ISSN / ANATABDER NO: 2026-B04 (EN)

BIOMATERIALS AND ADVANCED TEXTILE ENGINEERING

Structural and Functional Properties of Hemp (*Cannabis sativa* L.) Bast Fibers: A Comprehensive Review

Berk Sohtorik[1,2] | **Dr. Dilek Himam**[3]

[1] KenevirMED, Biotechnology and Materials Research • [2] ANATABDER (Anatolian Medical and Aromatic Plants Association) • [3] Izmir University of Economics, Faculty of Fine Arts and Design

ABSTRACT

Amid growing environmental concerns regarding petrochemical synthetic fibers and ubiquitous microplastic pollution, industrial hemp (*Cannabis sativa* L.) bast fibers provide an agronomic carbon-negative profile combined with extraordinary mechanical and biochemical properties. The remarkably low microfibril angle (MFA: 2° to 10°) within the dominant S2 secondary cell wall layer delivers exceptional tensile stiffness. Furthermore, the structural lignin matrix and co-localized phenolic acids grant intrinsic broad-spectrum antimicrobial efficacy and native ultraviolet photoprotection (UPF > 50). Coupled with the porous central lumen that regulates microclimates through dynamic moisture buffering, hemp bast fibers represent a scalable foundation for advanced circular textiles and biocomposites.

01 Introduction and Bio-Based Economy

The global transition toward regenerative material economies has spurred renewed scientific interest in industrial hemp bast fibers. Historically limited to utilitarian cordage and coarse sailcloth, hemp is now recognized as a premier functional substrate for technical apparel, wound dressings, and load-bearing structural biocomposites.[1]

Located in the outer phloem perimeter of the plant stem, hemp bast fibers reconcile carbon sequestration with exceptional mechanical tenacity. This review delineates the causal links between nanoscale cell wall architecture, non-cellulosic phenolic bioactivity, and macroscopic textile performance.

02 Cellular Morphology and Architecture

Hemp bast fibers are biological composites consisting of semi-crystalline cellulose microfibrils embedded in an amorphous, viscoelastic matrix of hemicellulose, pectin, and lignin.[2] The cell wall features a thin primary wall and a thick secondary wall subdivided into concentric S1, S2, and S3 layers.[3]

The S2 layer constitutes the majority of the cross-sectional area and bears primary axial mechanical stress. In high-grade hemp bast fibers, the Microfibril Angle (MFA) relative to the longitudinal fiber axis is exceptionally low, typically ranging from 2° to 10°.[4]

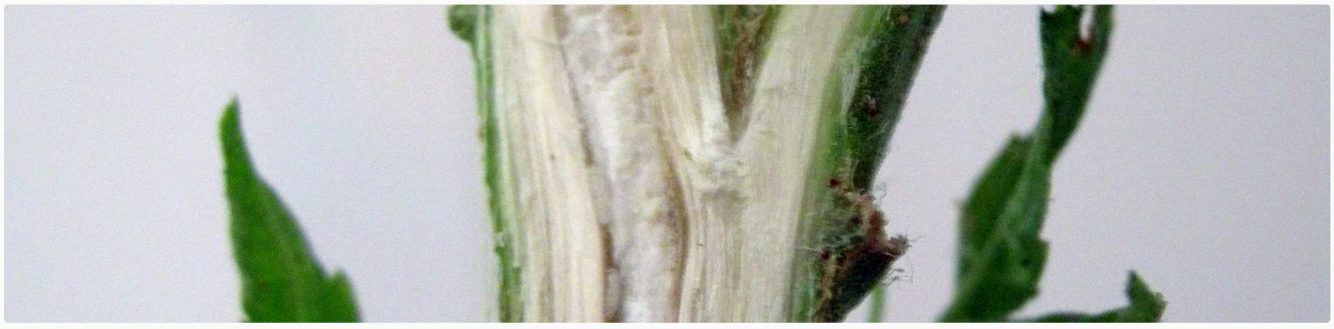


Figure 1: Optical micrograph cross-section of a *Cannabis sativa* L. stem, illustrating the outer perimeter phloem bast fiber bundles and central woody core.

03 Biomechanical Tenacity and Tensile Performance

Cellulose chains constitute between 64% and 78% of the fiber by dry weight. The near-parallel alignment of microfibrils minimizes shear deformation under axial tension, yielding tensile strengths between 550 and 1110 MPa alongside Young's moduli ranging from 30 to 92 GPa.[5] These mechanical metrics directly rival commercial E-glass fibers.[6]

FIBER TYPE	CELLULOSE (%)	HEMICELLULOSE (%)	LIGNIN (%)	DENSITY (G/CM³)	TENSILE STRENGTH (MPA)	YOUNG'S MODULUS (GPA)
Hemp (Bast)	**64 – 78**	**10 – 23**	**3 – 13**	**1.40 – 1.64**	**550 – 1110**	**30 – 92**
Flax (Bast)	64 – 71	10 – 12	3 – 5	1.50 – 1.54	502 – 1000	52 – 80
Cotton (Seed)	83 – 90	3 – 7	< 1	1.50 – 1.54	287 – 597	5 – 12
Polyester (PET)	-	-	-	1.38 – 1.40	400 – 600	2 – 4

