# Investigation of Antimicrobial Activity and Soil Biodegradation of Cellulosic Foams Treated with Natural Polymers

Petronela Nechita,[a,b] Nicoleta Ciobotaru,[a,*] and Silviu Marian Nastac [b,c,*]

Cellulose foams are potential sustainable alternatives for packaging, thermal insulation, and acoustic applications due to their porous structure and renewable origin. Besides good mechanical properties and moisture control, antimicrobial performance is essential for applications involving contact with moisture and organic matter, such as food packaging and medical materials. This study investigates the antibacterial, antifungal, and soil biodegradation behavior of cellulose foams coated with a thin layer (approximately 5 g/m²) of xylan hemicellulose and its modified derivatives, including acetylated and AKD (alkylketene dimer) modified xylan. The results showed that foams treated with acetylated xylan exhibited the highest antibacterial activity, with about 58% inhibition of *Bacillus* sp species after 24 h at 27 °C. A slight antifungal effect was also observed, with delayed growth of *Aspergillus* and *Penicillium* species. Both coating composition and xylan modification significantly affected the degradation kinetics.

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## INTRODUCTION

The concept of foam forming of paper was originally introduced by Radvan in 1964, who proposed substituting water with foam in the papermaking process. This approach emerged in response to the increasing demand for cost-efficient technologies capable of utilizing diverse raw materials to produce sustainable, high-value fiber-based products (Radvan 1964; Radvan and Gatward 1972; Gao 2018).

Foam forming has since attracted considerable interest due to its technical and economic advantages. The process incorporates a high volume of air (approximately 50 to 65%), leading to the formation of lightweight fibrous structures characterized by high bulk and excellent uniformity. Moreover, it enables operation at higher consistencies in the headbox, which contributes to improved sheet formation while significantly reducing water usage and energy requirements during dewatering and drying, compared to conventional papermaking processes (Punton 1975a,b; Burke *et al*. 2019; Burke 2021).

Another key aspect of this process is the rheological behavior of aqueous foam, which exhibits pseudoplastic properties. Specifically, it shows high viscosity under low shear conditions and reduced viscosity under high shear. This behavior promotes efficient fiber mixing and dispersion during the forming stage, as the elevated shear rates lower the foam viscosity (Sims and Khunniteekool 1994; Burke *et al.* 2021).

As a result, foam forming enables the fabrication of highly porous, three-dimensional cellulose-based materials, broadening their range of applications to areas such as nonwoven products, thermal insulation, filtration systems, and tissue engineering (Hong and Sohn 1985; Siljander *et al.* 2019; Hjelt *et al.* 2021).

Lightweight, porous cellulose-based materials produced *via* foam-forming techniques have been extensively developed using various types of cellulose fibers (Stanciu *et al.* 2018) and investigated primarily for acoustic insulation applications (Ionescu and Nechita 2017; Nechita and Nastac 2018; Debeleac *et al.* 2019; Nastac *et al.* 2022; Seciureanu *et al.* 2023). Owing to their highly porous structure, sustainability, and moisture management capability, cellulose foams represent an effective solution for both thermal and sound insulation, offering a viable alternative to conventional synthetic materials (Nastac *et al.* 2017; Nechita *et al.* 2023). Their ability to regulate moisture within wall cavities further reduces the risk of mold formation, contributing to improved indoor environmental quality.

However, their wider applicability remains limited by their sensitivity to moisture, water exposure, and microbial degradation, which adversely affect their performance (Petersen *et al.* 1999; Peelman *et al.* 2013). Various bio-based approaches have been investigated to improve the moisture resistance of cellulose materials, including the use of lignin and hemicellulose-derived coatings. Among these, xylan has attracted increasing attention due to its film-forming ability, compatibility with lignocellulosic substrates, and versatility for chemical modification (Huang *et al.* 2025; Lv *et al.* 2025). Moreover, hemicellulose-based coatings have demonstrated a significant improvement in the moisture barrier properties of cellulosic substrates, highlighting their potential for packaging and insulation applications where water resistance is critical (Josey *et al.* 2024).

The suppression of bacterial and fungal growth is a critical requirement for cellulose foams, particularly in insulation applications. Conventional antimicrobial materials typically rely on leaching mechanisms, where embedded biocides are gradually released to inhibit microbial activity. Consequently, significant research has focused on preventing biofilm formation through the incorporation of metal nanoparticles and other biocidal agents (Song *et al.* 2015). Among these, silver nanoparticles are widely used; however, their application raises concerns due to the toxicity of silver ions to mammalian cells and the potential development of microbial resistance (Silve 2003; Greulich *et al.* 2009; Kittler *et al.* 2010).

