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A.M. Belkozhayev[1]*, A. Abaildayev[1], B.D. Kossalbayev[1,2,3], N. Gizatullina[1], G. Toleutay[1,4],*
[1]Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University,
050013, Republic of Kazakhstan, Almaty, 22a Satpaev str.
[2]Al-Farabi Kazakh National University,
050040, Kazakhstan, Almaty, Al-Farabi Ave. 71,
[3]Ecology Research Institute, Khoja Akhmet Yassawi International Kazakh Turkish University,
Turkistan 161200, Kazakhstan
[4]University of Tennessee, Knoxville, TN 37996, USA
*e-mail: a.belkozhayev@satbayev.university

COMPARATIVE STRUCTURAL AND PHYSICOCHEMICAL ANALYSIS OF PLANT-DERIVED CELLULOSE FROM AGRICULTURAL RESIDUES AND BACTERIAL CELLULOSE

Abstract: *This study presents a comparative investigation of the structural and physicochemical properties of plant-derived cellulose extracted from agricultural residues (wheat, maize, cotton, and rice straw) and bacterial cellulose synthesized via fermentation using Komagataeibacter xylinus (K. xylinus). Plant-derived cellulose was obtained through an $AlCl_3$-glycerol pretreatment followed by alkaline purification, while bacterial cellulose was produced under static cultivation in a Hestrin – Schramm medium. The morphology, chemical structure, and thermal behavior of the resulting celluloses were systematically characterized using scanning electron microscopy (SEM), Fourier transform infrared (FTIR) spectroscopy, and thermogravimetric analysis (TGA/DTG). SEM analysis revealed that plant-derived cellulose exhibits elongated microfibrillar structures with fiber diameters ranging from 5 to 25 μm, accompanied by surface microcracks and pores resulting from effective removal of lignin and hemicellulose. In contrast, bacterial cellulose formed a dense, multilayered, and highly interconnected fibrillar network with significantly smaller fiber diameters (2.7-9.7 μm), reflecting its high structural uniformity and purity. FTIR spectra confirmed that both cellulose types share the same fundamental chemical backbone, while the weakening or absence of lignin-related absorption bands indicated efficient delignification and superior chemical purity in bacterial cellulose. Overall, the results demonstrate that plant-derived and bacterial cellulose possess distinct yet complementary structural characteristics. Plant-derived cellulose provides a fibrous structural framework, whereas bacterial cellulose offers a nanostructured network, suggesting their potential combined use in sustainable biopolymer composites and environmentally friendly packaging materials.*

Key words: *agricultural biomass; cellulose extraction; bacterial cellulose; sustainable packaging; FTIR; TGA; SEM.*

Introduction

In recent years, issues related to environmental sustainability, ecosystem preservation, and the reduction of carbon footprints have gained increasing global attention [1, 2]. In this context, there has been a growing interest in materials derived from renewable and biodegradable resources as viable alternatives to petroleum-based synthetic polymers. Among these materials, cellulose-based biopolymers have attracted particular interest due to their environmental friendliness, biocompatibility, and widespread availability [3, 4]. Cellulose is the most abundant biopolymer found in nature and serves as the primary structural component of plant cell walls [5]. Agricultural residues, including wheat, maize, rice, and cotton straw, represent inexpensive and cellulose-rich raw materials. Since such residues are commonly disposed of through open burning or other waste management practices, their valorization through recycling offers both environmental and economic advantages [6, 7]. Nevertheless, the presence of additional constituents such as lignin and hemicellulose within plant-derived biomass complicates the isolation of cellulose in its pure form, necessitating the development and application of efficient processing and pretreatment strategies [8]. In recent years, significant research efforts have been devoted to the development of environmentally friendly and efficient approaches for cellulose extraction [9]. Compared with conventional acid alkali treatment methods, systems based on ionic liquids and organic solvents including those employing glycerol and metal salts enable more effective lignin removal while preserving the structural integrity of cellulose [10, 11]. Such strategies are consistent with the

principles of green chemistry and contribute to reducing the environmental burden associated with biomass processing [12]. In addition to plant-derived cellulose, bacterial cellulose has recently attracted considerable scientific and practical interest due to its highly pure nanofibrous structure and its biosynthesis by bacteria belonging to the Komagataeibacter genus, which results in cellulose free of lignin and hemicellulose (Figure 1) [13-15]. Bacterial cellulose is characterized by a high degree of crystallinity, excellent mechanical strength, superior water-holding capacity, and outstanding barrier properties, making it a promising material for applications in packaging, biomedicine, and biocomposite development [16]. Although plant-derived and bacterial celluloses differ in their structural organization, their combined use allows for complementary enhancement of material properties [14, 16]. Plant-based cellulose contributes a fibrous structural framework and cost-effectiveness, whereas bacterial cellulose may act as a nanostructured reinforcing component, potentially contributing to improved structural and barrier properties of biopolymer matrices. Consequently, a comparative investigation of the structural and physicochemical characteristics of these two types of cellulose represents an important scientific objective for the development of environmentally friendly and high-performance biopolymeric materials [17, 18]. The aim of this study is to conduct a comprehensive investigation and comparative evaluation of the structural, chemical, and thermal properties of plant-derived cellulose obtained from agricultural biomass and bacterial cellulose synthesized via fermentation, as well as the biopolymeric materials developed on their basis. The findings of this work are expected to provide a scientific foundation for the design of environmentally friendly packaging materials and biocomposites, while also contributing to the valorization of agro-industrial residues into value-added products.

