocellulose coatings	[52]
Water Vapor Permeability ($g/m^2·day$)	0.5–100	Methylcellulose, CNF composites	[53]
Oil Resistance	50–70%	Cellulose esters, CNF films	[54]
UV Barrier	(85–99% UV absorption)	Nanocellulose-based coatings	[55]

APPLICATION OF CELLULOSE BASED BIOPOLYMERS

Food Applications

Cellulose and its derivatives have gained significant attention in the food industry due to their biodegradability, non-toxicity, and versatile functional properties. In food packaging, cellulose-based materials, such as films and coatings, are used to extend shelf life, improve barrier properties, and reduce reliance on synthetic plastics [56]. These materials offer excellent mechanical strength and gas barrier properties, making them ideal for preserving food quality. Additionally, cellulose-based hydrogels are increasingly used in food applications, such as encapsulating bioactive compounds, controlling moisture, and improving texture in processed foods. The emphasize on the potential of cellulose hydrogels in creating innovative food products, including edible films, nutrient delivery systems, and fat replacers [57,58].The biocompatibility and sustainability of cellulose make it a promising material for addressing food safety, waste reduction, and environmental concerns in the food industry.

Biomedical Applications

Cellulose, a natural polysaccharide derived from plant cell walls, is widely used in biomedical applications due to its biocompatibility, biodegradability, and non-toxicity [59][60]. Its derivatives and nanostructured forms have shown great potential in wound dressings, drug delivery, and tissue engineering. In wound management, cellulose-based hydrogels effectively absorb exudates, maintain a moist healing environment, and allow gas exchange while preventing microbial infiltration [61]. Bacterial cellulose (BC) mimics the extracellular matrix, promoting cell adhesion and proliferation, and has been commercialized for clinical use [62]. For drug delivery, cellulose nanofibers provide a high surface area and tunable chemistry for controlled drug release. Hydrogels derived from cellulose can encapsulate both hydrophilic and hydrophobic drugs, offering sustained release and improved therapeutic efficacy [63]. In tissue engineering, cellulose-based scaffolds support cell attachment, proliferation, and differentiation, with tunable porosity and mechanical strength for applications in skin, bone, and cartilage regeneration. Advances in 3D bioprinting further highlight cellulose's potential in creating complex tissue structures [64].

Textile Applications

Cellulose-based biopolymers are transforming the textile industry by offering sustainable alternatives to synthetic fibers, leveraging cellulose's abundance in terrestrial biomass (30-40%) for scalable production [65]. Nanocellulose enhances fabric performance with improved mechanical strength, flexibility, and environmental responsiveness, enabling smart textiles and wearables [66]. Cellulose hydrogels outperform synthetic counterparts, absorbing up to 1L water per gram for advanced moisture management [67]. With modification techniques boosting solubility and durability [68], these biodegradable textiles decompose in 60-180 days—unlike persistent synthetics—while meeting performance demands [69,67]. This positions cellulose as a key material for eco-conscious, high-functionality fabrics.

Environmental Applications

Cellulose-based biopolymers are emerging as sustainable solutions for water purification, leveraging their natural abundance, biodegradability, and functional hydroxyl groups [70]. Processed into hydrogels, membranes, and nanostructures, cellulose effectively adsorbs pollutants through its porous structure [71]. Nanocellulose provides high surface area for heavy metal and dye removal, while bacterial cellulose composites enhance efficiency when reinforced with biopolymers or metal oxides [72]. Surface-modified cellulose membranes trap bacteria without biocides [73], and integration with chitosan or metal oxides further improves performance. These innovations position cellulose as a key material for eco-friendly water treatment technologies.