In this context, xylan-based systems have emerged as promising sustainable alternatives. For example, Chen *et al.* (2025) reported a bamboo-derived xylan composite coating with controlled release behavior, capable of effectively inhibiting microbial growth while preserving freshness in food applications. These findings highlight the potential of xylan-based materials as environmentally friendly antimicrobial solutions that avoid the use of toxic metal ions (Chen *et al.* 2025). Other research has demonstrated the antimicrobial potential of xylan-based hemicellulose films (Yang *et al.* 2019; Xu *et al.* 2020; Solier *et al.* 2021). Although native xylan was found to exert only a modest inhibitory effect against pathogenic microorganisms such as *Escherichia coli* and *Staphylococcus aureus*, its antimicrobial performance can be substantially enhanced through chemical modification. In particular, esterification and crosslinking treatments have been reported to improve the physicochemical characteristics of xylan, leading to increased antimicrobial efficacy of the resulting materials.

One strategy to limit microbial colonization involves the design of non-fouling surfaces, which is typically achieved by enhancing surface hydrophilicity. Highly hydrophilic materials are capable of retaining a stable layer of bound water at the interface, which acts as a physical and energetic barrier that hinders protein adsorption and subsequent bacterial attachment. This hydration layer reduces the likelihood of biofilm development by minimizing direct interactions between microorganisms and the substrate. Such surface properties can be tailored through chemical modification or by applying hydrophilic coatings that promote surface hydration (Ratner and Hoffman 2013; Gu and Ren 2014).

Within this framework, xylan-based modifications have attracted growing interest due to their versatile chemical functionality. Huang *et al.* (2025) demonstrated that xylan can enhance interfacial compatibility in composite coatings while preserving a hydrophilic character that may contribute to reduced microbial adhesion (Huang *et al.* 2025). In a related study, Trogen *et al*. (2025) showed that cellulose-xylan hybrid systems can be engineered to achieve tunable surface and structural properties, making them suitable for advanced functional materials. Their results also indicated that the incorporation of xylan into cellulose networks improves structural organization and influences both morphology and thermal behavior, supporting the use of such systems as precursors for advanced carbon-based materials (Trogen *et al.* 2025).

Xylans represent the most abundant class of hemicelluloses and are widely distributed in lignocellulosic biomass, constituting approximately 30% of hardwood and around 10% of softwood, as well as being present in various agricultural residues. They are commonly recovered as secondary products from chemical pulping processes in the wood industry (Mikkonen and Tenkanen 2012; Zhang *et al.* 2020).

Xylan hemicellulose is generally an anionic biopolymer, due to the presence of acidic groups on its backbone, which can dissociate in water, resulting in a negative charge. This anionic nature influences how xylan interacts with other substances, particularly in its affinity for cationic species and its behavior in film formation and coating applications.

The antimicrobial properties of hemicellulose remain less explored compared to those of cellulose and lignin. The antimicrobial activity of xylan is one of the most studied among polymers derived from hemicellulose extracts (Lobo *et al.* 2021). Due to their bioactive components, there are many studies that report that hemicellulose polymers show significant antimicrobial potential. For example, Ahmad *et al.* (2020) reported that hemicellulose films were effective in inhibiting the growth of *S. aureus*, *E. coli*, and *P. aeruginosa*. Similarly, in their study, Bouaziz *et al.* (2017) found that hemicellulose showed higher inhibitory activity against *B. thuringiensis*, *S. enterica*, and *P. aeruginosa*, with moderate inhibition against *Actinomyces sp.*, *S. typhimurium*, *K. pneumoniae*, *L. monocytogenes*, and *B. subtilis*. Fu *et al.* (2020) demonstrated that gels made from xylan, gelatin, glycerol, and nicotinamide showed strong antimicrobial activity against yeast, but had lower effectiveness against *B. subtilis* and *S. aureus*. Arellano-Sandoval *et al*. (2020) developed hydrogels using xylan extracted from bagasse and poly (N-vinylcaprolactam), which effectively inhibited the growth of *E. coli*, *S. aureus*, and *P. aeruginosa*. Recent studies have reported on the antimicrobial and antifungal properties of xylan films and paper coated with hardwood xylan hemicelluloses (Yang *et al.* 2019; Xu *et al.* 2020). These studies concluded that native xylan exhibits moderate antifungal activity and mild antimicrobial effects against pathogenic bacteria, such as *E. coli* and *S. aureus*. However, the antibacterial activity of hemicellulose was lower compared to the positive control. These findings suggest that hemicellulose exhibits a bacteriostatic effect on the tested bacteria, indicating its potential use in applications where the antimicrobial properties are important.

Xylan hemicelluloses possess a structure that is rich in reactive functional groups, including hydroxyl, carboxyl, and carbonyl moieties, which allow their modification through a variety of chemical reactions. Such modifications are widely employed to tailor and enhance the functional performance of hemicelluloses, extending their applicability across multiple fields (Roman *et al.* 2024). Chemically modified xylans often exhibit improved hydrophobicity and thermal stability, with properties comparable to those of cellulose acetate (Cheng *et al.* 2021; Stepan 2013).