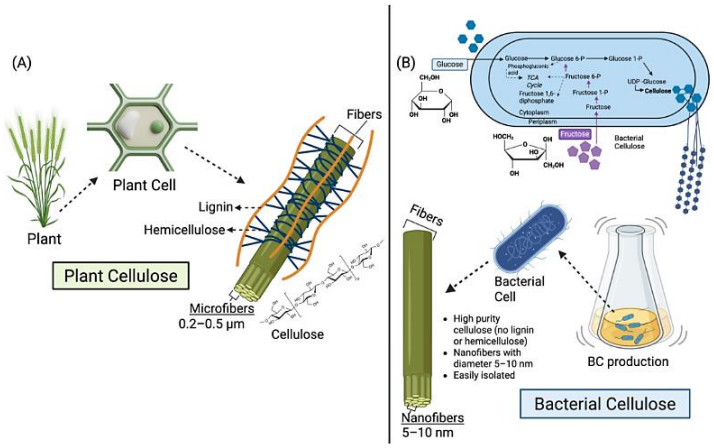


Figure 1 – Schematic illustration of the structural organization of plant-derived cellulose (A) and the biosynthesis and nanofibrillar structure of bacterial cellulose (B). (B) Created with BioRender.com (License No. SN298B73AX)

Materials and Methods

Raw materials and reagents

Agricultural residues, including wheat straw, maize stalks, cotton stalks, and rice straw, were used as raw materials for the extraction of plant-derived cellulose. All biomass samples were thoroughly cleaned to remove foreign impurities, repeatedly washed with running water, and subsequently dried prior to further processing. Glycerol, aluminum chloride ($AlCl_3$), sodium hydroxide (NaOH), ethanol, and other chemical reagents used in this study were of analytical grade. Distilled water was used in all experimental procedures.

Biomass pretreatment and chemical processing for plant-derived cellulose extraction

The overall experimental workflow for the extraction, purification, and characterization of plant-derived and bacterial cellulose is illustrated in Figure 2. Dried agricultural residues were mechanically milled to obtain particles with an average size of 1-2 mm. The ground biomass was sieved to ensure a uniform particle size distribution and stored in a dry environment prior to chemical processing. Chemical pretreatment was performed using an $AlCl_3$ – glycerol system to facilitate cellulose liberation and promote lignin removal. The reaction medium consisted of 80% glycerol, 20% distilled water, and 0.1 M $AlCl_3$ as a catalyst. The solid-to-liquid ratio was maintained at 1:10.

Pretreatment was carried out under a two-step autoclave regime: 120°C for 20 min followed by 132°C for 30 min. After pretreatment, the reaction mixture was separated into solid and liquid phases by vacuum filtration. The solid fraction enriched in cellulose fibers was subjected to further purification. In the present study, the focus was primarily on the structural and physicochemical characterization of the extracted cellulose. Therefore, the quantitative yield of cellulose from different biomass sources was not determined.

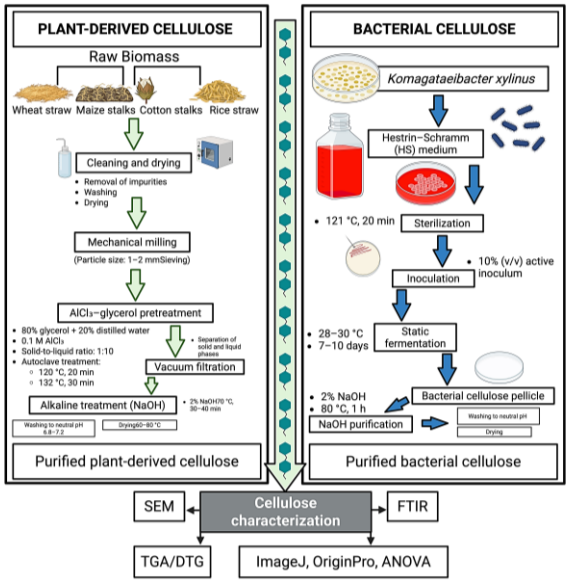


Figure 2 – Schematic workflow of plant-derived and bacterial cellulose production, purification, and subsequent characterization. Created with BioRender.com (License No. RB298AZ6KT)

Alkaline purification and drying of plant-derived cellulose

The obtained fibrous material was repeatedly washed with distilled water at 80°C and subsequently treated with 96% ethanol to remove residual waxes and resinous substances. To ensure complete removal of remaining lignin, the samples were subjected to alkaline treatment in a 2% (w/v) NaOH solution at 70°C for 30-40 min. After alkaline processing, the samples were thoroughly rinsed with distilled water until a neutral pH (6.8-7.2) was achieved. The purified cellulose fibers were then dried at 60-80 °C and stored in sealed containers prior to characterization.

Production of bacterial cellulose

Bacterial cellulose was produced using the K. xylinus strain. Fermentation was carried out in a standard Hestrin – Schramm (HS) medium composed of glucose (20 g/L), peptone (5 g/L), yeast extract (5 g/L), Na_2HPO_4 (2.7 g/L), and citric acid (1.15 g/L). The initial pH of the medium was adjusted to 5.0-5.5 prior to sterilization. The culture medium was sterilized in an autoclave at 121 °C for 20 min. After cooling to room temperature, an active inoculum (10%, v/v) was aseptically added. Fermentation was conducted under static conditions at 28-30°C for 7-10 days, during which a gelatinous bacterial cellulose pellicle formed at the air-liquid interface.

Purification and drying of bacterial cellulose

The obtained bacterial cellulose pellicles were thoroughly washed with distilled water and subsequently treated with a 2% (w/v) NaOH solution at 80 °C for 1 h to remove bacterial cells and residual proteins. The samples were then rinsed repeatedly with distilled water until a neutral pH was reached and dried at 40°C prior to further analysis.

Morphological analysis

The morphological features of plant-derived and bacterial cellulose samples were examined using scanning electron microscopy. Dried samples were mounted on aluminum stubs and analyzed under low-vacuum conditions at an accelerating voltage of 5-15 kV. Images were acquired over a magnification range of 100× to 20,000×.

Fourier transform infrared spectroscopy

FTIR spectroscopy was employed to investigate the chemical structure of the cellulose samples. Spectra were recorded in the range of 4000-400 cm^{-1} with a spectral resolution of 4 cm^{-1} and 32 scans per sample. The obtained spectra were used to identify characteristic functional groups of cellulose and to evaluate the efficiency of the delignification process.

Thermal analysis

The thermal stability of the cellulose samples was assessed using TGA and derivative thermogravimetric analysis (DTG). Measurements were performed under a nitrogen atmosphere from room temperature to 600°C at a heating rate of 10°C/min. The sample mass ranged between 10 and 15 mg.

Statistical analysis

Experimental data processing and graphical visualization were carried out using OriginLab Pro 2024 software. Quantitative analysis of fiber diameters was performed using ImageJ software. Statistical significance was evaluated using one-way analysis of variance (ANOVA) and Student's t-test, with $p < 0.05$ considered statistically significant.

