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BIOTECHNOLOGICAL VALORIZATION OF PLANT BIOMASS FOR ECO-FRIENDLY PACKAGING VIA BACTERIAL PROCESSES

The growing environmental impact of petroleum-based plastic packaging has intensified the need for biodegradable and sustainable alternatives. Among these, bacterial cellulose stands out as a promising biomaterial due to its remarkable purity, mechanical strength, and nanofibrillar structure. Unlike plant-derived cellulose, bacterial cellulose is naturally synthesized by specific bacteria in a form free from lignin and hemicellulose, making it highly suitable for use in eco-friendly packaging and biomedical applications. This review highlights recent advances in the biotechnological valorization of plant biomass, particularly agricultural residues such as straw, stalks, and husks, for bacterial cellulose production. These lignocellulosic feedstocks are abundant, renewable, and offer significant potential as substrates for microbial fermentation. The paper explores the chemical composition of various biomass types and evaluates their suitability for bacterial cellulose synthesis based on their cellulose, hemicellulose, and lignin content. In addition, the review outlines the enzymatic steps involved in bacterial cellulose biosynthesis and the microbial strains primarily responsible for its production. Together, these insights provide a scientific foundation for converting plant-based waste into biodegradable cellulose-based materials, contributing to the development of sustainable packaging solutions and supporting the transition toward a circular bioeconomy.

Key words: bacterial cellulose; lignocellulosic biomass; sustainable packaging; agricultural residues; microbial fermentation.

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Өсімдік биомассасын бактериялық процестер арқылы экологиялық таза орауыш материалдарға биотехнологиялық бағалау

Мұнай негізіндегі пластикалық орау материалдарының қоршаған ортаға әсері артқан сайын, биодеградацияланатын және тұрақты баламалардың қажеттілігі күшейді. Осы баламалардың арасында бактериялық целлюлоза ерекше тазалығы, механикалық беріктігі және нано-талшықты құрылымы арқасында перспективалы биоматериал ретінде ерекшеленеді. Өсімдіктен алынған целлюлозадан айырмашылығы, бактериялық целлюлоза арнайы бактериялармен табиғи түрде синтезделеді және лигнин мен гемицеллюлозадан еркін түрде болады, бұл оны экологиялық таза орау материалдары мен биомедициналық қолданбалар үшін өте қолайлы етеді. Бұл шолу өсімдік биомассасын, әсіресе сабан, сабандық дәндер және қауыз сияқты ауылшаруашылық қалдықтарын бактериялық целлюлоза өндіруге арналған биотехнологиялық құндылығын арттырудағы соңғы жетістіктерге назар аударады. Бұл лигноцеллюлозды шикізаттар кеңінен таралған, жаңартылатын және микроорганизмдер арқылы ашыту үшін маңызды әлеуетке ие. Бұл жұмыс әртүрлі биомасса түрлерінің химиялық құрамын зерттейді және олардың целлюлоза, гемицеллюлоза және лигнин құрамына негізделген бактериялық целлюлоза синтезіне жарамдылығын бағалайды.

ғалайды. Сонымен қатар, шолу бактериялық целлюлоза биосинтезіндегі ферменттік қадамдарды және оның өндірісіне жауапты микроорганизмдер штамдарын сипаттайды. Осы мәліметтер өсімдік қалдықтарын биодеградацияланатын целлюлоза негізіндегі материалдарға айналдыру үшін ғылыми негізді қамтамасыз етіп, тұрақты орау шешімдерін дамытуға және айналмалы биоэкономикаға көшуге үлес қосады.

Түйін сөздер: бактериялық целлюлоза; лигноцеллюлозды биомасса; тұрақты орау; ауылшаруашылық қалдықтары; микроорганизмдер арқылы ашыту.

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Биотехнологическая утилизация растительной биомассы для экологичной упаковки через бактериальные процессы

Увеличение воздействия пластиковых упаковок на основе нефти на окружающую среду усилило потребность в биодеградируемых и устойчивых альтернативах. Среди них бактериальная целлюлоза выделяется как перспективный биоматериал благодаря своей замечательной чистоте, механической прочности и нановолокнистой структуре. В отличие от целлюлозы растительного происхождения, бактериальная целлюлоза синтезируется специфическими бактериями в форме, свободной от лигнина и гемицеллюлозы, что делает ее высоко пригодной для использования в экологичной упаковке и биомедицинских приложениях. Этот обзор освещает последние достижения в биотехнологической утилизации растительной биомассы, в частности сельскохозяйственных отходов, таких как солома, стебли и шелуха, для производства бактерийной целлюлозы. Эти лигноцеллюлозные сырьевые материалы обильны, возобновляемы и обладают значительным потенциалом в качестве субстратов для микроорганизмной ферментации. В статье рассматриваются химический состав различных типов биомассы и оценивается их пригодность для синтеза бактерийной целлюлозы на основе содержания целлюлозы, гемицеллюлозы и лигнина. Кроме того, обзор описывает ферментативные этапы, вовлеченные в биосинтез бактерийной целлюлозы, и микроорганизмные штаммы, которые в основном ответственны за ее производство. Совокупность этих данных предоставляет научную основу для преобразования растительных отходов в биодеградируемые материалы на основе целлюлозы, способствуя разработке устойчивых решений для упаковки и поддержке перехода к круговой биоэкономике.

Ключевые слова: бактериальная целлюлоза; лигноцеллюлозная биомасса; устойчивая упаковка; сельскохозяйственные отходы; микробная ферментация.