Recent studies have highlighted the potential of modified xylan derivatives in advanced material applications. For instance, Lv *et al.* (2025) developed chemically tailored xylan-based systems for use in bio-based adhesives and coatings, demonstrating that controlled molecular modifications can significantly improve processability, interfacial interactions, and overall performance in sustainable material applications. Likewise, Josey *et al.* (2024) investigated hemicellulose-derived coatings aimed at enhancing the moisture barrier properties of cellulosic substrates, showing that such systems can simultaneously improve water resistance, barrier performance, and surface functionality, making them particularly suitable for packaging and insulation uses.

Acetylated xylan typically exhibits improved hydrophobicity due to the presence of acetyl groups. This can enhance the water-repellent characteristics of the surface, potentially reducing bacterial adhesion. In addition, acetylated xylan is biocompatible, making it suitable for applications where nonfouling properties are essential. The acetylation process can also improve barrier properties, further contributing to the creation of nonfouling surfaces.

Due to the strong compatibility between xylan and cellulose fibers, this study focuses on the use of xylan and its derivatives to enhance the wettability and microbial resistance of cellulose foams. These improvements can increase the suitability of such materials for insulation purposes, including thermal and acoustic applications. For this purpose, native hardwood xylan hemicellulose, together with its acetylated and AKD modified derivatives, was applied as a surface treatment for cellulose foams. The treated materials were further evaluated in terms of structural characteristics, water absorption behavior, antimicrobial activity, and soil biodegradability.

## EXPERIMENTAL

### Materials

Cellulose foams, produced using the method described by the authors in previous studies (Nastac *et al.* 2017; Nechita and Nastac 2018; Seciureanu *et al.* 2023), were used for treatment with xylan hemicelluloses. Bleached softwood cellulose with 43°SR was employed as the raw material for obtaining cellulose foams.

Xylan hemicellulose with a molecular mass of (132)n from beechwood was purchased from Carl Roth Company, Karlsruhe, Germany, and used as received.

Acetylated xylan (XyAc) and xylan modified with alkylketene dimer (XyAKD) as products of native xylan reaction with acetic anhydride and alkylketene dimer that had been synthetized in the laboratory according to the methods presented in previous studies (Roman *et al.* 2023).

## Obtaining Functionalized Cellulose Foams

Following the methodology outlined in references (Nastac *et al.* 2017; Nechita and Nastac 2018; Seciureanu *et al.* 2023), cellulose foams were produced through the following process: after refining, the cellulose pulp with a 2% consistency was mixed with approximately 4% surfactant relative to the fiber weight. This mixture was subjected to high shear velocity, reaching up to 2200 rpm for 20 min, to facilitate air entrainment. The filtering and dewatering of fiber and foam suspension was performed on a Buchner funnel under low vacuum for about 20 min to maintain the structural integrity of pulp foam. The dewatered foams were dried at room temperature (around 22 °C) with 50 to 60% relative humidity for 24 to 48 h.

Functionalized cellulose foams were obtained according to the following procedure: aqueous dispersions (2.5%) of native xylan and its derivatives were applied by spraying as a thin layer (approximately 5 g/m²) onto the surface of cellulose foams. Three different treated cellulose foam samples were prepared and coded as follows: cellulose foam treated with native xylan (CFXy), cellulose foam treated with AKD-modified xylan (CFXyAKD), and cellulose foam treated with acetylated xylan (CFXyAc). An untreated cellulose foam sample was used as the reference material (Nastac *et al.* 2023).

## Structural Analysis of Cellulose Foams by Microscopy Techniques

Cross-section images of cellulose foams were acquired using an optical microscopy technique with transmitted diffuse white light. This technique utilized a DELTA Optical Three-Ocular Microscope model SZ-450T® (Delta Optical, Minsk Mazowiecki, Poland) and a Bresser MikrOkular Full HD Digital Camera® (Bresser GmbH, Rhede, Germany).

The surface morphology of the cellulose foams was examined using scanning electron microscopy (SEM) with the Quanta 200 system (FEI). SEM images, with 100 µm and 10 µm scale bars, were obtained at an accelerating voltage of 20 kV, utilizing the secondary electron signal in low-vacuum conditions. The paper samples were mounted onto metal support stubs using carbon double-sided tape. To enhance conductivity, the samples were coated with a thin metallic layer using sputtering equipment (SPI Supplies, West Chester, NY, USA). The surface structure of the materials was assessed at 1000× magnification, with a representative selection of images captured and analyzed.

