

Process Optimization and Material Evaluation of Natural Fiber Fabrics for Sustainable Fashion Apparel Design

Zhihui Li

How to cite: Li Z. Process Optimization and Material Evaluation of Natural Fiber Fabrics for Sustainable Fashion Apparel Design. Textile & Leather Review. 2026; 9:1527-1540.

<https://doi.org/10.31881/TLR.2026.1527>

How to link: <https://doi.org/10.31881/TLR.2026.1527>

Published: 18 May 2026



Process Optimization and Material Evaluation of Natural Fiber Fabrics for Sustainable Fashion Apparel Design

Zhihui Li

School of Finance and Economics, Chongqing Industry & Trade Polytechnic, Fuling District, 408000, Chongqing, China
mzlihzhui@126.com

Article

<https://doi.org/10.31881/TLR.2026.1527>

Received 24 March 2026; Accepted 22 April 2026; Published 18 May 2026

ABSTRACT

Natural fiber fabrics are increasingly used in sustainable fashion apparel because of their renewability and biodegradability, but hemp- and linen-containing fabrics often suffer from excessive stiffness, poor drape, and dimensional instability after laundering. This study developed an integrated framework for process optimization and apparel-oriented evaluation of natural-fiber fabrics. Three woven fabrics, namely organic cotton, hemp/organic cotton, and linen/organic cotton, were selected. An enzyme-assisted finishing process for hemp/organic cotton fabric was optimized using a Box–Behnken design with cellulase concentration, treatment temperature, and treatment time as variables. Flexural rigidity, tensile strength retention, air permeability, and residual shrinkage were used as response indicators. The optimum condition was 1.18% owf cellulase, 54 °C, and 42 min. Under this condition, flexural rigidity decreased by 28.6%, tensile strength retention remained 93.6%, air permeability improved, and residual shrinkage was reduced to 2.5%. Comparative evaluation showed that the optimized hemp/cotton fabric achieved the highest overall apparel suitability index among the tested materials. However, the improvement in softness and dimensional behavior was accompanied by a moderate loss in tensile strength retention, indicating a practical compromise rather than simultaneous optimization of all properties.

KEYWORDS

natural fibers, sustainable fashion, apparel design, enzyme finishing, material evaluation

INTRODUCTION

The clothing and textile industry is under increasing pressure to reduce resource consumption, waste generation, and environmental burden, which has accelerated interest in circularity, renewable materials, and more sustainable product systems. Natural fibers have therefore received renewed attention in apparel development because they are derived from renewable sources and are generally more compatible with sustainable

fashion goals than petroleum-based materials. At the same time, the sustainability value of a garment depends not only on fiber origin, but also on the processing route and end-use performance of the material [1-4].

Among natural fibers used in apparel, cotton remains the dominant material because of its softness and consumer familiarity, while hemp and flax are increasingly considered attractive alternatives due to their relatively low agricultural input requirements, breathability, and distinctive tactile and visual character. However, hemp- and flax-containing fabrics often exhibit higher stiffness, greater crease tendency, and more challenging garment construction behavior than cotton-based fabrics. These limitations are particularly important in sustainable fashion, where a material must satisfy both ecological expectations and actual wearing, aesthetic, and manufacturing requirements [5].

In sustainable fashion practice, material selection is not determined solely by ecological attributes such as renewability or biodegradability. Designers must also consider whether a fabric can satisfy practical garment requirements, including drape behavior, dimensional stability, seam performance, and comfort-related properties under repeated use. Therefore, the evaluation of natural-fiber fabrics for apparel applications should integrate both sustainability-oriented and performance-oriented criteria rather than relying on fiber origin alone.

Previous studies have shown that clothing comfort is a multidimensional concept involving physical, physiological, and psychological perception, and that fabric selection for apparel cannot rely on a single property such as strength or air permeability alone. For apparel design, softness, drape, seam behavior, dimensional stability, and moisture transfer must be considered together. Moreover, studies on hemp- and flax-blended apparel fabrics have confirmed their promising comfort characteristics, while also indicating the need for suitable post-finishing treatment to improve handle and usability [6-9].