Introduction

Plastic packaging waste has emerged as a major global environmental concern [1]. Conventional petroleum-based polymers such as polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP) are extensively utilized in food and consumer goods packaging due to their excellent mechanical strength and barrier properties [2,3]. However, the long-term persistence of these synthetic materials in the environment, along with their resistance to biodegradation, leads to the accumulation of plastic debris and the formation of microplastics both of which pose significant risks to ecosystems and human health [4]. In light of these issues, there is a growing demand for sustainable alternatives that are both biodegradable and environmentally benign. Among the most promising candidates is bacterial cellulose (BC) [5], a highly pure biopolymer synthesized by certain prokaryotic microorganisms [6]. Unlike plant-derived cellulose, which is typically extracted from wood or cotton and contains residual lignin and hemicellulose, BC is naturally produced by bacteria in a pristine form devoid of these impurities [7]. This results in an ultrafine nanofibrillar cellulose network with exceptional purity and structural integrity [8]. Such unique properties make BC an attractive material for a wide range of advanced applications, from biomedical engineering to the development of eco-friendly packaging solutions [9,10].

BC demonstrates a range of key attributes that make it highly suitable for use in packaging technologies [11]. Notably, its elevated degree of crystal-

linity and polymer chain alignment endow BC films with remarkable tensile strength reaching up to approximately 200 MPa in dry conditions while maintaining a high degree of flexibility [12,13]. Furthermore, BC exhibits exceptional resistance to oxygen and moisture permeation, often outperforming conventional bioplastic materials in barrier functionality [14]. The films produced from BC are typically transparent, flavourless, and inherently non-toxic, which renders them safe for direct contact with food products. In addition to these functional benefits, BC is fully biodegradable and compostable by nature; it undergoes decomposition in natural environments without generating harmful residues or microplastic particles [15]. These combined features position BC as a highly promising and environmentally responsible substitute for petroleum-based plastic packaging [16].

BC can be produced from renewable raw materials, particularly agricultural and industrial lignocellulosic residues [17]. Utilizing plant-based waste such as straw, stalks, and husks for BC synthesis aligns with circular economy principles by transforming low-value biomass into high-value bioproducts [18]. This review highlights recent advances in the biotechnological conversion of plant biomass into biodegradable packaging materials through bacterial processes. It begins with an overview of the chemical composition of common plant residues namely their cellulose, hemicellulose, and lignin content and evaluates their potential as substrates for microbial fermentation.

2 Plant biomass feedstocks: composition and availability

2.1. Agricultural lignocellulosic residues: composition and suitability for microbial conversion

Agricultural lignocellulosic residues refer to solid plant-based wastes generated as by-products of crop production that are not directly utilized for food or feed [19]. These biomass sources include the straw of cereal and leguminous crops such as wheat, barley, and rice; stalk and leaf residues of maize and sunflower; sugarcane bagasse; and the woody stems and hulls of cotton and other indus- trial crops [20,21]. Such residues are produced in enormous quantities annually, with global estimates reaching several billion tons of agricultural plant waste per year [22]. However, a significant portion of these materials remains underutilized, often being burned in open fields or left to decompose, leading not only to the loss of valuable resources but also to increased greenhouse gas emissions and air pollution [23]. Despite this, plant-derived lignocellulosic biomass holds substantial potential as an accessible and low-cost feedstock for renewable energy generation and bioproduct manufacturing [24].

Agricultural crop residues are primarily composed of lignocellulosic material, which is derived from the rigid cell walls of plant tissues [25]. Lignocellulosic biomass consists of three major structural components: cellulose, hemicellulose, and lignin (Figure 1). Cellulose is a long-chain polysaccharide made up of glucose monomers, forming the structural backbone of the plant cell wall and accounting for approximately 40–50% of the dry weight [26]. It assembles into microfibrils, providing high mechanical strength to plant fibers [27]. Hemicellulose, in contrast, is a branched heteropolymer composed of various pentose and hexose sugars; it binds cellulose microfibrils and, together with lignin, forms an amorphous matrix within the cell wall. In agricultural residues, hemicellulose typically makes up about 20–30% of the biomass [28]. Lignin is a complex, aromatic polymer built from phenylpropanoid units, conferring water resistance and structural rigidity to plant tissues, and is highly resistant to biological degradation [29]. The precise chemical composition of agricultural residues can vary significantly depending on the plant species, cultivar characteristics, and growing conditions [30].

The relative proportions of cellulose and lignin vary significantly among different types of agricultural residues. For instance, wheat straw contains a relatively low lignin content (~14%), whereas corn stover and sugarcane bagasse have higher lignin levels, around 20% [31, 32]. As reported by Fortunati et al. [33], the lignocellulosic profile of barley straw includes about 56.2% cellulose, 7% hemicellulose, and 9.2% lignin. The cellulose content also differs considerably: it exceeds 30–43% in rice straw [34], while in cotton stalks it typically ranges between 35% and 40% [35-37]. Cotton stalks exhibit even greater lignin content ranging from 20% to 31% which may contribute to their resistance to microbial degradation [38,39].