## Water Absorption Capacity

The water absorption capacity (W, %) of the cellulose foams was determined by immersing pre-dried and weighed samples into a fixed volume (50 mL) of distilled water for 24 h at a temperature of 27 °C. Equation 1 was used for the calculation (Demitri *et al.* 2014),

$$W\,(\%) = \frac{M_2 - M_1}{M_1} \text{ x } 100 \tag{1}$$

where $M_1$ is the weight of the dried sample (g) and $M_2$ is the weight of the water-saturated sample (g).

## Antimicrobial Properties

The antimicrobial performance of the cellulose foams was evaluated against Gram-positive bacteria (*Bacillus* sp.) and two fungal strains, *Aspergillus niger* and *Penicillium* sp., obtained from the MIUG Collection of Dunărea de Jos University of Galați. The antibacterial activity was determined using a modified procedure adapted from the ISO 22196 (2011) standard. Prior to testing, the cellulose foam samples coated with xylan derivatives were sterilized by UV exposure for 15 min and then placed on the surface of Plate Count Agar (PCA) medium (Merck Millipore, Darmstadt, Germany). Inoculation was performed by spraying 1 μL of bacterial suspension ($10^6$ CFU/mL, 18 h culture) onto the sample surface. The inoculated samples were incubated at 37 °C and examined after 24 and 48 h. The degree of bacterial growth was assessed by assigning a score defined as follows: very good growth (+++), good growth (++−), poor growth (+−−), and no growth (−−−), which inversely correlates with the inhibition potential of the analyzed cellulose foam samples, or by calculating the inhibition percentage of the coated surface, based on the extent of bacterial growth observed on and around the samples. According to the mentioned standard, the greater degree of microbial growth (*i.e.*, the more numerous the colonies), the lower the antimicrobial activity score.

The antifungal activity was investigated using fungal suspensions of approximately $10^7$ CFU/mL cultivated on Rose Bengal medium (Merck, Darmstadt, Germany). Two testing methods were applied: the first involved spraying the cellulose foam samples with a conidial suspension before placing them on the culture medium, while the second consisted of flooding the medium surface with the fungal suspension prior to positioning the samples. In both cases, incubation was carried out at 25 °C and 85% relative humidity for 21 days. The degree of fungal development was monitored after 3, 7, 14, and 21 days by measuring the percentage of the paper surface covered by fungi.

To evaluate the effectiveness of the xylan and xylan-derivative treatments and ensure reproducibility, samples for antibacterial and antifungal analyses were obtained by cutting surface sections (about 0.5 mm thickness) from the polymer-treated areas. The measurements were performed in triplicate, and the results are expressed as mean values ± standard deviation.

## Assessment of Soil Biodegradation

The aspect of films as integrity, homogeneity, the presence of microcracks, flexibility or resistance to handling were evaluated by visual inspection.

Samples of cellulose foams were tested to assess their biodegradability (organic matter degradation) under the following laboratory conditions (Roman *et al.* 2024). Cellulose foam samples (CF, CFXy, CFXyAKD, CFXyAc) with known mass, previously oven-dried at 105 °C, were placed into synthetic sachets (pre-weighed) in order to ensure complete recovery of the degraded material. The bag containing the test sample was placed in a vessel filled with a soil substrate (intended for indoor ornamental plant cultivation), previously prepared and moistened to 60 to 65% of its water-holding capacity. The vessels containing the prepared samples were incubated at a temperature of 24 to 26 °C for 7, 14, and 28 days and were watered once daily with 0.10 to 0.15 L of water. After the incubation period, the bags were removed from the soil, washed under running water, oven-dried at 105 °C for 4 h, and subsequently weighed. The contents of each bag were transferred onto a Petri dish and subjected to visual examination by photographic documentation. All tests were performed in triplicate, and the results are expressed as mean values ± standard deviation.

The biodegradation rate (degree of decomposition) was calculated as follows,

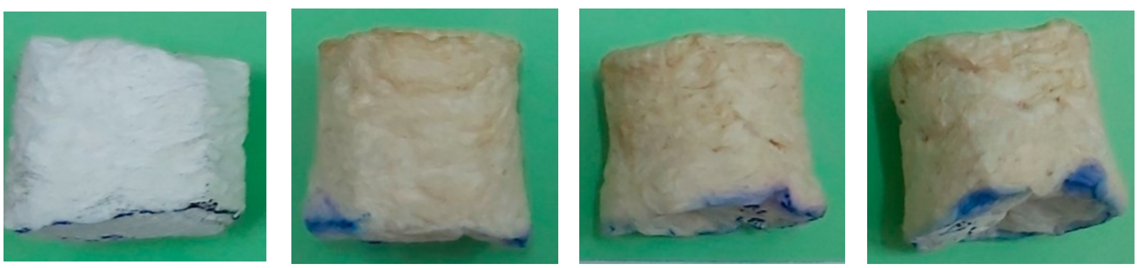
$$Decomposed\ material\ \% = \frac{G_i - G_f}{G_i - G_s} x\ 100 \qquad (2)$$

where $G_i$ is the sum of the weight of the sample and the weight of the bag before being placed in the vessel (g), $G_f$ is the sum of the weight of the sample and the weight of the bag after being removed from the vessel and oven-dried (g), and $G_s$ is the weight of the bag (g).