Bio-finishing using cellulase is a recognized approach for cellulosic textiles because it can improve surface smoothness, softness, and handle through controlled enzymatic action. Previous studies have also shown that enzyme washing of hemp/organic cotton fabrics is feasible, although excessive treatment may cause undesirable weight and strength loss. This means that process optimization is essential if natural-fiber fabrics are to be effectively integrated into sustainable fashion apparel [10-16].

Although previous studies have reported the comfort and finishing behavior of selected natural-fiber fabrics, fewer studies combine eco-friendly process optimization with apparel-oriented material evaluation within one framework. To address this gap, the present study optimized an enzyme-assisted finishing process for

a hemp/organic cotton apparel fabric and then evaluated the optimized material against organic cotton and linen/cotton fabrics from the perspective of sustainable fashion design. The objectives of the study were: (1) to optimize the cellulase finishing condition for a hemp/cotton woven fabric; (2) to analyze the effects of treatment variables on flexibility, tensile strength retention, air permeability, and dimensional stability; (3) to compare the apparel-related properties of three natural-fiber fabrics; and (4) to identify a more suitable material–process combination for sustainable fashion garment applications. Hemp/cotton fabric was selected as the optimization target, while organic cotton and linen/cotton fabrics were included as reference materials for comparative apparel evaluation.

MATERIALS AND METHODS

Materials

Three woven apparel fabrics were selected as representative natural-fiber materials: Fabric C (100% organic cotton plain weave), Fabric HC (55/45 hemp/organic cotton twill weave), and Fabric LC (60/40 linen/organic cotton plain weave). To improve the reproducibility of the study, their basic structural parameters, including areal density, thickness, yarn linear density, and fabric sett, were recorded prior to finishing. All fabrics were sourced from the same commercial supplier and production system to reduce variability associated with material sourcing and pre-treatment history, while differences in weave structure and fabric parameters were intentionally retained to represent realistic variations among apparel fabrics. Before the experiments, all fabrics had undergone scouring and bleaching under the supplier’s standard preparation process.

The measured structural parameters are listed in Table 1. Because the selected fabrics differed in both fiber composition and structural parameters, the subsequent comparison was intended as an evaluation of representative natural-fiber apparel fabrics rather than a fiber-only effect analysis.

Table 1. Basic structural parameters of the selected fabrics

Fabric code	Fiber composition	Weave	Areal density (g/m ²)	Thickness (mm)	Warp yarn count (tex)	Weft yarn count (tex)	Warp density (ends/cm)	Weft density (picks/cm)
C	100% organic cotton	Plain	148 ± 3	0.42 ± 0.02	18.5	18.3	32	28
HC	55/45 hemp/organic cotton	Twill	176 ± 4	0.51 ± 0.03	21.4	20.8	29	24
LC	60/40 linen/organic cotton	Plain	164 ± 3	0.47 ± 0.02	19.8	19.2	31	26

Enzyme-Assisted Finishing Process

The finishing experiments were conducted using a laboratory dyeing and finishing machine equipped with programmable temperature control and mechanical agitation. A commercial liquid neutral cellulase preparation was used as the bio-finishing agent. According to the supplier specification, the nominal enzyme activity was approximately 9,500 U/mL, and the treatment bath was adjusted to pH 5.0 using a sodium acetate/acetic acid buffer system. The bath pH was maintained at 5.0 because this range is commonly recommended for neutral cellulase activity and controlled bio-finishing of cellulosic fabrics.

For each run, fabric specimens of 30 cm × 30 cm were treated at a fixed liquor ratio of 1:15. The bath volume was adjusted according to the fabric mass to maintain a constant liquor ratio throughout the experiment. The treatment temperature, enzyme concentration, and treatment duration were varied according to the Box–Behnken design. Mechanical agitation was maintained at 80 rpm during finishing.

After the enzymatic treatment, the bath was heated to 85 °C for 10 min to deactivate the enzyme. The samples were then rinsed twice with deionized water at 40 °C for 5 min each, neutralized in a mild buffer bath for 5 min, and dried in a forced-air oven at 60 °C under low-tension conditions. Before testing, all treated samples were conditioned for 24 h under standard atmospheric conditions of 20 ± 2 °C and 65 ± 4% RH.

Experimental Design

A three-factor, three-level Box–Behnken response surface design was employed to optimize the finishing process of Fabric HC. The independent variables were A, cellulase concentration (0.8, 1.2, and 1.6% owf); B, treatment temperature (45, 55, and 65 °C); and C, treatment time (30, 45, and 60 min).