Environmental growing conditions also play a significant role; under stress conditions such as drought, plants tend to enhance lignin biosynthesis to reinforce their cell walls [40]. Daniel et al. [41] showed that water deficiency led to an approximately 18.4% increase in lignin content in Douglas-fir wood under drought-induced abiotic stress. Certain residues also contain distinct inorganic components for instance, rice straw can have up to ~18% ash content in the form of silicon dioxide, which further

complicates microbial breakdown [42]. Overall, the high cellulose and hemicellulose content in agricultural residues highlights their potential as feedstocks for microbial conversion into fermentable sugars and various bioproducts. However, a high lignin content can act as a limiting factor, reducing the overall efficiency of bioconversion processes (Table 1) [43,44].

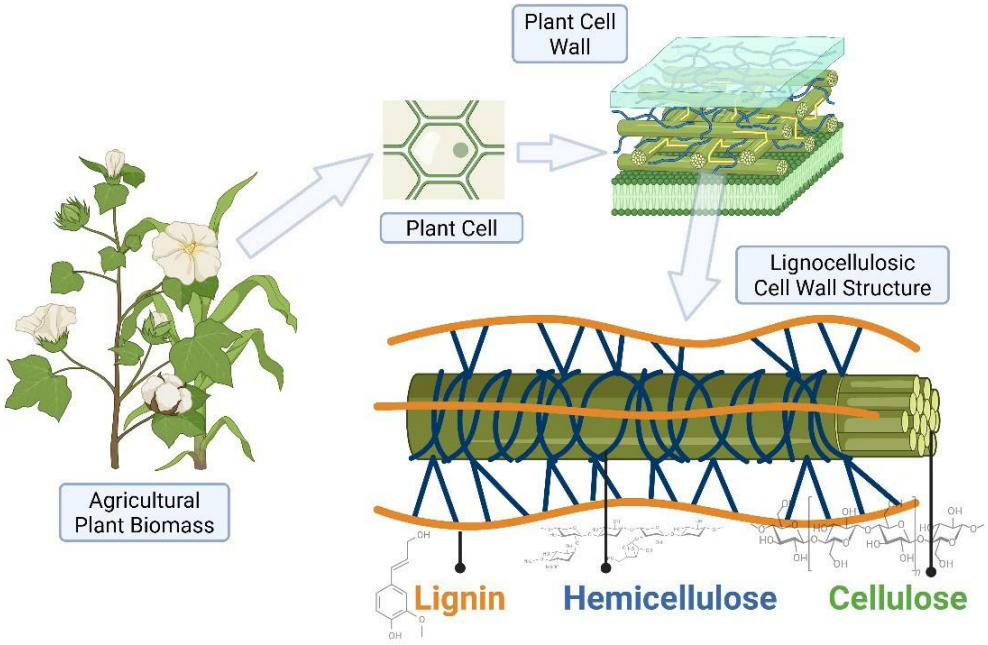

Figure 1 – Lignocellulosic structure of agricultural plant biomass. Cellulose microfibrils (green) are bound by hemicellulose chains (blue) and embedded in a lignin matrix (orange), forming a strong and integrated plant cell wall network.
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Table 1 – Composition of lignocellulosic components in various agricultural residues

Type of Residue	Cellulose, %	Hemicellulose, %	Lignin, %	References
Wheat straw	37	26.5	14	[31, 32]
Barley straw	56.2	7	9.2	[33]
Corn stover (stalks)	35.2	25.1	23.7	[31, 32]
Rice straw	30-43	27.9	17.2	[34]
Sugarcane bagasse	41.6	25.1	20.3	[31, 32]
Cotton stalks	35–40	20–25	20–31	[35-37], [38,39]
Hardwood stem	40–50	24–40	18–25	[45]
Softwood stem	45–50	25–35	25–35	[45]
Nut shells	25–30	25–30	30–40	[45]
Grasses	25–40	35–50	10–30	[45]
Leaves	15–20	80–85	0	[45]
Sorted refuse	60	20	20	[45]

Continuation of the table

Type of Residue	Cellulose, %	Hemicellulose, %	Lignin, %	References
Coastal Bermuda grass	25	35.7	6.4	[45]
Switch grass	30–50	10–40	5–20	[45]
Solid cattle manure	1.6–4.7	1.4–3.3	2.7–5.7	[45]
Swine waste	6	28	-	[45]
Primary wastewater solids	8–15	-	24–29	[45]
Paper	85–99	0	0–15	[45]
Newspaper	40–55	25–40	18–30	[45]
Waste papers from chemical pulps	60–70	10–20	5–10	[45]

To enable the efficient microbial conversion of lignocellulosic residues, it is first necessary to disrupt their complex structure, as cellulose microfibrils are tightly embedded within a matrix of lignin and hemicellulose in their natural state [46]. This arrangement acts as a physical barrier, significantly limiting enzyme access and hindering microbial degradation [47]. In a study by Mosier et al. [48] it was shown that lignin not only blocks enzymatic access but also adsorbs enzyme molecules onto its surface, thereby reducing their activity and decreasing bioconversion efficiency. Furthermore, phenolic compounds such as vanillin, ferulic acid, and furfuralgenerated during thermochemical pretreatment are known to exert toxic effects on microorganisms and inhibit fermentation [49]. Therefore, recent studies recommend pretreatment strategies to alter the lignocellulosic structure and improve substrate accessibility. For instance, Kumar et al. [50] demonstrated that acid, alkaline, and steam-based pretreatments enhance enzymatic access to cellulose. Following pretreatment, enzymatic hydrolysis is performed, breaking down polysaccharides into glucose and xylose monomers. According to Chandel et al. [51] the yeast *Saccharomyces cerevisiae* is the most widely used strain in fermentation processes. In addition, filamentous fungi such as *Aspergillus*, *Trichoderma*, and *Rhizopus*, as well as bacteria like *Clostridium* and *Lactobacillus*, are effectively employed to produce various biochemicals. In summary, the main challenge in converting agricultural lignocellulosic waste into bio-based products via microbial processes lies in their inherent resistance to biological degradation. However, modern biotechnological solutions such as optimized pretreatment methods, enzyme cocktails, and selected microbial strains offer promising strategies to overcome these limitations.