A continuous longitudinal lumen occupies the center of each elementary fiber cell, reducing bulk density (1.40 - 1.64 g/cm³) while enhancing acoustic dampening.[7] Ambient moisture plasticizes the amorphous hemicellulose matrix. Under cyclic fatigue loading, microfibrils dynamically rotate toward the fiber axis, temporarily increasing stiffness by up to 250%.[8]

04 Lignin Phenolics and Antimicrobial Action

The inherent antimicrobial and antifungal efficacy of hemp textiles stems from non-cellulosic constituents. Lignin is synthesized via the oxidative coupling of p-coumaryl, coniferyl, and sinapyl monolignols.[9] Associated low-molecular-weight phenolic acids, notably p-coumaric and ferulic acid, act as primary bioactives.[10]



Figure 2: Macerated hemp bast fiber bundles showing parallel microfibril alignment.

These amphipathic phenolics intercalate into the phospholipid bilayer of *Staphylococcus aureus* and *Escherichia coli*, disrupting electrochemical potential and inducing cell lysis.[11] Residual phytocannabinoids (CBD) and terpenes further impair bacterial division. Under ISO 20743, enzymatically processed hemp fabrics retain 95% to 99% bacterial inhibition after 50 wash cycles.[12]

05 Photoprotection and Native UV Resistance

While untreated cotton and flax provide insufficient protection against ultraviolet radiation, greige hemp textiles naturally achieve Ultraviolet Protection Factor ratings of UPF > 50, the highest classification under AS/NZS 4399 and ASTM D6603 standards.[13]

This barrier is driven by lignin chromophores. Aromatic rings and conjugated double bonds absorb high-energy UV photons in the 280 to 400 nm band.[14] Delocalized pi-electrons safely dissipate this ionizing energy through non-radiative internal conversion as low-level thermal heat.[15]

06 Thermodynamics and Moisture Kinetics

Hemp fibers exhibit very low thermal conductivity values ranging between 0.022 and 0.083 W/m·K.[16] This thermal insulation derives from cellular morphology: the hollow central lumen traps microscopic pockets of still air, which possess a thermal conductivity of ~0.026 W/m·K, forming a natural barrier against convective heat loss in winter and radiant heat gain in summer.[17]

Hemp has a standard moisture regain of 12% to 13% (cotton: 8.5%; polyester: <1%).[18] Free hydroxyl (-OH) groups in hemicellulose form hydrogen bonds with water vapor.

PROTECTION CATEGORY	UPF RANGE	UV TRANSMISSION (%)	PERFORMANCE ASSESSMENT
Good Protection	15 – 24	6.7 – 4.2	Standard daytime baseline
Very Good Protection	25 – 39	4.1 – 2.6	Enhanced outdoor protection
Excellent Protection	**40 – 50+**	**< 2.5**	**Complete photoprotection (Raw Hemp: UPF 50+)**



Figure 3: Historical archival documentation of hemp sheaves undergoing field retting and maceration (1950).

Sorption Hysteresis and Microclimate Regulation

At constant relative humidity, equilibrium moisture content is higher during desorption than during adsorption.[19] This hysteresis creates a high Moisture Buffering Value (MBV). Hemp garments absorb vaporous perspiration prior to skin condensation, wicking moisture externally via capillary action and eliminating synthetic dampness.[20]

07 Degumming Trade-Offs and Bioprocessing

Extracting pliable yarns from stalks requires degumming to remove pectins, hemicellulose, and excessive lignin. Traditional dew retting is ecologically benign but weather-dependent,[21] while water retting produces high biochemical oxygen demand (BOD) water pollution.[22]

Modern textile bioprocessing employs alkaline pectinase and xylanase systems to selectively hydrolyze pectins within 5.5 hours (75% pectin, 40% hemicellulose removed).[23] This targeted bio-treatment preserves fiber tenacity (>5.6 cN/dtex) and crucial bioactive lignin, maintaining native antimicrobial and UV resistance.[24]

08 Soil Biodegradability and Phytoremediation

Unlike persistent petrochemically derived fibers, hemp textiles integrate into terrestrial carbon cycles. Soil burial tests (ISO 11721) demonstrate enzymatic hydrolysis driven by microbial cellulases, xylanases, and laccases.[25] Pure hemp textiles achieve 100% mass loss within 2 to 4 months in vermicomposting, stabilizing soil C/N ratios near 11 and fostering humification.[26]

During cultivation, deep taproots extract heavy metals (Cd, Pb) through phytoremediation.[27] Crucially, bast fibers selectively exclude these toxins (Cd < 0.59 mg/kg), ensuring full regulatory compliance for skin-contact textiles.[28]