Results

Morphological analysis of wheat straw derived and bacterial cellulose

The morphological features of cellulose fibers isolated from wheat straw via an organic pretreatment approach were examined using scanning electron microscopy (Figure 3). SEM micrographs revealed that the fibers exhibit a clearly elongated morphology and form an interconnected network structure. Such morphological characteristics are typical of plant-derived cellulose and may contribute to the structural stability of the material. Quantitative analysis indicated that the diameter of cellulose fibers obtained from wheat straw varied within the range of 5-25 μm, which is consistent with values reported for natural plant-based cellulose. Notably, one representative SEM measurement showed a fiber diameter of approximately 5.25 μm, suggesting a relatively uniform microfibrillar structure. At higher magnifications, the fiber surfaces displayed the presence of microcracks and small pores. These morphological features are attributed to the removal of lignin and hemicellulose during organic pretreatment and subsequent alkaline purification. The resulting porous surface increases the specific surface area of the fibers and may enhance their adhesion to polymeric and biological matrices, potentially contributing to improved structural stability of composite materials. The SEM analysis confirmed that cellulose derived from wheat straw possesses high structural integrity and a homogeneous microfibrillar morphology. These characteristics demonstrate its potential as an environmentally friendly, recyclable raw material suitable for the development of biopolymer composites intended for sustainable packaging applications.

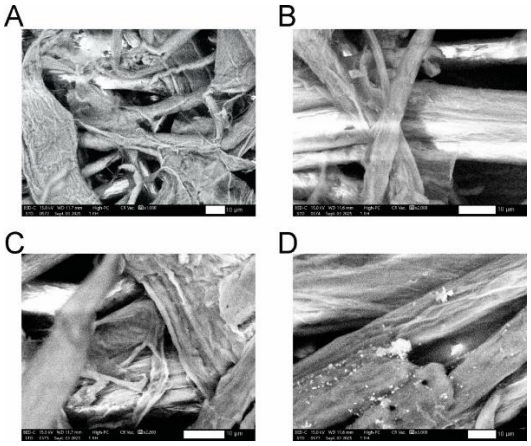


Figure 3 – Morphological structure of cellulose fibers obtained from wheat straw via organic pretreatment. The fibers exhibit a distinctly elongated morphology and an interconnected network structure. The presence of microcracks and small pores on the fiber surface indicates the effective removal of lignin and hemicellulose.
Magnification scales: (A) ×1000, (B) ×2000, (C) ×2200, (D) ×3000.

The morphological characteristics of bacterial cellulose (BC) synthesized via fermentation were examined using scanning electron microscopy (SEM) (Figure 4). SEM observations revealed that BC forms a dense and highly interconnected fibrillar network with a compact, mesh-like architecture. At ×1500 magnification (Figure 4A), the BC fibers appeared extensively intertwined, forming compact microfibrillar bundles and multilayered arrangements. Quantitative measurements indicated that the fiber diameters ranged within from 2.7 to 9.7 μm., reflecting the formation of well-developed microfibrillar structures. Such dense entanglement and bundle formation contribute to the

development of a three-dimensional network, which is closely associated with the high structural stability and water-holding capacity of bacterial cellulose. At a higher magnification of ×2000 (Figure 4B), individual fibrils and their preferential orientation became more clearly distinguishable. At this scale, a broader distribution of fiber diameters was observed, suggesting partial fibril aggregation and hierarchical structural organization within the cellulose network. The fiber surfaces appeared smooth and homogeneous, with no observable bacterial cells or foreign impurities, confirming the effectiveness of the purification process. The SEM analysis demonstrates that bacterial cellulose synthesized by K. xylinus exhibits a compact, uniform, and well-organized fibrillar morphology. These structural features highlight the high degree of molecular ordering and make bacterial cellulose a promising material for applications in sustainable food packaging, biomedical materials, tissue engineering scaffolds, and environmentally friendly biopolymer composites.

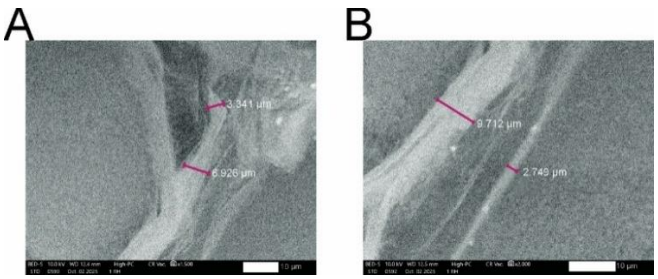


Figure 4 – Morphological structure of bacterial cellulose observed by scanning electron microscopy. The images reveal a dense, interconnected fibrillar network characteristic of bacterial cellulose. Magnification: (A) ×1500 and (B) ×2000

The morphological architecture of cellulosic materials plays a crucial role in determining their functional performance. In this study, clear morphological differences were observed between plant-derived and bacterial cellulose. Cellulose isolated from wheat straw exhibited a microfibrillar structure that provides bulk mechanical strength, whereas bacterial cellulose formed a dense, nanoscale, interconnected fibrillar network that enhances structural reinforcement. These complementary morphological features indicate that the combined use of plant-derived and bacterial cellulose is a promising approach for developing environmentally friendly packaging materials with improved mechanical and functional properties.

FTIR analysis

FTIR spectroscopy was employed to examine the chemical structure and functional groups of plant-derived celluloses obtained from agricultural biomass, including wheat, maize, cotton, and rice straw, as well as bacterial cellulose synthesized via fermentation. FTIR analysis enabled the evaluation of cellulose chemical purity, assessment of lignin and hemicellulose removal efficiency, and comparison of structural differences between plant-based and bacterial cellulose samples.

FTIR spectra of plant-derived celluloses (wheat, maize, cotton, and rice)

The FTIR spectra of celluloses isolated from wheat, maize, cotton, and rice straw exhibited highly similar profiles, confirming the presence of characteristic absorption bands associated with cellulose. A broad band observed in the region of 3300-3400 cm^{-1} corresponds to the stretching vibrations of hydroxyl (–OH) groups, indicating the presence of extensive intermolecular hydrogen bonding within the cellulose macromolecules (Figure 5). The absorption band located near 2890 cm^{-1} is attributed to aliphatic C–H stretching vibrations, confirming the preservation of the cellulose hydrocarbon backbone. A pronounced peak around 1050 cm^{-1} is associated with C–O–C stretching vibrations of β-1,4-glycosidic linkages, while the band observed near 897 cm^{-1} further confirms the presence of β-glycosidic bonds. These features provide clear evidence of the cellulosic nature of the extracted materials. The absence or very weak intensity of aromatic vibration bands typically associated with lignin in the range of 1510-1600 cm^{-1} indicates the effective removal of lignin and hemicellulose during organic pretreatment and alkaline purification. Additionally, a weak band observed near 1640 cm^{-1} corresponds to the deformation vibrations of bound water, reflecting the hygroscopic character of cellulose. The FTIR results demonstrate that celluloses obtained from wheat, maize, cotton, and rice straw exhibit similar chemical compositions and represent sufficiently purified cellulose materials.