3. Microbiological synthesis of BC

3.1. Key bacterial strains responsible for cellulose biosynthesis

BC is an exopolysaccharide nanomaterial synthesized by specific microbial species. Unlike plant-derived cellulose, BC is characterized by its exceptional purity, high water-holding capacity, and robust three-dimensional fibrous architecture [52,53]. The most efficient BC-producing microorganisms are Gram-negative rods belonging to the acetic acid bacteria group. Among them, *Komagataeibacter xylinus* (*K. xylinus*) is widely recognized for its high cellulose productivity [54]. Other closely related strains such as *K. Hansenii* [55], *K. Rhaeticus* [56], *K. Sucrofermentans* [57], and *K. Medellinensis* [58] also exhibit strong cellulose-synthesizing capabilities and are extensively used in both fundamental research and industrial-scale BC production.

K. xylinus has been extensively studied as a model organism in this group due to its high cellulose-producing capacity and well-characterized biosynthetic pathways [59]. These bacteria are known to form thick surface layers often referred to as the “mother of vinegar” and are commonly found in sugar-rich substrates such as fermented tea (kombucha), fruit juices, and palm sap [60,61]. The cellulose forms a floating biofilm that enables the cells to remain at the air–liquid interface, thereby facilitating efficient oxygen uptake [62]. As a result, BC is typically synthesized at the interface between the liquid medium and the air, making oxygen availability a critical factor for optimal production. Species of *Komagataeibacter* are obligate aerobes that derive energy through partial oxidation of carbon sources [63,64]. For instance, glucose is converted to gluconic acid and ethanol to acetic acid, and these metabolic by-products lead to acidification of the

culture medium. This metabolic behavior not only supports cellulose biosynthesis but also influences the physicochemical conditions of the surrounding environment [65,66].

The metabolic profile of *Komagataeibacter* strains is closely linked to their cellulose-producing ability [67]. Cellulose producers exhibit ~100-fold higher UDP-glucose pyrophosphorylase activity compared to non-producers, facilitating efficient synthesis of UDP-glucose a key precursor for cellulose biosynthesis [68]. Essential genes (*bcsA*, *bcsB*, *bcsC*, *bcsD*) are organized into operons. In *K. xylinus*, two operon types have been identified: type I includes the core *bcs* genes and regulatory elements (*cmcAx*, *ccpAx*, *bglAx*), while type II contains an additional acyltransferase gene, potentially involved in acylated cellulose production. These genetic features influence the quantity and quality of BC [69].

3.2 Biochemical pathway and regulation of BC biosynthesis

The biosynthesis of BC involves several sequential enzymatic steps [70]. When glucose is used as the carbon source, it is first phosphorylated to glucose-6-phosphate by the enzyme glucokinase upon entering the cell [71]. In the second step, glucose-6-phosphate (Glc6P) is isomerized to glucose-1-phosphate (Glc1P) through the catalytic action of phosphoglucomutase [72]. In the third step, Glc1P is converted into uridine diphosphate glucose (UDP-glucose) via the enzyme UDP-glucose pyrophosphorylase (UGPase) [73]. This reaction involves the condensation of Glc1P with UTP, releasing pyrophosphate and forming high-energy UDP-glucose [74]. UDP-glucose is an activated compound that serves as the direct precursor for cellulose biosynthesis [75]. While it is a common intermediate in the synthesis of various polysaccharides in many microorganisms, only certain specialized bacteria possess the ability to polymerize UDP-glucose into cellulose (Figure 2) [76]. In cellulose-producing bacteria, the exceptionally high activity of UGPase and the enhanced flux through associated pathways promote the accumulation and efficient utilization of UDP-glucose for polymerization [77]. The fourth and principal step is the polymerization of UDP-glucose. This process is catalyzed by a membrane-bound multienzyme complex known as cellulose synthase, which sequentially adds glucosyl residues from UDP-glucose to elongate the β-1,4-glucan chain [78,79].