The response variables were selected according to apparel performance requirements: Y1, flexural rigidity (N-cm), to be minimized; Y2, tensile strength retention (%), to be maximized; Y3, air permeability (mm/s), to be maximized; and Y4, residual shrinkage after washing (%), to be minimized.

A total of 17 experiments were carried out, including five center points.

Testing Methods

Flexural rigidity was measured by the cantilever method according to ASTM D1388. Five specimens were tested in both warp and weft directions, and the average value was reported.

Tensile strength was measured according to ASTM D5035 using the strip method. Strength retention was calculated as:

$$\text{Strengthretention}(\%) = \frac{S_f}{S_0} \times 100 \quad (1)$$

where S_f is the tensile strength of the treated sample and S_0 is the tensile strength of the untreated control. Air permeability was determined according to ASTM D737 at a pressure differential of 125 Pa. Five replicate measurements were taken from different positions of each fabric sample.

Residual shrinkage was measured after five laundering cycles according to AATCC 135. Warp and weft dimensional changes were determined separately, and the residual shrinkage index was calculated as the arithmetic mean of the absolute warp and weft shrinkage values:

$$\text{Residualshrinkage}(\%) = \frac{|\Delta L_w| + |\Delta L_f|}{2} \quad (2)$$

where ΔL_w and ΔL_f are the dimensional changes in the warp and weft directions, respectively.

For comparative material evaluation, the following additional tests were conducted: moisture vapor transmission rate (MVTR, ASTM E96), wrinkle recovery angle (AATCC 66), drape coefficient (Cusick drape test), seam efficiency (ASTM D1683), and pilling resistance (ISO 12945-2).

Apparel Suitability Index

To support apparel-oriented material selection, a study-specific Apparel Suitability Index (ASI) was used as a decision-support indicator. The ASI was not intended to represent a universal standard, but rather to provide a structured comparison among the selected fabrics under the present research objective. The index integrated four performance dimensions: comfort, appearance and drape, durability, and garment processability.

The normalized score was calculated as:

$$ASI = \sum_{i=1}^n w_i Z_i \quad (3)$$

where w_i is the assigned weight and Z_i is the normalized value of the i -th indicator. The weights were determined based on apparel performance priorities in sustainable casual fashion products and literature-informed judgment, with greater emphasis on comfort and balanced garment usability. In the present study,

the weights were set as 0.35 for comfort, 0.25 for appearance and drape, 0.25 for durability, and 0.15 for processability.

Therefore, the ASI values should be interpreted only within the scope of the present study.

Statistical Analysis

A second-order polynomial model was used for response surface analysis:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \quad (4)$$

where Y is the predicted response, X_i and X_j are the coded independent variables, and β values are the regression coefficients.

All tests were conducted with at least five replicates unless otherwise stated. Data are presented as mean \pm standard deviation. ANOVA and Tukey's test were applied at a significance level of $p < 0.05$. The overall experimental workflow of the study is illustrated in Figure 1.

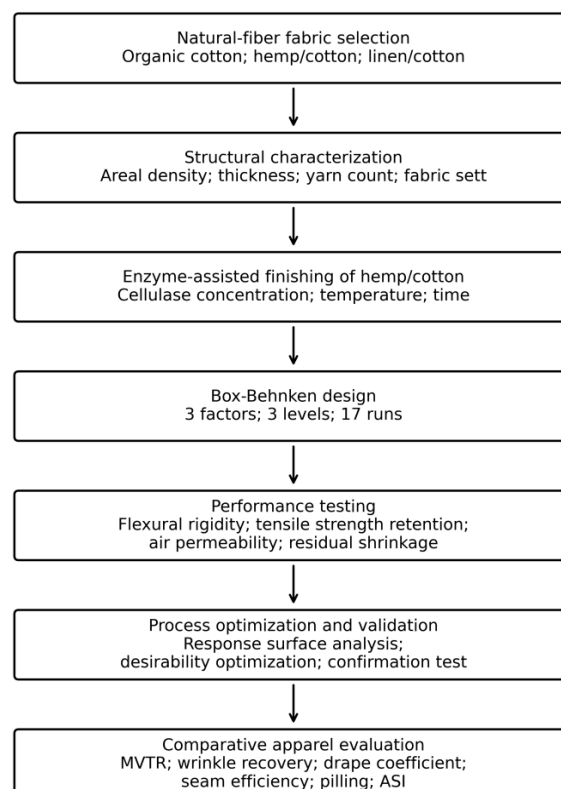


Figure 1. Experimental workflow for process optimization and apparel-oriented material evaluation of natural-fiber fabrics

RESULTS AND DISCUSSION

Box–Behnken Experimental Results

The experimental matrix and measured responses are shown in Table 2.