Packaging Applications

Cellulose, the most abundant biopolymer on Earth, is gaining attention as a sustainable and biodegradable alternative to conventional plastic packaging [74][75]. Derived from plant cell walls, cellulose is an organic carbohydrate polymer that decomposes naturally, reducing environmental pollution compared to petroleum-based plastics [64]. In food packaging, cellulose-based materials offer excellent barrier properties against oxygen, carbon dioxide, and water vapor, helping to preserve food quality and extend shelf-life [76]. Advanced cellulose films and paper have been developed to enhance these properties, with recent innovations improving their functionality. For example, the VTT Technical Research Centre of Finland has created formable cellulose-based webs with up to 30% extensibility, enabling their use in rigid packaging applications, such as trays and containers, to replace single-use plastic [77]. However, challenges remain in terms of cost and scalability, as cellulose-based materials are currently more expensive to produce than petroleum-based plastics, limiting their competitiveness. Additionally, developing scalable manufacturing processes to meet industrial demands is crucial for broader adoption.

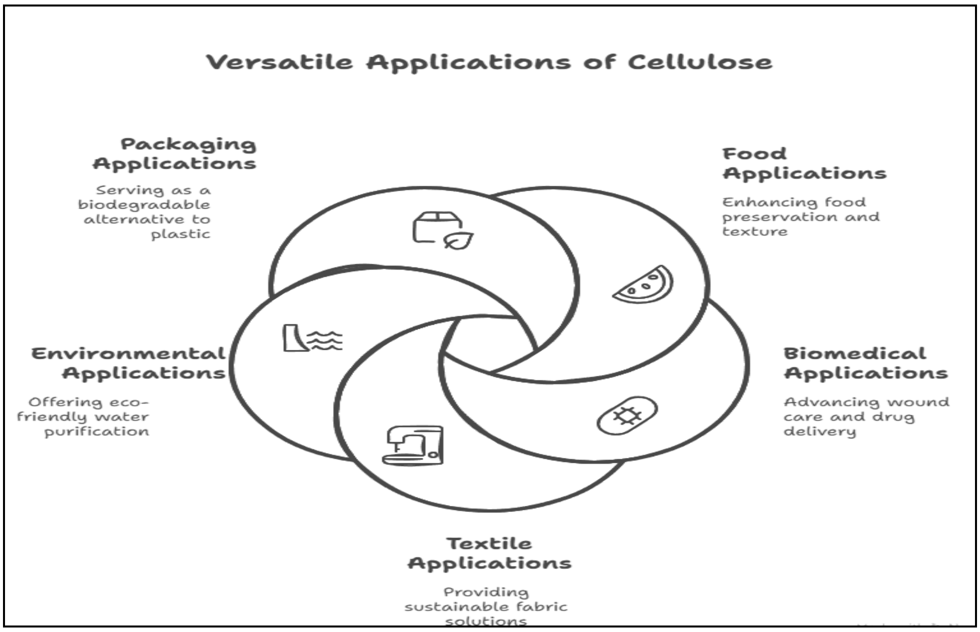

Figure 4: Applications of Cellulose based Biopolymers

CHALLENGES AND LIMITATIONS IN SCALING CELLULOSE BASED INNOVATIONS

Despite the significant potential of cellulose as a sustainable material, scaling up its production faces multiple challenges. One major limitation is the high energy consumption and cost-intensive processes required for cellulose extraction and processing, particularly in nanocellulose production. Techniques such as mechanical fibrillation, acid hydrolysis, and enzymatic treatments demand substantial energy and resources, hindering large-scale industrial adoption [78]. Additionally, traditional extraction methods often rely on harsh chemicals, such as strong acids or alkalis, raising environmental and safety concerns. This has prompted the need for greener and more sustainable processing techniques that minimize chemical waste while maintaining efficiency. Another challenge is the variability in raw material quality, which affects the consistency and performance of cellulose-based products. Cellulose properties differ significantly based on the source whether derived from wood, agricultural residues, or algae due to variations in composition, crystallinity, and fiber morphology. This inconsistency complicates standardization, particularly for high-performance applications. Non-plant-based cellulose sources, such as algal and bacterial cellulose, offer unique advantages like high purity and crystallinity, but their scalability remains limited by lower production yields and higher costs [48]. Additionally, the lack of infrastructure and advanced manufacturing techniques for large-scale nanocellulose production further restricts commercialization. Although promising methods like spray deposition are emerging [78], their widespread implementation requires further research into cost-effective, energy-efficient, and environmentally friendly production methods, alongside greater investment in industrial infrastructure to support a cellulose-based economy.