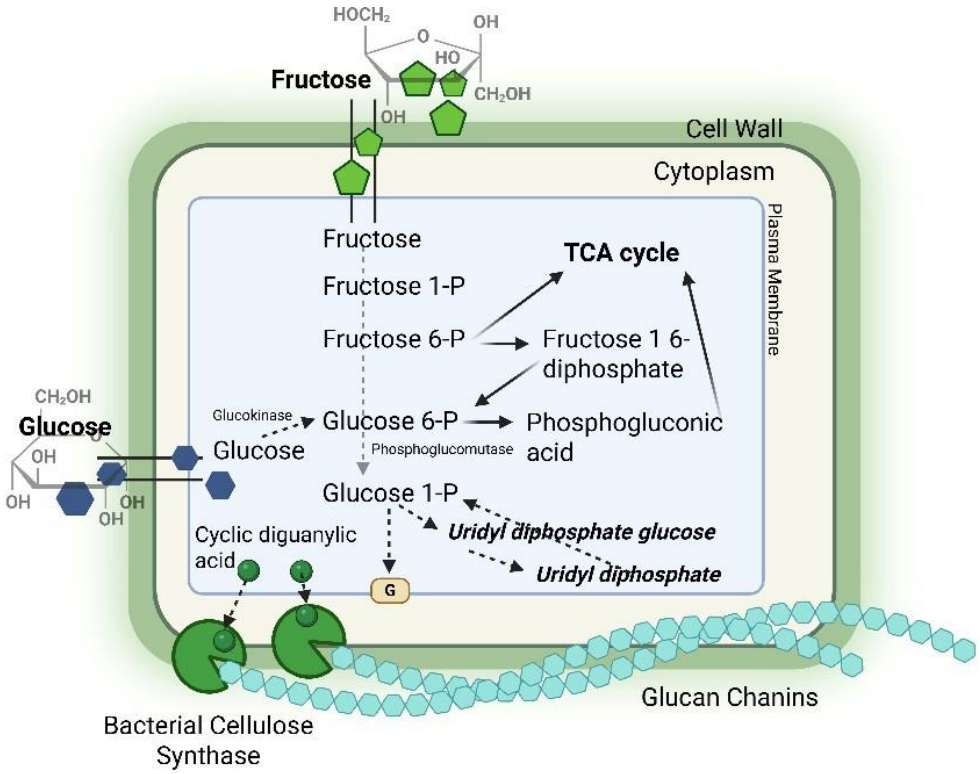

Figure 2 – Cellulose formation mechanism in K. xylinus
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The cellulose synthase complex is anchored in the inner cytoplasmic membrane and is composed of protein products encoded by the *bcs* operon. At the core of the complex are the BcsA and BcsB proteins [80]. BcsA is an integral membrane protein with multiple transmembrane domains; its cytosolic region contains a glycosyltransferase catalytic site and a PilZ domain that binds the second messenger cyclic di-GMP (c-di-GMP) [81]. BcsB is a periplasmic protein that non-covalently associates with BcsA and contains carbohydrate-binding domains, which assist in guiding the nascent glucan chain through the cell envelope. The activity of this enzyme complex is directly regulated by c-di-GMP, which allosterically binds to the PilZ domain of BcsA, thereby activating its glycosyltransferase function [82,83]. Studies in *Gluconacetobacter xylinus* (now *K. xylinus*) and other cellulose-producing bacteria have shown that elevated intracellular levels of c-di-GMP significantly enhance cellulose biosynthesis [84,85]. The concentration of c-di-GMP is dynamically controlled by the opposing activities of two types of enzymes: diguanylate cyclases (DGCs) and phosphodiesterases (PDEs), which respond to environmental cues and thus indirectly regulate the rate of cellulose synthesis [86,87].

BC biosynthesis begins with the synthesis of β-1,4-glucan chains on the inner membrane, which are transported through the periplasm and extruded via the BcsC pore in the outer membrane [88]. These chains self-assemble into protofibrils (~2–4 nm), microfibrils (~80 nm), and eventually ribbon-like nanofibers [89-91]. Core proteins (BcsA–C) drive synthesis, while BcsD aids in fibril crystallization its deletion in *K. xylinus* reduces yield by up to 90%. Auxiliary genes like *ccpAx*, *cmcAx*, and *bglAx* assist in cellulose modification. Biosynthesis is sensitive to environmental factors [68]. Optimal pH (~6.0) is essential, while byproducts like gluconic acid lower pH and inhibit production; buffering agents (e.g., sodium acetate) help stabilize conditions. Genetic modifications (e.g., *gdh* knockouts or chemically induced mutants) improve yield by minimizing acid production and optimizing NADH usage [68,92]. Oxygen availability is also critical: static cultures may suffer from limited diffusion, whereas aeration systems enhance productivity though excessive agitation can reduce yield [93]. Overall, BC synthesis is a highly regulated process influenced by genetics, metabolism, and culture conditions, with modern biotechnological advances enabling more efficient industrial-scale production.

4. BC derived from agricultural residues and its properties for packaging applications

BC is a highly pure polymer produced by certain bacteria, with nanofibers thinner and more ordered than those of plant cellulose [94]. As a natural biomaterial, BC offers an eco-friendly alternative to petroleum-based plastics. However, its industrial production traditionally relies on expensive carbon sources like glucose and yields remain relatively low [95]. To address this, recent studies have focused on using agricultural residues and by-products as cost-effective substrates to reduce production costs and enhance sustainability. These waste materials such as fruit peels, straw, bagasse, rice husks, corn cobs, and glycerol by-products contain abundant carbohydrates, nitrogen compounds, and micronutrients, making them viable substitutes for conventional media [96,97]. This section reviews recent advances in BC production from agro-waste, examines its packaging-related properties, and compares BC-based films to traditional plastics.