Table 2. Box–Behnken design matrix and experimental results for Fabric HC

Run	A	B	C	Flexural rigidity (N-cm)	Tensile strength retention (%)	Air permeability (mm/s)	Residual shrinkage (%)
1	-1	-1	0	0.234	96.8	161	3.7
2	1	-1	0	0.206	95.4	168	3.3
3	-1	1	0	0.217	95.7	169	3.5
4	1	1	0	0.187	92.9	181	2.9
5	-1	0	-1	0.229	96.5	158	3.8
6	1	0	-1	0.199	94.6	176	3.1
7	-1	0	1	0.213	95.1	168	3.3
8	1	0	1	0.182	93.0	182	3.0
9	0	-1	-1	0.222	96.3	163	3.6
10	0	1	-1	0.201	94.5	176	3.2
11	0	-1	1	0.209	94.9	172	3.3
12	0	1	1	0.179	92.8	184	2.8
13	0	0	0	0.184	94.3	186	2.6
14	0	0	0	0.180	93.7	184	2.5
15	0	0	0	0.182	94.0	188	2.4
16	0	0	0	0.177	93.9	185	2.6
17	0	0	0	0.183	94.1	187	2.5

Across the 17 experimental runs, flexural rigidity ranged from 0.177 to 0.234 N-cm, tensile strength retention ranged from 92.8% to 96.8%, air permeability ranged from 158 to 188 mm/s, and residual shrinkage ranged from 2.4% to 3.8%. These results indicate that the selected treatment variables produced measurable changes in both handle-related and performance-related properties of the hemp/cotton fabric.

The center-point runs showed acceptable repeatability under the selected laboratory conditions. For the five repeated center runs, the measured values remained within relatively narrow ranges, suggesting that the experimental procedure provided sufficient short-term process stability for subsequent response surface analysis.

In general, increasing treatment severity reduced flexural rigidity and residual shrinkage, while excessive treatment also caused a decrease in tensile strength retention. Air permeability tended to increase under moderate-to-high treatment intensity. However, the responses did not change in a strictly linear manner

across all runs, and small fluctuations were observed among individual experiments. This suggests that the effects of cellulase concentration, temperature, and treatment time were interactive rather than purely additive.

In particular, the lower flexural rigidity values observed under moderate-to-high treatment conditions indicate an evident softening effect of the enzyme-assisted finishing process. At the same time, the corresponding reduction in tensile strength retention under more severe conditions suggests that excessive treatment intensity may compromise structural integrity. This trade-off highlights the need to identify an intermediate processing region that can improve flexibility-related behavior without causing excessive mechanical deterioration. These response patterns indicate that further statistical modeling was necessary to determine the relative importance of each factor and to identify a balanced processing window for improved handle-related performance and acceptable mechanical preservation.

ANOVA and Regression Analysis

The ANOVA results confirmed that all quadratic models were statistically significant, whereas the lack-of-fit terms were not significant within the investigated experimental domain. The model adequacy statistics summarized in Table 3 further showed acceptable coefficients of variation and adequate precision values greater than 4 for all response variables, indicating that the fitted models provided sufficient signal for navigation of the design space. Here, LOF denotes lack-of-fit, Adj. R^2 denotes adjusted R^2 , and Pred. R^2 denotes predicted R^2 .