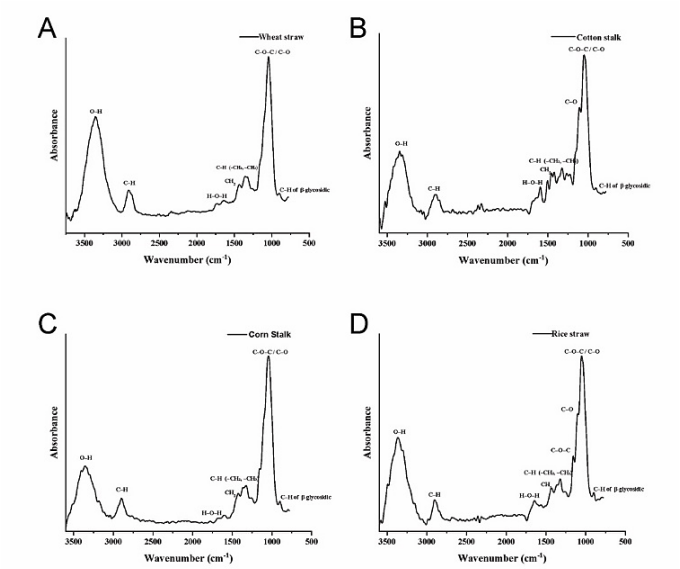


Figure 5 – FTIR spectra of cellulose extracted from different agricultural residues:
(A) wheat straw, (B) cotton stalk, (C) corn stalk, and (D) rice straw. All spectra exhibit characteristic cellulose absorption bands, including O–H stretching vibrations (3300–3400 cm^{-1}), C–H stretching vibrations (~2900 cm^{-1}), C–O–C/C–O stretching vibrations (~1050 cm^{-1}), and β-glycosidic bond vibrations (~897 cm^{-1}). The absence of lignin-related aromatic bands (1510–1600 cm^{-1}) indicates effective removal of non-cellulosic components during pretreatment.

FTIR spectrum of bacterial cellulose

The FTIR spectrum of BC exhibited the same characteristic cellulose-related absorption bands observed for plant-derived celluloses. The broad –OH stretching band in the range of 3300-3400 cm^{-1}, together with the C–H stretching vibration near 2890 cm^{-1}, indicates a well-developed hydrogen-bonding network within the bacterial cellulose structure (Figure 6) .In addition, the pronounced peaks observed at approximately 1050 cm^{-1} and 897 cm^{-1} confirm the presence of an ordered structure based on β-1,4-glycosidic linkages. The complete absence of absorption bands associated with lignin and hemicellulose in the bacterial cellulose spectrum further demonstrates its high chemical purity and confirms its biosynthetic origin as a naturally produced cellulose.

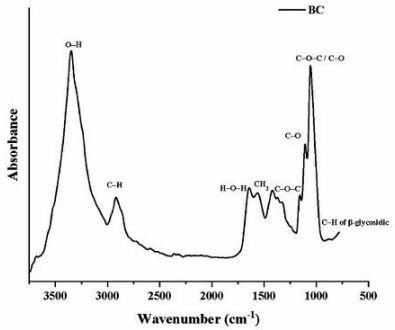


Figure 6 – FTIR spectrum of bacterial cellulose synthesized via fermentation

Compared to plant-derived celluloses, the FTIR spectrum of bacterial cellulose exhibited more distinct and intense absorption bands, indicating a higher degree of structural order, which is consistent with the well-organized nanofibrillar structure of bacterial cellulose (Figure 7). FTIR analysis confirmed that plant-derived and bacterial celluloses share the same fundamental chemical nature; however, notable differences were observed in their purity levels and structural organization. Although organic pretreatment effectively removed most lignin and hemicellulose from plant-based celluloses, bacterial cellulose demonstrated superior chemical purity and structural homogeneity. Overall, the FTIR results verify that both plant-derived celluloses obtained from agricultural biomass and bacterial cellulose are chemically suitable to produce biopolymer composites and environmentally friendly packaging materials.

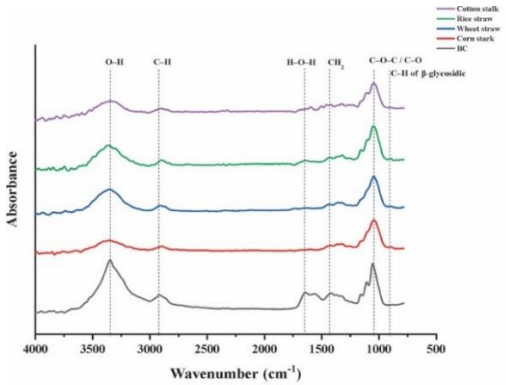
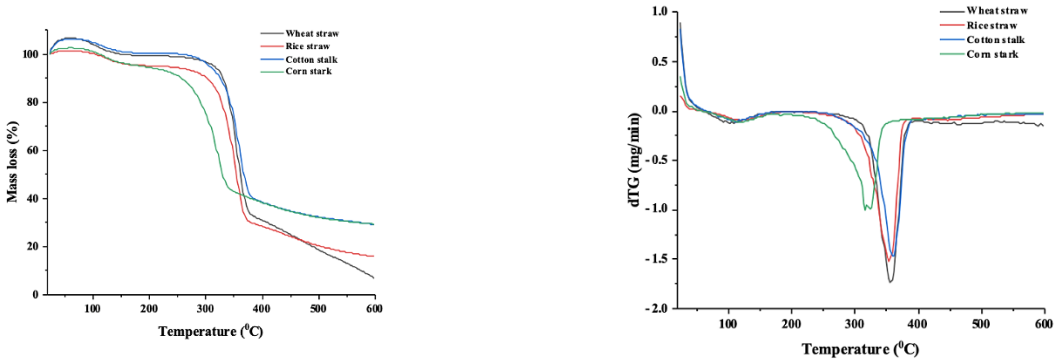