4.1 Research on BC production from agricultural waste

Recent studies have demonstrated that various agricultural and food industry wastes can serve as low-cost substrates for BC production. For example, Andritsou et al. [98] evaluated the potential of citrus waste, using unsold orange and grapefruit juices and their aqueous peel extracts as media for *Komagataeibacter sucrofermentans*. After 6–7 days of cultivation, BC yields reached 6.7 g/L and 6.1 g/L, respectively. Lower yields were observed when using lemon, grapefruit, and orange peel extracts—5.2, 5.0, and 2.9 g/L, respectively. BC produced from orange peel hydrolysate exhibited significantly higher water-holding capacity, degree of polymerization, and crystallinity compared to samples derived from purified plant cellulose [98,99]. Starchy vegetable waste can also serve as an effective substrate. Abdelraof et al. [100] reported that acid-pretreated potato peel hydrolysate supported the production of 4.7 g/L of BC by *Gluconacetobacter xylinus* after 6 days under optimal conditions (35 °C, pH 9, and 8% inoculum in the initial medium). Sugar industry and fruit processing residues have also been investigated as substrates. Abol-Fotouh et al. utilized a newly isolated strain, *Komagataeibacter saccharivorans* MD1, to produce BC from date juice waste, fig processing residues, and sugarcane molasses. After 168 hours of incubation, the highest yield was

achieved using molasses-based medium (~3.9 g/L), compared to only ~1.1 g/L in conventional HS medium [101,102]. Researchers reported that BC produced in agro-waste-based media showed no significant differences in fiber diameter or branching structure compared to samples grown in glucose-based media, indicating that nutrient extraction from waste substrates does not adversely affect cellulose quality [102]. Cereal straw and other biomass-based substrates have also proven effective. In a study by Ishola et al., two natural *Komagataeibacter* strains isolated from rotten banana and kombucha were used for fermentation with enzymatic hydrolysates of corncob and sugarcane bagasse as substrates [103]. This study compared static, intermittent, and continuous agitation modes. Continuous stirring significantly improved BC yield: *Komagataeibacter sp*. (CCUG73629) produced 1.6 g/L in corncob hydrolysate under agitation, versus 0.9 g/L in static HS medium. Similarly, strain CCUG73630 yielded 1.2 g/L from sugarcane bagasse under agitation, compared to just 0.3 g/L under static conditions. Another promising direction is the use of food industry by-products, such as apple pomace from juice production and stale bread hydrolysate. Esmail et al. [104] demonstrated that sugar mixtures derived from these wastes significantly enhanced BC production by *K. xylinus* DSM 2004. Cultivation in apple pomace alone yielded ~1.5 g/L of BC, which increased to 3.38 g/L when supplemented with nitrogen sources. Similarly, BC yield from bread hydrolysate rose to 2.07 g/L with nutrient supplementation. The BC produced in this medium also exhibited distinctive structural and functional properties: films derived from apple pomace were thicker, showed slightly higher crystallinity (59–69% vs. 55%), greater tensile modulus and strength, and lower moisture absorption and oxygen/CO_2 permeability compared to those from bread hydrolysate.

4.2 Functional properties of BC for packaging applications

The structural features of BC provide it with several unique material properties. Most notably, BC forms a three-dimensional network of nanofibers with diameters in the nanometer range. It exhibits a very high degree of crystallinity typically between 70–90% or even higher contributing to its excellent mechanical strength and stability [102, 105]. High crystallinity and strong intermolecular hydrogen bonding provide BC with excellent mechanical strength. In dry conditions, pure BC films often surpass many polymers in tensile strength. For instance, compressed BC films can reach tensile strengths of 150–200 MPa, exceeding those of some conventional plastics such as PET. Additionally, BC exhibits a high elastic modulus, which can exceed 10 GPa [103,106]. BC is also favourable in terms of flexibility: thin cellulose films remain pliable and retain a certain degree of elasticity and stretchability without becoming brittle [107]. This property is also moisture-dependent: in a hydrated state, BC is very soft and elastic which is why it is widely used in wound dressings whereas in a fully dry state, it becomes stiffer. However, its flexibility can be adjusted by adding plasticizers or maintaining a humid environment.

In addition to mechanical strength, an essen- tial property for packaging materials is their barrier performance specifically, the ability to prevent the transmission of water vapor and gases [108]. BC demonstrates excellent oxygen barrier properties due to its dense nanofibrous structure, which effectively blocks oxygen molecules. In fact, its gas permeability is significantly lower than that of common plastics such as PE and PP [109]. For example, BC films derived from apple pomace have been experimentally shown to exhibit reduced permeability to both oxygen and carbon dioxide compared to standard samples [104]. BC-based films can also act as a barrier to microbes—its dense nanostructure is impermeable to bacteria. Moreover, incorporating natural antimicrobial agents into the cellulose matrix enables the development of active packaging capable of protecting food from spoilage microorganisms. Regarding moisture permeability, pure BC is a hydrophilic polymer, which limits its effectiveness as a water vapor barrier. It readily absorbs moisture, and under high ambient humidity, its gas barrier performance may decrease accordingly [110]. However, this limitation is being addressed through various scientific approaches. One strategy involves coating BC films with hydrophobic layers such as waxes or plant oil-based nanoparticles to create water-resistant composite materials [111]. Another approach is to blend the cellulose matrix with natural poly- mers like pectin or carboxymethyl cellulose, which reduces moisture sensitivity and enhances water vapor barrier properties [112,113]. For instance, researchers in China developed a composite BC film by incorporating soy protein and applying a thin oil-based surface layer. The resulting material was fully transparent, mechanically robust, and showed improved water resistance [114,115].