Table 3. ANOVA summary and model adequacy statistics for the four response variables

Response variable	Model F	Model p	LOF p	R^2	Adj. R^2	Pred. R^2	C.V. (%)	Adeq. precision	Significant terms
Flexural rigidity	24.86	0.0002	0.214	0.970	0.931	0.882	2.43	16.28	A, B, C, AB, A ² , B ²
Tensile strength retention	18.74	0.0004	0.296	0.960	0.909	0.851	0.62	14.91	A, B, C, AB, A ²
Air permeability	36.95	<0.0001	0.281	0.979	0.953	0.910	1.17	18.44	A, B, C, AB, AC, A ² , B ²
Residual shrinkage	12.81	0.0014	0.257	0.943	0.870	0.804	4.36	12.76	A, B, C, AB, A ²

As shown in Table 3, all four fitted models exhibited statistically significant regression effects and non-significant lack-of-fit terms, indicating acceptable model adequacy within the investigated factor range. The relatively low coefficients of variation and the adequate precision values greater than 4 further suggest that the models provided sufficient signal for response surface interpretation and optimization.

Among the three process variables, cellulase concentration and treatment temperature generally exerted stronger influences than treatment time. However, the sensitivity of the four response variables to the selected process factors was not identical. For flexural rigidity, the significant main effects and quadratic terms suggest that increasing treatment severity promoted fabric softening within the selected range. For tensile strength retention, the negative influence of higher concentration and temperature indicates that excessive enzymatic action may cause partial fiber-surface damage. For air permeability, the model suggests a favorable increase under moderate-to-high treatment intensity, whereas the response of residual shrinkage indicates improved dimensional stability under controlled finishing conditions.

Not all interaction and quadratic terms were significant for every response variable, indicating response-dependent relationships between process parameters and fabric properties. Such variation is expected in multi-response textile finishing systems, where flexibility-related, mechanical, and dimensional properties may respond differently to the same treatment condition.

In addition, the relatively high R^2 values, together with the reasonable agreement between Adj. R^2 and Pred. R^2 , suggest that the models had acceptable explanatory and predictive capability within the investigated factor range. The summarized ANOVA and model adequacy statistics therefore support the use of response surface analysis for identifying a moderate treatment window rather than an excessively severe condition in order to balance handle improvement and mechanical preservation. The detailed regression coefficients are not listed here, because the summarized ANOVA and model adequacy statistics are sufficient to demonstrate the predictive adequacy of the fitted models.

Optimization and Validation

A multi-response desirability approach was used to minimize flexural rigidity and residual shrinkage while maximizing tensile strength retention and air permeability. In practical apparel applications, however, the optimum does not correspond to extreme values of individual properties; instead, it represents a balanced functional range that can satisfy handle, comfort, dimensional stability, and durability requirements simultaneously. The predicted optimum condition was a cellulase concentration of 1.18% owf, a treatment temperature of 54 °C, and a treatment time of 42 min.

Under this condition, the predicted responses were 0.175 N·cm for flexural rigidity, 93.9% for tensile strength retention, 188 mm/s for air permeability, and 2.5% for residual shrinkage. Verification experiments yielded measured values of 0.178 ± 0.005 N·cm, $93.6 \pm 0.7\%$, 186 ± 4 mm/s, and $2.5 \pm 0.1\%$, respectively. The predicted

and measured values showed acceptable agreement, indicating that the developed model was suitable for optimization within the investigated parameter range. This agreement also suggests that the selected desirability-based optimization strategy was effective in identifying a practically balanced treatment condition.

Compared with the untreated HC fabric, the optimized treatment reduced flexural rigidity and improved air permeability while maintaining tensile performance at an acceptable level for apparel use. Although the optimization did not aim to maximize any single response independently, the results indicate that the improvements in softness-related behavior and dimensional stability were achieved with a moderate reduction in tensile strength retention. Thus, the selected condition should be interpreted as a practical compromise among handle improvement, air permeability, dimensional stability, and mechanical preservation, rather than as a simultaneous improvement of all properties. These findings suggest that the selected bio-finishing route may improve the handle-related performance and overall usability of hemp/cotton fabric for fashion-oriented apparel applications.

Comparative Material Evaluation

The comparative results are presented in Table 4.