Figure 7 – Overlaid FTIR spectra of plant-derived celluloses obtained from wheat, maize, cotton, and rice straw, together with bacterial cellulose

Thermal analysis

Thermogravimetric analysis (TGA) and derivative thermogravimetric analysis (DTG) were performed to evaluate the thermal stability and degradation behavior of celluloses obtained from agricultural residues (wheat, maize, cotton, and rice straw) and bacterial cellulose. The analysis was conducted in a nitrogen atmosphere within the temperature range of 50-600°C (Figure 8). The TGA curves revealed a characteristic three-stage thermal degradation pattern typical for cellulose-based materials. The first stage, occurring at 50-120°C, corresponds to the evaporation of physically adsorbed moisture, resulting in a mass loss of approximately 5-8%. The second stage, observed in the 250-380°C range, represents the main thermal degradation region associated with the depolymerization of cellulose chains and the cleavage of β-1,4-glycosidic bonds, where the major mass loss (60-70%) occurs. The third stage, above 400°C, corresponds to the slow decomposition of residual carbonaceous structures and mineral components.

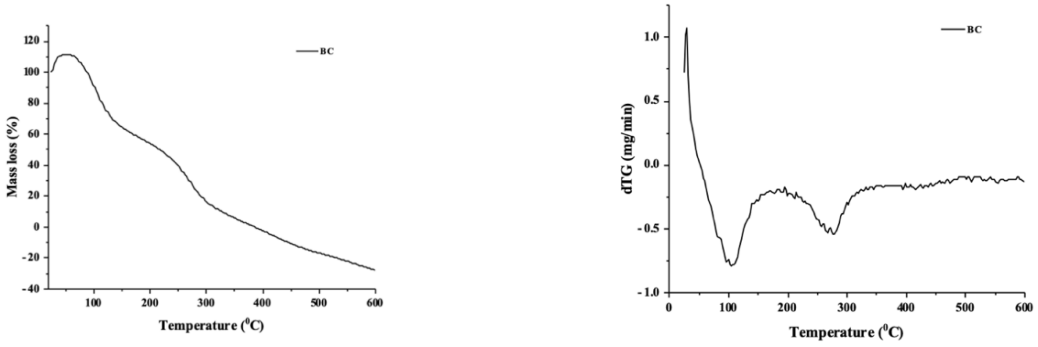
DTG analysis provided a more precise description of the degradation kinetics. The maximum degradation rate (Tmax) for most plant-derived cellulose samples was observed within the 330-360 °C range. Among the studied samples, cellulose obtained from cotton stalks showed the highest thermal stability with a Tmax close to 360°C, which can be attributed to its more homogeneous fiber structure and higher structural organization. Cellulose derived from maize stalks exhibited a Tmax around 350°C, while wheat straw cellulose showed moderate thermal stability with the main degradation occurring between 350-370°C. In contrast, cellulose from rice straw demonstrated a broader degradation profile and higher residual mass, which is likely associated with the presence of inorganic components such as silica (SiO_2).



(A) (B)

Figure 8 – Thermal properties of celluloses obtained from agricultural biomass:
(A) TGA curve showing mass loss as a function of temperature;
(B) DTG curve showing the temperature dependence of the degradation rate

The thermogravimetric behavior of bacterial cellulose (BC) showed a similar multistage degradation pattern (Figure 9). An initial mass loss of 8-12% was observed in the 30-120°C range due to the evaporation of bound water, reflecting the high water-holding capacity of BC. The main degradation stage occurred between 300-380°C, with a Tmax in the range of 330-355°C, corresponding to the decomposition of the cellulose backbone. Above 400°C, the degradation rate decreased significantly, indicating the formation of carbonaceous residues.



(A) (B)

Figure 9 – Thermogravimetric and derivative thermogravimetric analysis of bacterial cellulose:
(A) TGA curve showing mass change as a function of temperature;
(B) DTG curve showing the temperature dependence of the degradation rate

The results demonstrate that both plant-derived and bacterial celluloses exhibit relatively high thermal stability, with the main degradation occurring around 330-360°C. The slightly higher thermal stability of bacterial cellulose is associated with its high structural order, uniform nanofibrillar morphology, and absence of lignin and hemicellulose. These findings confirm that both types of cellulose possess sufficient thermal stability for potential applications in biopolymer composites and sustainable packaging materials.

Discussion

The comparative SEM and FTIR analyses provide insight into how the origin and biosynthesis pathways of cellulose influence its structural organization and potential functionality. The observed distinctions between plant-derived and bacterial cellulose reflect fundamentally different formation mechanisms, with plant cellulose originating from lignocellulosic cell walls and bacterial cellulose being biosynthesized in situ as a highly ordered fibrillar network. From a materials science perspective, such origin-dependent structural organization is critical, as microfibrillar architectures are typically associated with bulk mechanical reinforcement, whereas densely interconnected nanofibrillar networks are more effective in providing nanoscale reinforcement, enhanced interfacial interactions, and improved functional performance in composite systems. The present study highlights the complementary rather than competitive roles of plant-derived and bacterial cellulose, emphasizing their combined potential for the rational design of sustainable biopolymer materials.

These findings are supported by recent studies. For example, Efthymiou et al. (2022) demonstrated, through SEM and FTIR analyses, that bacterial cellulose exhibits a well-developed network-like nanofibrillar structure with a high degree of structural organization and crystallinity [19]. Similarly, Yilmaz et al. (2024) reported that bacterial cellulose production by K. xylinus can be effectively optimized and emphasized that the resulting BC morphology and structural properties are strongly dependent on the cultivation medium and fermentation conditions [20]. Furthermore, in line with the solvent-based approach employed in the present study using an $AlCl_3$ – glycerol system, Zhao et al. (2025) reported that glycerol-based pretreatment facilitates lignin redistribution and fiber defibrillation, resulting in pronounced alterations in cellulose structure and enhanced accessibility [21]. Consistently, our FTIR results revealed a noticeable weakening of lignin-related absorption bands, confirming the effectiveness of glycerol-assisted pretreatment in reducing lignin interference and promoting cellulose structural reorganization.