ADVANCEMENTS AND FUTURE PROSPECTS OF CELLULOSE BASED BIOPOLYMERS

Cellulose-based biopolymers have gained significant attention as sustainable alternatives to synthetic polymers due to their biodegradability, biocompatibility, and renewability. Recent advancements in extraction techniques, such as enzymatic treatments, ionic liquid-assisted processes, and mechanochemical methods, have improved the efficiency and environmental sustainability of cellulose production from diverse sources, including plants, algae, and bacteria. These green methodologies reduce energy consumption, minimize the use of harsh chemicals, and enhance the purity and crystallinity of cellulose, making it more suitable for high-performance applications. Additionally, chemical modifications like esterification, etherification, and oxidation have expanded the functional properties of cellulose, improving its mechanical strength, thermal stability, and responsiveness to external stimuli. As a result, cellulose-based biopolymers are being explored for applications in packaging, biomedical devices, and water purification, where both sustainability and functionality are key considerations. Despite these advancements, challenges remain in scaling up production and ensuring economic feasibility. High production costs, energy-intensive processing techniques, and variability in raw material quality continue to hinder large-scale commercialization. The properties of cellulose can vary significantly depending on the source, leading to inconsistencies in performance, particularly in advanced applications. While synthetic polymers remain dominant due to their cost-effectiveness and versatility, they pose long-term environmental risks, reinforcing the need for sustainable alternatives. Addressing these challenges requires investment in infrastructure, the development of scalable and cost-efficient processing technologies, and enhanced standardization across production methods. Looking ahead, cellulose-based biopolymers hold immense potential in emerging fields such as 3D printing, where their tunable properties enable innovations in tissue engineering and customized medical devices. Their integration with other biopolymers, such as chitosan and starch, further enhances functionalities like antimicrobial activity, moisture resistance, and mechanical reinforcement, expanding their applications in food packaging, wound care, and drug delivery systems. The future of cellulose-based biopolymers lies in fostering stronger collaborations between academia, industry, and policymakers to drive innovation, reduce production costs, and establish a circular bioeconomy. With continued research and technological advancements, cellulose-based materials have the potential to revolutionize multiple industries while contributing to global sustainability efforts.

CONCLUSION

Cellulose-based biopolymers offer biodegradability, renewability, and non-toxicity, making them promising alternatives to synthetic materials. Their diverse applications in packaging, biomedical devices, water purification, and emerging fields like 3D printing highlight their potential to address pressing environmental challenges, particularly plastic pollution and the overuse of fossil-fuel-based materials. Unlike conventional plastics, cellulose-based materials decompose naturally, reducing long-term waste accumulation and contributing to a cleaner ecosystem. Despite these advantages, the large-scale adoption of cellulose biopolymers is hindered by challenges such as high production costs, energy-intensive extraction methods, and variability in raw material quality. Conventional processing techniques like mechanical fibrillation and acid hydrolysis require significant energy input, making industrial-scale production expensive. Additionally, ensuring consistent performance across different sources of cellulose, whether from wood, agricultural residues, or bacterial cellulose, remains a challenge. To overcome these barriers, research is focusing on developing greener extraction techniques, such as enzymatic treatments and ionic liquids, to improve efficiency and reduce environmental impact. Enhancing the properties of cellulose by modifying it with other biopolymers like chitosan and starch can further expand its applications. With continued innovation and collaboration between academia and industry, cellulose-based biopolymers can drive the transition toward a circular bioeconomy, reducing environmental footprints and promoting sustainable industrial practices.

ACKNOWLWDGEMENT

The author would like to express sincere gratitude to the Research Department and the Department of Food Technology, Ramaiah University of Applied Sciences, for their continuous support and guidance throughout the development of this review article. This article has been written as part of the author's ongoing research and dissertation work at the college. The author also gratefully acknowledges the financial assistance provided through the Project Seed Money Grant, which facilitated the successful completion of this work.

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