## RESULTS AND DISCUSSION

### Structural Analysis of Functionalized Cellulose Foams

The dry-state samples with xylan-based surface treatments are shown in Fig. 1. To analyze the xylan-foam interactions and assess the effects of the treatments on the foam structure, a longitudinal cross-section of the samples was prepared. A thin slice, 4 mm in thickness, was cut from each sample. These cross-sectional samples were then analyzed using both reflected and transmitted diffuse white light (without optical magnification) as well as optical transmitted light microscopy (Fig. 2).

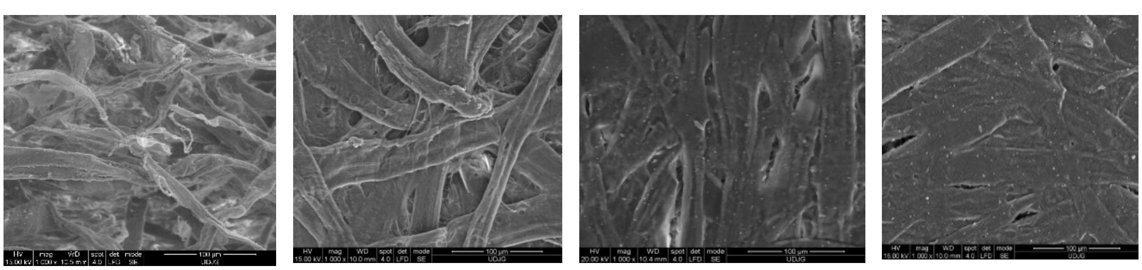


43/CF CFXy CFXyAKD CFXyAc

**Fig. 1.** Dry state cellulose foams treated with xylan hemicellulose

43/CF CFXy CFXyAKD CFXyAc

**Fig. 2.** Dry state cellulose foams treated with xylan hemicellulose



43/CF CFXy CFXyAKD CFXyAc

**Fig. 3.** SEM images of cellulose foams treated with xylan and xylan derivatives

Figure 2 shows that xylan treatments penetrated the cellulose fiber-based foam to an extent dependent on xylan type, reaching ~40% for native xylan and ~60% for acetylated xylan in highly porous samples (Nastac *et al.* 2023). Penetration was more evident in the longitudinal section. The micrographs indicate that xylan and its derivatives infiltrated the porous network, filling internal voids and leading to a denser structure with a smoother surface. SEM analysis further confirmed these findings, revealing a more homogeneous morphology and partially to fully closed pores in coated samples, in contrast to the highly porous structure of untreated cellulose foams (Fig. 3).

## Absorption Capacity of Cellulose Foams

The free water absorption capacity of foam-formed, low-density structures typically ranged between 20 and 30 g/g, while the absorption capacity under load was between 16 and 20 g/g. Both dry and wet tensile strengths of these structures were generally low (Ketola *et al.* 2023). The water absorption capacity of cellulose foams treated with xylan hemicelluloses is presented in Fig. 4.

A decrease in water absorption was observed for xylan-treated cellulose foams compared to untreated samples. The most pronounced reduction (15.2%) was obtained for samples treated with acetylated xylan, which is consistent with literature data. Similar trends were reported by Demitri *et al.* (2014).