Another key advantage of BC is its biodegradability. As a pure form of cellulose, BC can be readily broken down by environmental microorganisms such as fungi and bacteria that produce cellulase

enzymes into water, carbon dioxide, and biomass. Studies have shown that BC films undergo complete degradation in soil within a few weeks; in some cases, total breakdown has been observed within 40 days [107, 116]. Importantly, BC does not require specialized industrial composting conditions it decomposes naturally under ambient environmental conditions. In contrast, one of the most widely used commercial bioplastics, polylactic acid (PLA), degrades only under industrial composting settings and takes several months to break down; in soil or at room temperature, its degradation is extremely slow and may take years. On the other hand, polyhydroxyalkanoates (PHAs) can undergo complete mineralization in various natural environments, including marine settings, within a few months to a year [117-119]. BC, being structurally like plant cellulose, follows a comparable environmental degradation pathway like that of natural cellulose fibers found in paper or wood making its breakdown both rapid and non-toxic. This property enables BC-based packaging to be composted directly after use, allowing it to re-enter the biological cycle in a sustainable and circular manner (Figure 3).

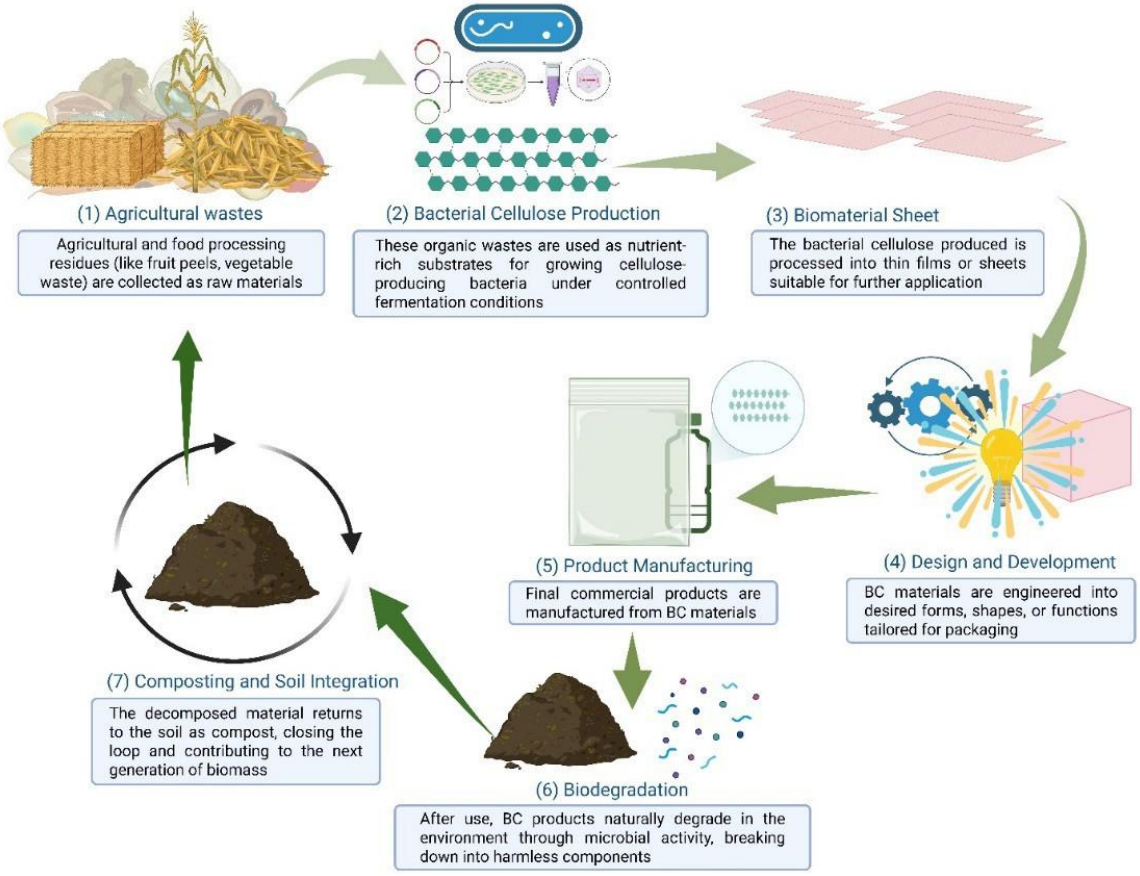

Figure 3 – The cycle of utilizing agricultural waste for the production and application of BC-based packaging materials
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4.3 Comparison with conventional plastics and other materials

BC-based packaging materials can be compared to conventional petrochemical plastics (e.g., PE, PET) and modern bioplastics (PLA and PHA) across several aspects. In terms of mechanical strength, BC matches or even surpasses many plastics. For instance, the tensile strength of high-density PE is approximately 20–30 MPa, and PET films range from about 50–70 MPa. In contrast, properly dried pure BC films typically reach 50–100 MPa and can be enhanced up to 150–200 MPa through specific processing techniques [107,120,121]. Thus, BC-based packaging can serve as a viable alternative to plastics in applications that require mechanical durability such as impact resistance or load bearing during

transportation.