From an applied perspective, Sun et al. (2022) demonstrated that the three-dimensional reticulated nanofibrillar structure of bacterial cellulose provides an effective matrix for the incorporation of bioactive components. SEM analysis revealed a highly uniform fibrillar structure of bacterial cellulose – based composite films, suggesting potential advantages for their structural organization. These observations complement the findings of the present study, as our SEM results likewise indicate a dense and interconnected fibrillar network in bacterial cellulose, suggesting its potential role as a nanostructural reinforcing phase in composite materials [22]. Jiang et al. (2022) investigated the development of cellulose-based paper materials for food packaging through multilayer functional surface modification. Their study demonstrated that coating cellulose paper with polylactic acid (PLA) significantly enhanced tensile strength, while the introduction of nanoscale

SiO_2/stearic acid layers imparted superhydrophobic behavior and markedly improved gas, moisture, and oil barrier properties [23]. The authors emphasized that the inherent fibrous structure of cellulose paper provides the primary mechanical framework, whereas nanoscale surface and structural features play a critical role in improving functional performance. These observations are in line with the findings of the present study, where clear structural distinctions were identified between plant-derived and bacterial cellulose. In our work, plant-derived cellulose exhibited a microfibrillar architecture that mainly contributes bulk mechanical support, while bacterial cellulose formed a dense and highly interconnected nanofibrillar network, as revealed by SEM analysis. Such a nanostructured morphology suggests that bacterial cellulose may contribute to property enhancement at the nanostructural level, complementing the role of plant-derived cellulose as a fibrous structural framework in biopolymer composites intended for sustainable packaging applications.

The comparative analysis highlights the complementary roles of plant-derived and bacterial cellulose in biopolymer systems. Plant-derived cellulose provides a mechanically robust fibrous framework, while bacterial cellulose, owing to its highly ordered and interconnected nanofibrillar structure, offers advantages at the nanoscale that can contribute to enhanced functional performance. The combination of these structural features, together with effective pretreatment and purification strategies, supports the rational design of environmentally friendly and high-performance cellulose-based composites for sustainable packaging applications.

Conclusion

This study presented a detailed comparative analysis of plant-derived cellulose extracted from wheat, maize, cotton, and rice straw and bacterial cellulose synthesized via K. xylinus, with a focus on their structural and physicochemical characteristics. SEM analysis demonstrated that plant-derived cellulose exhibits elongated microfibrillar structures with fiber diameters ranging from 5 to 25 μm, accompanied by surface microcracks and pores formed because of effective lignin and hemicellulose removal during $AlCl_3$ – glycerol pretreatment and subsequent alkaline purification. These features indicate good structural integrity and suitability of plant-derived cellulose as a bulk reinforcing framework in biopolymer systems. In contrast, bacterial cellulose formed a dense, multilayered, and highly interconnected fibrillar network with significantly smaller fiber diameters (2.7-9.7 μm), smooth surfaces, and the absence of visible impurities, reflecting its high structural homogeneity and purification efficiency. FTIR spectroscopy confirmed that both plant-derived and bacterial celluloses share the same fundamental cellulose chemical backbone. However, the pronounced weakening or absence of lignin-related absorption bands in plant-derived samples, together with their complete absence in bacterial cellulose, verified effective delignification and the inherently high chemical purity of bacterial cellulose. Moreover, the stronger and sharper FTIR absorption bands observed for bacterial cellulose suggest a higher degree of structural order and molecular organization, consistent with its uniform nanofibrillar morphology. The results demonstrate that plant-derived cellulose and bacterial cellulose possess distinct yet complementary structural characteristics. Plant-derived cellulose primarily contributes bulk mechanical strength through its microfibrillar architecture, whereas bacterial cellulose, owing to its dense nanofibrillar network and higher structural order, is well suited for nanostructural reinforcement. The combined utilization of agricultural biomass–derived cellulose and bacterial cellulose, supported by environmentally friendly pretreatment and purification strategies, offers a scientifically grounded approach for the development of sustainable cellulose-based biopolymer composites and packaging materials.

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А.М. Белкожаев[1]*, А.О. Абайлдаев[1], Б.Д. Қосалбаев[1,2,3], Н. Ғизатуллина[1], Г. Толеутай[1,4]*
[1]Қ. Тұрысов атындағы геология Және Мұнай-Газ Ісі Институты, Сәтбаев Университеті,
050013, Қазақстан Республикасы, Алматы қ., Сәтбаев к-сі, 22а.
[2]ал-Фараби атындағы қазақ Ұлттық Университеті,
050040, Қазақстан, Алматы Қ., Әл-Фараби Даңғ. 71,
[3]Экология Ғылыми-Зерттеу Институты, Қожа Ахмет Ясауи Атындағы халықаралық
қазақ-түрік Университеті, Түркістан Қ., 161200, Қазақстан
[4]Теннесси университеті, Ноксвилл, TN 37996, АҚШ
*e-mail: a.belkozhayev@satbayev.university

АУЫЛШАРУАШЫЛЫҚ ҚАЛДЫҚТАРЫНАН АЛЫНҒАН ӨСІМДІК ТЕКТІ ЦЕЛЛЮЛОЗА МЕН БАКТЕРИЯЛЫҚ ЦЕЛЛЮЛОЗАНЫҢ ҚҰРЫЛЫМДЫҚ ЖӘНЕ ФИЗИКА-ХИМИЯЛЫҚ ҚАСИЕТТЕРІН САЛЫСТЫРМАЛЫ ТАЛДАУ