Table 4. Comparative material properties and apparel suitability of the selected fabrics

Property	C	HC-opt	LC
Air permeability (mm/s)	144 ± 5	166 ± 6	156 ± 5
MVTR (g/m ² ·24 h)	5320 ± 115	5820 ± 120	5750 ± 118
Wrinkle recovery angle (°)	227 ± 6	214 ± 6	210 ± 5
Drape coefficient (%)	42.5 ± 1.1	39.9 ± 1.1	37.6 ± 1.0
Seam efficiency (%)	87.1 ± 1.3	88.2 ± 1.4	85.3 ± 1.5
Pilling grade	4.1 ± 0.1	4.0 ± 0.1	3.8 ± 0.1
Warp tensile strength (N)	731 ± 15	724 ± 15	694 ± 13
Weft tensile strength (N)	481 ± 11	486 ± 12	458 ± 10
Apparel Suitability Index (ASI)	0.796	0.832	0.805

Among the three evaluated fabrics, HC-opt exhibited the highest overall ASI value, suggesting the most balanced performance profile for sustainable casual apparel applications. However, the optimized hemp/cotton fabric was not uniformly superior in every individual property. Organic cotton showed the highest wrinkle recovery angle and slightly higher warp tensile strength, whereas linen/cotton exhibited the lowest drape coefficient, indicating better drape behavior.

Compared with Fabric C, HC-opt provided higher air permeability, higher moisture vapor transmission, and slightly better seam efficiency, which are favorable for breathable and wearable apparel products. At the same time, the relatively close overall scores among the three fabrics indicate that the final material choice should still depend on garment type and design emphasis. The present results therefore suggest that the optimized hemp/cotton fabric offered the best overall balance in this study, rather than universal superiority across all apparel-performance dimensions.

The observed differences among the three fabrics were influenced not only by fiber composition, but also by differences in weave structure, mass, and yarn configuration. Thus, the comparison reflects the performance of selected natural-fiber apparel fabrics rather than a fiber-only effect analysis.

To evaluate the potential influence of subjective weight assignment on the Apparel Suitability Index (ASI), a sensitivity check was additionally performed by moderately varying the weights of the four evaluation dimensions while keeping the total weight equal to one. Several alternative weighting schemes were considered, including slightly reduced and increased emphasis on the comfort dimension as well as an equal-weight scenario. The resulting comparison indicated that the relative ranking of the three fabrics did not change under these alternative weighting configurations. This suggests that the superiority of HC-opt observed in the present study was not solely dependent on one specific weighting combination, but rather reflected its relatively balanced performance across comfort, appearance and drape, durability, and garment processability. Therefore, although the ASI is a study-specific comparative indicator, the final material ranking can be considered reasonably robust within the investigated weighting range.

As illustrated in Figure 2, the ASI comparison provides a concise visual summary of the overall ranking of the three evaluated fabrics.

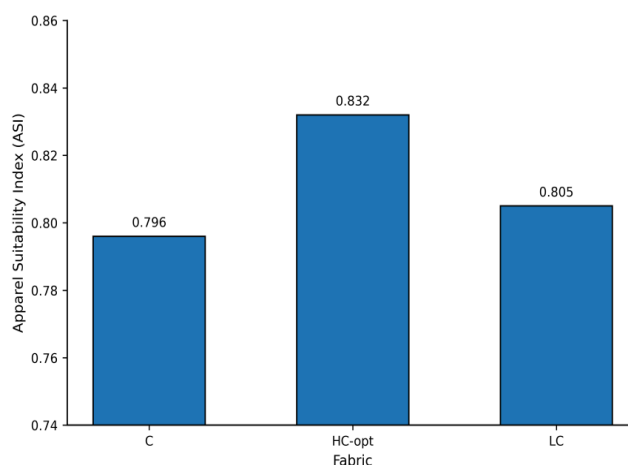


Figure 2. Comparative apparel suitability index (ASI) of organic cotton (C), optimized hemp/cotton (HC-opt), and linen/cotton (LC) fabrics

CONCLUSION

This study developed an integrated framework for process optimization and apparel-oriented evaluation of selected natural-fiber fabrics for sustainable fashion applications. A hemp/organic cotton woven fabric was chosen as the optimization target because it combines sustainability relevance with practical stiffness-related limitations in apparel use. Using a Box–Behnken response surface design, the optimum enzyme-assisted finishing condition was identified as 1.18% owf cellulase, 54 °C, and 42 min.

Under the optimized condition, the hemp/cotton fabric exhibited reduced flexural rigidity, improved air permeability, and acceptable tensile strength retention and dimensional stability. Comparative evaluation further indicated that the optimized hemp/cotton fabric offered the most balanced overall performance among the selected fabrics in this study. However, the observed differences among the materials were associated with both fiber composition and fabric structural parameters. Therefore, the conclusions should be interpreted within the scope of the selected fabrics and test conditions.