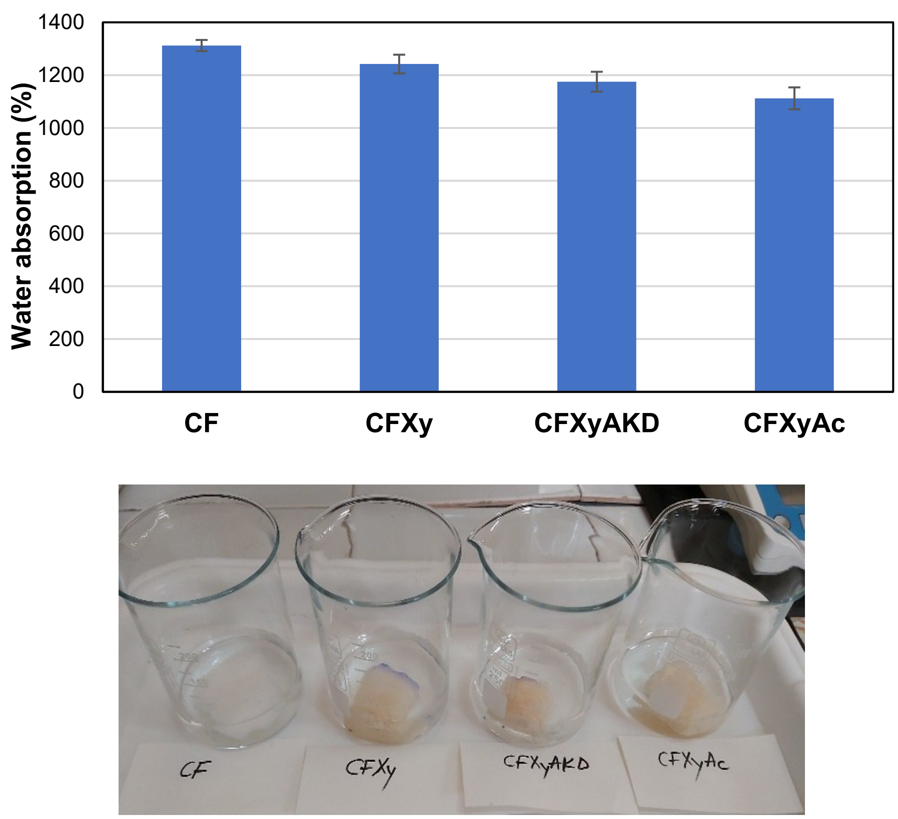



**Fig. 4.** Water absorption capacity of cellulose foams treated with xylan hemicelluloses

## Antimicrobial Properties

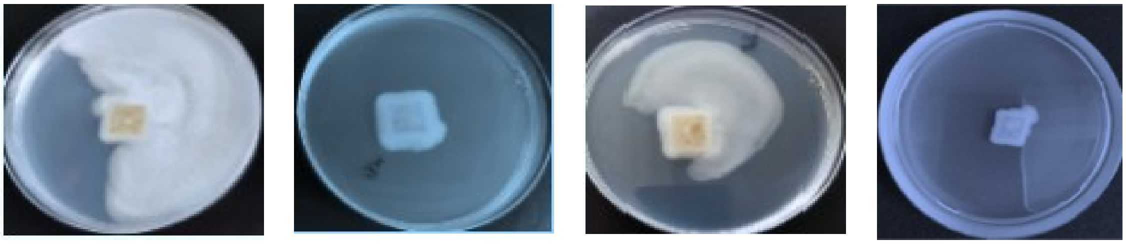
*Bacillus sp.* was used to assess the antibacterial activity of the xylan- and xylan derivative-coated cellulose foams. *Bacillus* sp. was selected because members of this genus are widely used as model Gram-positive bacteria in laboratory studies and are often considered representative counterparts to Gram-negative model organisms such as *E. coli*. (Roman *et al.* 2024).

The results presented in Table 1 demonstrate that xylan-based treatments influenced the growth of *Bacillus subtilis* colonies on cellulose foam surfaces. The untreated sample (CF) exhibited extensive bacterial growth (+++) and the lowest colony inhibition value (11.7 ± 0.14%), confirming the high susceptibility of the cellulosic substrate to bacterial colonization in the absence of a protective coating (Xu *et al.* 2020). Coating the cellulose foams with native xylan (CFXy) reduced bacterial growth (+−−), increasing the colony inhibition rate to 39.1 ± 0.26%. This improvement can be attributed to the formation of a xylan layer that acts as a physical barrier, limiting bacterial adhesion and proliferation while modifying the surface properties of the substrate. The AKD-modified xylan sample (CFXyAKD) showed a lower antibacterial effect, with a colony inhibition of 18.3 ± 0.18% and moderate bacterial growth (++−). The relatively low inhibition of *B. subtilis* observed for these samples indicates that increased hydrophobicity alone is insufficient to effectively suppress bacterial growth, highlighting the importance of the chemical structure and surface characteristics of the coating. The highest antibacterial activity was achieved by the acetylated xylan-coated sample (CFXyAc), which exhibited the greatest colony inhibition (58.7 ± 0.45%) and limited bacterial growth (+−−). The superior performance of this treatment can be associated with the structural modifications induced by acetylation, which increase the hydrophobic character of the coating, reduce water availability at the material surface, and improve barrier properties. These effects create less favorable conditions for bacterial adhesion and growth. A partial inverse correlation was observed between water absorption capacity (Fig. 4) and antibacterial activity against *Bacillus subtilis*. The untreated cellulose foam (CF), characterized by the highest water absorption (1310%), exhibited the lowest colony inhibition (11.7%). Conversely, the acetylated xylan-coated sample (CFXyAc) displayed the lowest water uptake (1110%) and the highest antibacterial efficiency (58.7%). The reduced water availability at the material surface likely limited bacterial adhesion and proliferation. However, the behavior of the sample coated with AKD-modified xylan (CFXyAKD), which showed lower water absorption than native xylan-coated foam but a weaker antibacterial effect, suggests that antibacterial performance is not governed solely by hydrophobicity. The chemical structure of the coating, surface morphology, and barrier properties generated by xylan modification appear to play a decisive role in controlling bacterial growth. Therefore, acetylated xylan provides the most favorable balance between moisture resistance and antibacterial protection among the investigated treatments.