In terms of barrier properties, BC outperforms many polymers particularly in blocking oxygen and aroma compounds [122]. Polyolefins such as PE and PP allow relatively high permeability to oxygen and carbon dioxide due to their non-polar molecu- lar structure. In contrast, cellulose films are rich in polar hydroxyl groups, which can adsorb gas mol- ecules within their structure and significantly hin- der their diffusion [123,124]. Therefore, BC-based packaging demonstrates excellent protective capabilities in vacuum-sealed applications or for foods sensitive to oxidation. While polyesters like PET also provide moderate oxygen barrier properties, their effectiveness increases mainly with thickness [125,16]. In contrast, due to its nanostructured architecture, BC can offer high barrier performance even in very thin layers. As previously mentioned, hydrophobic plastics such as PE and PP have a clear advantage in water vapor resistance, they are virtually impermeable to moisture [127,128]. For this reason, moisture-sensitive products like dry foods, pharmaceuticals, and electronics are often packaged in such materials. In its pure form, BC is less effective in this aspect. However, water resistance is being successfully enhanced through the development of composite structures, such as BC combined with biodegradable polymers or coated with thin hydrophobic layers [129,130]. In terms of environmental and health safety, the advantages of BC and other biopolymers are clear (Figure 4) [131]. Petroleum-derived plastics such as PE, PET, and others persist in the natural environment for hundreds of years, contributing significantly to plastic pollution. Moreover, their production processes generate substantial amounts of greenhouse gas emissions [132,133]. There are also notable differences in production processes and practical applications. Conventional thermoplastics are processed through high-temperature techniques such as melt molding, blow molding, or extrusion [134]. In contrast, BC is produced through low-temperature fermentation, during which it grows directly into its final form typically as a surface membrane. This means that BC production consumes significantly less energy but proceeds more slowly, often requiring several days per batch [135,136]. Plastics, on the other hand, can be extruded and molded within minutes, allowing for rapid mass production. To address this limitation, current research focuses on intensifying BC fermentation through strategies such as agitated cultures and continuous feeding [137]. Additionally, emerging approaches include shaping BC into filaments via 3D printing or extrusion, which can then be woven into textile-like materials for various structural applications [138,139].

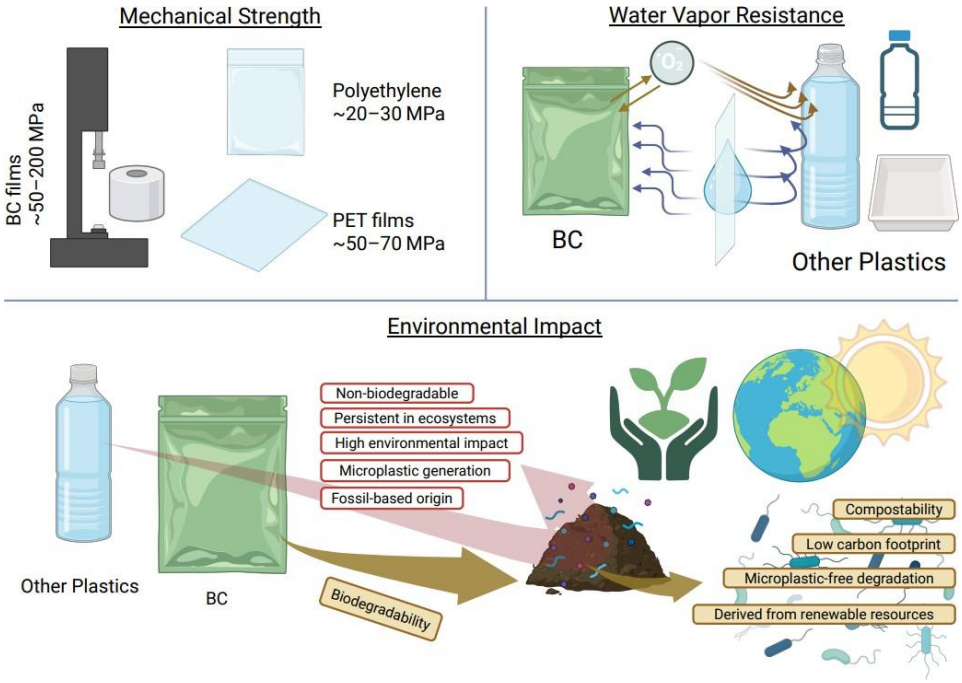

Figure 4 – Comparison of BC and conventional plastics in packaging applications
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BC derived from agricultural waste is emerging as a highly promising material for packaging applications due to its outstanding mechanical strength, excellent gas barrier properties, complete biodegradability, and the ability to be processed into thin, transparent films. By utilizing BC-based packaging, we can reduce plastic waste and contribute to environmental improvement, while also transforming agricultural and food industry residues into high-value, functional materials. However, for large-scale industrial implementation, several challenges remain such as enhancing fermentation productivity, accelerating production processes, improving moisture resistance, and increasing overall economic feasibility.

Conclusion

In conclusion, this review highlights the high potential of converting lignocellulosic plant biomass into environmentally friendly packaging materials through bacterial biotechnology. Monosaccharides derived from the hydrolysis of primary biomass components such as cellulose and hemicellulose can serve as carbon sources for bacteria during fermentation. Certain acetic acid bacteria can polymerize these sugars to produce extracellular BC. Utilizing agro-industrial residues as accessible carbon sources not only reduces the production cost of BC but also promotes process sustainability. Due to its high purity, strength, and biodegradability, BC represents a valuable and sustainable alternative for packaging. Compared to conventional plastics and some bioplastics, BC stands out for its complete biodegradability and origin from renewable waste materials. However, scaling BC production to an industrial level still faces several challenges, including high production costs and difficulties in upscaling and standardizing the process. Furthermore, the brittleness and moisture sensitivity of pure BC films complicate their direct substitution for plastic materials. To overcome these limitations, it is necessary to optimize bioreactor processes, improve high-yield bacterial strains through genetic engineering, and develop new BC-based composite materials. In addition, future directions should focus on industrial-scale implementation, comprehensive life cycle assessment to confirm environmental benefits, and integration of BC packaging into the circular bioeconomy. These efforts will significantly contribute to the development of zero-waste production and sustainable consumption systems.

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