Бұл зерттеуде ауылшаруашылық қалдықтарынан (бидай, жүгері, мақта және күріш сабаны) алынған өсімдік текті целлюлозаның және Komagataeibacter xylinus (K. xylinus) көмегімен ферментация арқылы синтезделген бактериялық целлюлозаның құрылымдық және физика-химиялық қасиеттеріне салыстырмалы талдау жүргізілді. Өсімдік текті целлюлоза $AlCl_3$–глицеринмен алдын ала өңдеуден кейін сілтілік тазалау арқылы алынды, ал бактериялық целлюлоза Hestrin–Schramm қоректік ортасында статикалық культивирлеу жағдайында синтезделді. Алынған целлюлоза үлгілерінің морфологиясы, химиялық құрылымы және термиялық тұрақтылығы сканерлеуші электрондық микроскопия (SEM), Фурье түрлендірулі инфрақызыл спектроскопия (FTIR) және термогравиметриялық талдау (TGA/DTG) әдістері арқылы жүйелі түрде зерттелді. SEM талдауы өсімдік текті целлюлозаның талшық диаметрі 5-25 мкм аралығында болатын ұзын микрофибриллярлы құрылымдарға ие екенін, сондай-ақ лигнин мен гемицеллюлозаның тиімді жойылуы нәтижесінде бетінде микрожарықтар мен кеуектердің пайда болғанын көрсетті. Ал бактериялық целлюлоза тығыз, көпқабатты және өзара тығыз байланысқан фибриллярлы тор түзді, оның талшық диаметрі айтарлықтай кіші (2,7-9,7мкм), бұл оның жоғары құрылымдық біртектілігі мен тазалығын көрсетеді. FTIR спектрлері екі целлюлоза түрінің де негізгі химиялық қаңқасы бірдей екенін растады, ал лигнинге тән жұтылу жолақтарының әлсіреуі немесе болмауы тиімді делигнификацияны және бактериялық целлюлозаның жоғары химиялық тазалығын көрсетті. Жалпы алғанда, алынған нәтижелер өсімдік текті және бактериялық целлюлозаның құрылымдық қасиеттері әртүрлі, бірақ өзара толықтыратын сипатқа ие екенін дәлелдейді. Өсімдік текті целлюлоза көлемдік механикалық беріктік берсе, бактериялық целлюлоза наноқұрылымдық арматура қызметін атқарады, бұл олардың тұрақты биополимерлі композиттер мен экологиялық таза қаптама материалдарын әзірлеуде бірлесіп қолданылуын негіздейді.

Түйін сөздер: *ауылшаруашылық биомассасы; целлюлозаны экстракциялау; бактериялық целлюлоза; тұрақты қаптама; FTIR; TGA; SEM.*

А.М. Белкожаев[1]*, А.О. Абайлдаев[1], Б.Д. Косалбаев[1,2,3], Н. Гизатуллина[1], Г. Толеутай[1,4]
[1]Институт геологии и нефтегазового дела имени К. Турысова, Университет Сатпаева,
050013, Республика Казахстан, г. Алматы, ул. Сатпаева, 22а.
[2]Казахский национальный университет им. аль-Фараби,
050040, Казахстан, Алматы, пр. Аль-Фараби, 71,
[3]Институт экологических исследований, Международный Казахско-Турецкий университет имени
Ходжи Ахмета Яссави, Туркестан, 161200, Казахстан
[4]Университет Теннесси, Ноксвилл, Теннесси 37996, США
*e-mail: a.belkozhayev@satbayev.university

СРАВНИТЕЛЬНЫЙ СТРУКТУРНЫЙ И ФИЗИКО-ХИМИЧЕСКИЙ АНАЛИЗ ЦЕЛЛЮЛОЗЫ РАСТИТЕЛЬНОГО ПРОИСХОЖДЕНИЯ ИЗ СЕЛЬСКОХОЗЯЙСТВЕННЫХ ОТХОДОВ И БАКТЕРИАЛЬНОЙ ЦЕЛЛЮЛОЗЫ

В данном исследовании представлен сравнительный анализ структурных и физико-химических свойств целлюлозы растительного происхождения, выделенной из сельскохозяйственных отходов (солома пшеницы, кукурузы, хлопка и риса), и бактериальной целлюлозы, синтезированной методом ферментации с использованием Komagataeibacter xylinus (K. xylinus). Растительная целлюлоза была получена путем предварительной обработки системой $AlCl_3$-глицерин с последующей щелочной очисткой, тогда как бактериальная целлюлоза синтезировалась в статических условиях культивирования в среде Хестрина-Шрамма. Морфология, химическая структура и термическое поведение полученных образцов целлюлозы были систематически охарактеризованы с использованием сканирующей электронной микроскопии (SEM), инфракрасной спектроскопии с преобразованием Фурье (FTIR) и термогравиметрического

анализа (TGA/DTG). Результаты SEM показали, что целлюлоза растительного происхождения характеризуется вытянутыми микрофибриллярными структурами с диаметром волокон в диапазоне 5-25 мкм, а также наличием поверхностных микротрещин и пор, сформированных в результате эффективного удаления лигнина и гемицеллюлозы. В отличие от нее, бактериальная целлюлоза формирует плотную, многослойную и высоко взаимосвязанную фибриллярную сеть с существенно меньшим диаметром волокон (2,7-9,7мкм), что отражает ее высокую структурную однородность и чистоту. FTIR-спектры подтвердили наличие общей фундаментальной химической структуры для обоих типов целлюлозы, тогда как ослабление или отсутствие полос поглощения, характерных для лигнина, свидетельствовало об эффективной делигнификации и более высокой химической чистоте бактериальной целлюлозы. В целом результаты демонстрируют, что растительная и бактериальная целлюлоза обладают различными, но взаимодополняющими структурными характеристиками. Целлюлоза растительного происхождения обеспечивает объемную механическую прочность, тогда как бактериальная целлюлоза выполняет функцию наноразмерного армирования, что обосновывает их совместное применение при разработке устойчивых биополимерных композитов и экологически безопасных упаковочных материалов.

Ключевые слова: *сельскохозяйственная биомасса; экстракция целлюлозы; бактериальная целлюлоза; устойчивая упаковка; FTIR; TGA; SEM.*

Information about the authors

Ayaz Maratovich Belkozhayev* – PhD, Associate Professor of Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Almaty, Kazakhstan; e-mail: a.belkozhayev@satbayev.university. ORCID: https://orcid.org/0000-0001-7429-4994.

Arman Orazalyuly Abaildayev – Senior lecturer of Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Almaty, Kazakhstan; e-mail: a.abaildayev@satbayev.university. ORCID: https://orcid.org/0000-0002-1813-1338.

Bekzhan Duisenbiuly Kossalbayev – PhD, Associate Professor of Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Almaty, Kazakhstan; e-mail: kossalbayev.bekzhan@gmail.com. ORCID: https://orcid.org/0000-0003-3892-7920.

Nargiz Gizatullina – PhD student, Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Almaty, Kazakhstan; e-mail: nar.gn@bk.ru. ORCID: https://orcid.org/0000-0003-4230-1031.