**Table 1.** Antibacterial Activity of Cellulose Foams Coated with Native Xylan/Xylan Derivatives Against *Bacillus* sp.

| Sample Code | Sample Description | Degree of Colony Development (*) | Colony Inhibition, [%] |
|---|---|---|---|
| **CF** | Cellulose foam untreated | (+ + +) | 11.7+0.14 |
| **CFXy** | Cellulose foam treated with native xylan | (+ - -) | 39.1+0.26 |
| **CFXyAKD** | Cellulose foam treated with AKD modified xylan | (+ + -) | 18.3+0.18 |
| **CFXyAc** | Cellulose foam treated with acetylated xylan | (+ - -) | 58.7+0.45 |

(*) (+++) very good development; (++−) good development; (+−−) poor development; (−−−) no development. (cf. SR EN ISO 846:2000)
*** Values are presented as mean ± standard deviation.*



CF CFXy CFXyAKD CFXyAc

**Fig. 5.** The antibacterial activity of xylan coated cellulose foams

Antifungal tests were performed by pulverization and flooding method, using two strains of fungi *Aspergillus niger* and *Penicillium* sp. The results are presented in Table 2.

**Table 2.** Degree of Fungal Inhibition (%) of Cellulose Foams

| Paper Sample | Percentage of Fungal Growth Inhibition (%)/ Assessment Method | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Spraying | | | | Flooding | | | |
| | 3 days | 7 days | 14 days | 21 days | 3 days | 7 days | 14 days | 21 days |
| strain *Aspergillus niger* | | | | | | | | |
| **CF** | 1.21± 0.07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CFXy** | 2.23± 0.04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CFXyAKD** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CFXyAc** | 2,81± 0.06 | 1.32± 0.03 | 0 | 0 | 0 | 0 | 0 | 0 |
| strain *Penicillium* sp. | | | | | | | | |
| **CF** | 1.00± 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CFXy** | 0 | 0 | 0 | 0 | 2.31± 0.03 | 1.18± 0.01 | 0 | 0 |
| **CFXyAKD** | 0 | 0 | 0 | 0 | 1.42± 0.07 | 0 | 0 | 0 |
| **CFXyAc** | 0 | 0 | 0 | 0 | 3.38± 0.05 | 2.45± 0.08 | 1.56± 0.02 | 0 |

In general, all samples exhibited low fungal growth inhibition values, with the observed effect being limited to the early stages of incubation and almost completely disappearing as the testing period progressed. Overall, the results indicate that the samples coated with acetylated xylan showed the highest antifungal performance, particularly against *Penicillium* sp. compared to *Aspergillus niger*. However, the inhibition values remained very low (below 4%) and decreased rapidly over time, suggesting that the xylan and xylan derivative-coated cellulose foams did not exhibit inhibitory effects against the growth of fungal strains.

## Assessment of the Extent of Biodegradation

The results presented in Table 3 and Fig. 6 highlight a clear time-dependent increase in the percentage of decomposed material for all tested samples, indicating the progressive nature of the biodegradation process under soil incubation conditions.

During the initial incubation period (7 days), all samples exhibited low biodegradation levels, which may indicate an adaptation phase of the microbial community to the tested materials. The AKD-modified sample (CFXyAKD) showed the lowest mass loss (0.32%), suggesting that hydrophobization effectively delayed the onset of biodegradation by reducing water penetration and limiting the accessibility of the substrate to microorganisms. After 14 days, clear differences in biodegradation behaviour were observed among the samples. The CFXyAKD sample exhibited a marked increase in mass loss, while CFXy and CFXyAc showed more moderate biodegradation levels. The accelerated degradation observed for CFXyAKD suggests that the protective effect of the AKD treatment was mainly temporary. As soil incubation progressed, the hydrophobic barrier may have been progressively overcome, allowing microbial access to both cellulose and xylan components and resulting in enhanced degradation. The control sample (CF) displayed a gradual increase in mass loss throughout the test period, confirming the biological activity of the soil environment. At the end of the incubation period (28 days), CFXy exhibited the highest biodegradation level (69.8%), indicating that the presence of native xylan did not hinder long-term microbial degradation. In contrast, CFXyAKD (61.3%) and particularly CFXyAc (46.7%) showed lower mass losses. The reduced biodegradation of the acetylated xylan-coated sample may be attributed to the increased hydrophobicity and lower enzymatic accessibility associated with acetyl substitution. Overall, the results demonstrate that all investigated cellulose foam materials were biodegradable under the tested conditions. The different xylan-based treatments mainly affected the biodegradation kinetics rather than the ultimate biodegradability of the materials.