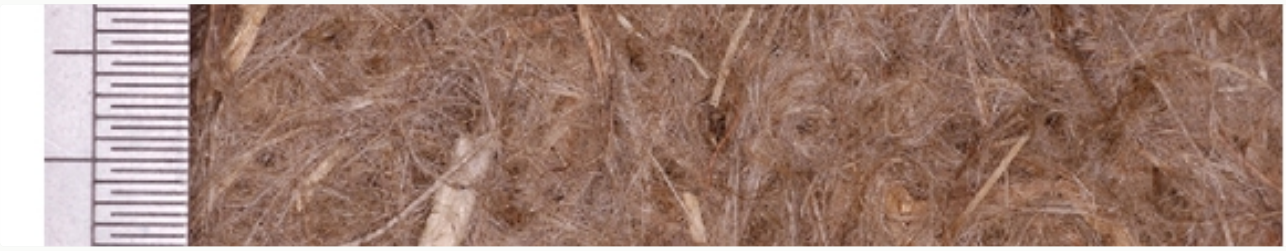


Figure 4: Non-woven hemp bast fiber mat; structural reinforcement for biocomposites and insulation.

09 NOTES

1. P. Petit et al., "Physicochemical Properties of Hemp Fibers," *Bioresource Tech.* 340 (2021): 126.
2. J. Mussig, "Biomechanical Properties of Bast Fibers," *BioResources* 11 (2016): 4850.
3. N. Graupner and J. Mussig, "Technical Aspects of Hemp," *Composites Part A* 118 (2019): 102.
4. K. Charlet et al., "Micro-Fibrillar Angle in Bast Fibers," *J. Mater. Sci.* 42 (2007): 154.
5. H. Lilholt, "Comprehensive Composite Materials: Organic Fibres" (Oxford: Elsevier, 2000), 303.
6. A. Bourmaud et al., "Microstructure of Industrial Hemp," *Ind. Crops Prod.* 112 (2018): 87.
7. C. Baley, "Morphological Porosity Under Heat Transfer," *Mater. Lett.* 56 (2002): 779.
8. M. Hughes, "Humidity on Tensile Behaviour of Hemp," *Composites Part A* 41 (2010): 1205.
9. R. Vanholme et al., "Lignin Biosynthesis and Structure," *Plant Physiol.* 153 (2010): 895.
10. S. Ralph et al., "Lignin Fractions in Industrial Hemp," *Phytochemistry* 68 (2007): 1120.
11. E. Ceballos et al., "Bacteriostatic Action of Phenolic Compounds," *Appl. Microbiol.* 98 (2014): 4511.
12. V. Radivojevic et al., "Bioactive Hemp Clothing with CBD," *Materials* 14 (2021): 6031.
13. AS/NZS 4399:2020, "Sun Protective Clothing Evaluation" (Sydney: Standards Australia, 2020).
14. Y. Lu et al., "Ultraviolet Protection of Hemp Fabrics," *Textile Res. J.* 88 (2018): 1823.
15. H. Liu et al., "Review of UV Radiation and Bast Textiles," *Cellulose* 31 (2024): 211.
16. M. Srebrenkoska et al., "Thermal Comfort Properties of Hemp," *Polymers* 17 (2025): 903.
17. G. Gourlay, "Moisture Buffering of Plant Fibers," *JTATM* 12 (2022): 1.
18. F. Collet et al., "Hygric Behaviour of Hemp-Starch Panels," *BioResources* 9 (2014): 6321.
19. H. Rahim et al., "Hygrothermal Behavior of Hemp: Hysteresis," *Build. Environ.* 165 (2019): 106.
20. D. Akin, "Microbial Communities in Hemp Retting," *Ind. Crops Prod.* 44 (2013): 323.
21. M. Tahir et al., "Traditional vs Bio-Retting Processes," *J. Cleaner Prod.* 211 (2019): 1102.
22. W. Zhou et al., "Alkaline Pectinase-Xylanase Degumming," *Textile Res. J.* 91 (2021): 2341.
23. S. Pang et al., "Ionic Liquids for Hemp Degumming," *ACS Sustainable Chem.* 12 (2024): 1560.
24. ISO 11721-1:2001, "Resistance of Cellulose to Micro-Organisms" (ISO, 2001).
25. A. Kowalska et al., "Biodegradability of Natural Fibers," *Agronomy* 15 (2025): 2700.
26. K. Smith, "Enzymatic Degradation in Soil Ecologies," *Appl. Soil Ecol.* 142 (2021): 88.
27. P. Angelini et al., "Phytoremediation by Industrial Hemp," *Agronomy* 13 (2023): 995.
28. M. Meers et al., "Hemp in a Phytoattenuation Strategy," *Environ. Pollut.* 298 (2022): 118.