Gaukhar Toleutay – PhD of Department of Chemical and Biochemical Engineering, Geology and Oil-Gas Business Institute Named After K. Turyssov, Satbayev University, Republic of Kazakhstan; e-mail: gaukhar.toleutay@gmail.com. ORCID: https://orcid.org/0000-0003-0381-6665.

Авторлар туралы мәліметтер

Аяз Маратович Белкожаев* – PhD, Химиялық және биохимиялық инженерия кафедрасының қауымдастырылған профессоры, К. Тұрысов атындағы Геология және мұнай-газ ісі институты, Сәтбаев университеті, Алматы, Қазақстан; e-mail: a.belkozhayev@satbayev.university. ORCID: https://orcid.org/0000-0001-7429-4994.

Арман Оразалыұлы Абайлдаев – Химиялық және биохимиялық инженерия кафедрасының аға оқытушысы, К. Тұрысов атындағы Геология және мұнай-газ ісі институты, Сәтбаев университеті, Алматы, Қазақстан; e+mail: a.abaildayev@satbayev.university. ORCID: https://orcid.org/0000-0002-1813-1338.

Бекжан Дуйсенбиұлы Қосалбаев – PhD, Химиялық және биохимиялық инженерия кафедрасының қауымдастырылған профессоры, К. Тұрысов атындағы Геология және мұнай-газ ісі институты, Сәтбаев университеті, Алматы, Қазақстан; e-mail: kossalbayev.bekzhan@gmail.com. ORCID: https://orcid.org/0000-0003-3892-7920.

Наргиз Ғизатуллина – химиялық және биохимиялық инженерия кафедрасының докторанты, К. Тұрысов атындағы Геология және мұнай-газ ісі институты, Сәтбаев университеті, Алматы, Қазақстан; e-mail: nar.gn@bk.ru. ORCID: https://orcid.org/0000-0003-4230-1031.

Гаухар Толеутай – PhD, Химиялық және биохимиялық инженерия кафедрасы, К. Тұрысов атындағы Геология және мұнай-газ ісі институты, Сәтбаев университеті, Қазақстан; e-mail: gaukhar.toleutay@gmail.com. ORCID: https://orcid.org/0000-0003-0381-6665.

Сведения об авторах

Аяз Маратович Белкожаев* – PhD, ассоциированный профессор кафедры химической и биохимической инженерии Института геологии и нефтегазового дела им. К. Турысова, Университет Сатпаева, Алматы, Казахстан; e-mail: a.belkozhayev@satbayev.university. ORCID: https://orcid.org/0000-0001-7429-4994.

Арман Оразалыулы Абайлдаев – старший преподаватель кафедры химической и биохимической инженерии Института геологии и нефтегазового дела им. К. Турысова, Университет Сатпаева, Алматы, Казахстан; e-mail: a.abaildayev@satbayev.university. ORCID: https://orcid.org/0000-0002-1813-1338.

Бекжан Дуисенбиулы Коссалбаев – PhD, ассоциированный профессор кафедры химической и биохимической инженерии Института геологии и нефтегазового дела им. К. Турысова, Университет Сатпаева, Алматы, Казахстан; e-mail: kossalbayev.bekzhan@gmail.com. ORCID: https://orcid.org/0000-0003-3892-7920.

Наргиз Гизатуллина – докторант кафедры химической и биохимической инженерии Института геологии и нефтегазового дела им. К. Турысова, Satbayev University, Алматы, Казахстан; e-mail: nar.gn@bk.ru. ORCID: https://orcid.org/0000-0003-4230-1031.

Гаухар Толеутай – PhD кафедры химической и биохимической инженерии Института геологии и нефтегазового дела им. К. Турысова, Университет Сатпаева, Казахстан; e-mail: gaukhar.toleutay@gmail.com. ORCID: https://orcid.org/0000-0003-0381-6665.

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А.Б. Джумагазиева[*], Ж.А. Искакбаева[1], У.Е. Жантикеев[2], К.С. Бексеитова[2], С. Азат[2]
[1]Лаборатория микробиологии, АО «Научный центр противоинфекционных препаратов»,
Республика Казахстан, г. Алматы, пр. Аль-фараби, 75Б
[2]Satbayev University,
050013, Республика Казахстан, г. Алматы, ул. Сатпаева, 22
*e-mail: r_dawa@mail.ru

ОЧИСТКА ВОДЫ МЕТОДОМ ХОЛОДНОЙ ПЛАЗМЫ: ЭКСПЕРИМЕНТАЛЬНАЯ ОЦЕНКА БАКТЕРИЦИДНОГО ДЕЙСТВИЯ

Аннотация: *Целью данного исследования являлась оценка эффективности установки холодной плазмы для обеззараживания воды, контаминированной бактериальной микрофлорой. Экспериментальная установка CD Plasma генерирует холодную плазму путем ионизации частиц обрабатываемой жидкости, предварительно преобразованной в двухфазную жидко-газовую среду. Холодная плазма оказывает выраженное антимикробное действие за счет синергетического влияния активных форм кислорода и азота, ультрафиолетового излучения и заряженных частиц, которые вызывают окислительное повреждение клеточной стенки, нарушение целостности мембраны, инактивацию белков и фрагментацию ДНК микроорганизмов. В качестве тест-объектов использованы бактерии Escherichia coli и Pseudomonas aeruginosa как представители санитарно-показательной и условно-патогенной микрофлоры. Показано, что воздействие холодной плазмы в течение 5 минут обеспечивает значительное снижение микробной обсеменённости в отношении обеих культур, однако в большей степени в отношении Pseudomonas aeruginosa. Полученные результаты свидетельствуют о высокой эффективности холодной плазмы в инактивации бактерий без использования химических реагентов и указывают на перспективность её применения в технологиях очистки и обеззараживания воды. Метод отличается энергоэффективностью, масштабируемостью и минимальным образованием побочных продуктов при небольших эксплуатационных затратах.*

Ключевые слова: *холодная плазма, обеззараживание воды, бактерии, экологически чистые технологии.*

1. ВВЕДЕНИЕ

Дефицит и загрязнение воды остаются двумя наиболее острыми глобальными проблемами, имеющими глубокие последствия для общественного здравоохранения, экологической устойчивости и экономического развития [1]. В связи с продолжающимся