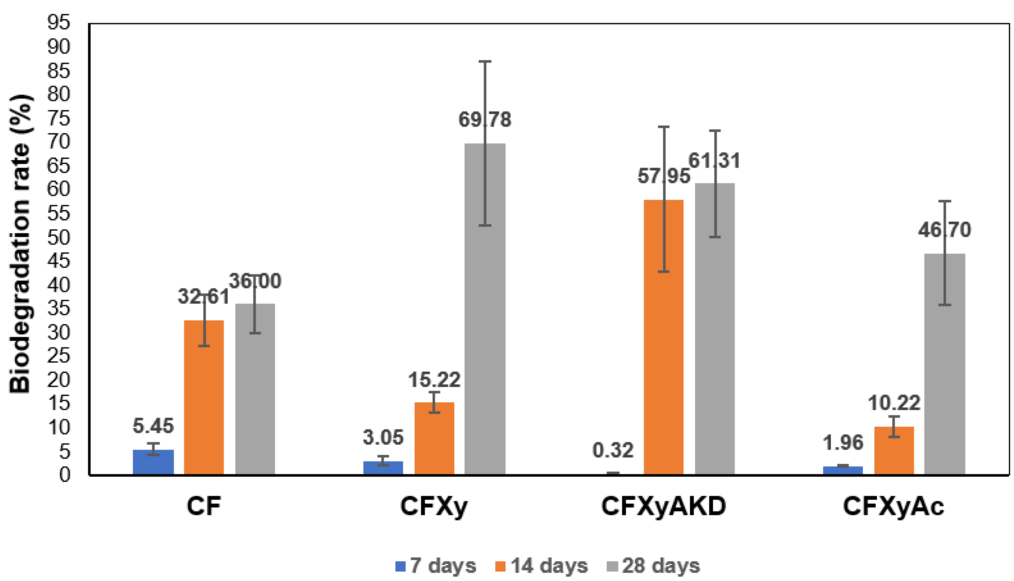
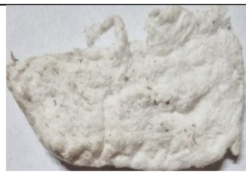
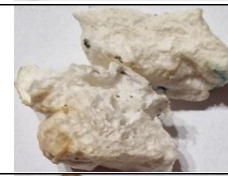
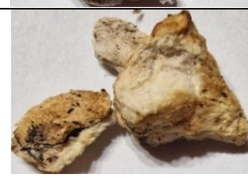



**Fig. 6.** Extent of biodegradation (%) of the cellulose foams

The observed differences in biodegradation rate suggest that material composition and treatment significantly influence degradation kinetics, with implications for the environmental performance (environmental behaviour and potential for integration into natural degradation cycles) of the tested materials.

**Table 3.** Visual Appearance of the Samples after Biodegradation

| | CF | CFXy | CFXyAKD | CFXyAc |
|---|---|---|---|---|
| 7 days |  |  |  |  |
| 14 days |  |  |  |  |
| 28 days |  |  |  |  |

## CONCLUSIONS

1. This paper presents findings on the antimicrobial, water absorption, and biodegradation properties of cellulose foams treated with xylan hemicellulose and its derivatives, namely alkylketene dimer (AKD) modified xylan and acetylated xylan. Cellulose foams coated with acetylated xylan exhibited promising antibacterial activity against the Gram-positive bacterium *Bacillus subtilis*. These results, together with the acoustic performance of these materials previously reported by the authors, highlight their potential for application as sustainable soundproofing and insulation materials.
2. The cellulose foams treated with acetylated xylan provided the most favorable balance between moisture resistance and antibacterial protection among the investigated treatments.
3. Regarding the antifungal properties, only cellulose foams coated with acetylated xylan exhibited slight inhibitory effects; however, the inhibition values remained very low (below 4%) and decrease rapidly over time, suggesting that the xylan and xylan derivative-coated cellulose foams did not exhibit inhibitory effects against the growth of fungal strains.
4. The biodegradation results highlighted that the treatment with native xylan promoted the biodegradation of cellulose foams, whereas hydrophobic or acetylated modifications tended to slow down or stabilize, with significant influences on the kinetics of biodegradation process.
5. Overall, these results highlight the potential of this versatile, eco-friendly material for various applications. However, further research is needed to optimize formulations and

clarify the mechanisms behind its antimicrobial activity, as specific outcomes and comparisons with other treatments may differ across studies.

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