The results suggest that scientifically optimized bio-finishing can improve the wearability and design applicability of hemp-containing apparel fabrics. However, the present comparison was limited to three selected woven fabrics and laboratory-scale finishing conditions. Future work should include morphology characterization, detailed regression reporting, broader wear-trial validation, and process assessment under industrially relevant conditions.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Zhihui Li designed, collected and analyzed the data, and drafted the manuscript. Zhihui Li conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zhihui Li participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Conflict of Interest

The author declares no conflict of interest.

Funding

This research received no external funding.

Acknowledgment

Not applicable.

REFERENCES

- [1] Islam T, Hossain MM, Covington S. Natural fibers towards fashion sustainability: A review of raw materials, production, application, and perspective. *Journal of Natural Fibers*. 2025; 22(1). doi: 10.1080/15440478.2025.2462218.
- [2] Chen X, Memon HA, Wang Y, Marriam I, Tebyetekerwa M. Circular economy and sustainability of the clothing and textile industry. *Materials Circular Economy*. 2021; 3:12. doi: 10.1007/s42824-021-00026-2.
- [3] Abbate S, Centobelli P, Cerchione R, Oropallo E. Sustainability trends and gaps in the textile, apparel and fashion industries. *Environment, Development and Sustainability*. 2024; 26:2291-2320. doi: 10.1007/s10668-022-02887-2.
- [4] Thakker AM, Sun D. Sustainable Development Goals for Textiles and Fashion. *Environmental Science and Pollution Research*. 2023; 30(46):101989-102009. doi: 10.1007/s11356-023-29453-1.
- [5] Mariz J, Guise C, Silva TL, Rodrigues L, Silva CJ. Hemp: From Field to Fiber-A Review. *Textiles*. 2024; 4(2):165-182. doi: 10.3390/textiles4020011.
- [6] Kamalha E, Zeng Y, Mwasiagi JI, Kyatuheire S. The comfort dimension: A review of perception in clothing. *Journal of Sensory Studies*. 2013; 28(6):423-444. doi: 10.1111/joss.12070.
- [7] Kaplan S, Okur A, Sarıışık M. The meaning and importance of clothing comfort: A case study for Turkey. *Journal of Sensory Studies*. 2008; 23(5):688-706. doi: 10.1111/j.1745-459X.2008.00180.x.
- [8] Saricam C, Kalaoglu F. The comfort properties of hemp and flax blended denim fabrics treated with selected common industrial washing treatments. *Textile Research Journal*. 2022; 92(17-18):3164-3178. doi: 10.1177/00405175211054216.
- [9] Zimniewska M, Kozłowski R, Batog J. Bioactive hemp clothing modified with cannabidiol (CBD) cannabis extract. *Materials*. 2021; 14(20):6040. doi: 10.3390/ma14206040.
- [10] Ibrahim NA, El-Zairy MR, Eid BM. A new approach for biofinishing of cellulose-containing fabrics using cellulases. *Carbohydrate Polymers*. 2011; 83(1):116-121. doi: 10.1016/j.carbpol.2010.07.025.
- [11] Aly AS, Moustafa AB, Hebeish A. Bio-technological treatment of cellulosic textiles. *Journal of Cleaner Production*. 2004; 12(7):697-705. doi: 10.1016/S0959-6526(03)00074-X.

- [12] Ibrahim NA, El-Zairy MR, El-Shafei A. Effect of cellulase treatment on the extent of post-finishing and dyeing of cotton fabrics. *European Polymer Journal*. 2005; 41(11):2653-2664. doi: 10.1016/j.eurpolymj.2004.11.010.
- [13] Koo H, Ueda M, Wakida T, Yoshimura M, Ohtani T. Cellulase treatment of cotton fabrics. *Textile Research Journal*. 1994; 64(2):70-74. doi: 10.1177/004051759406400202.
- [14] Yang CQ, Tao X, Xu Y. Cellulase treatment of durable press finished cotton fabric. *Textile Research Journal*. 2003; 73(12):1105-1110. doi: 10.1177/004051750307301205.
- [15] Sankarraj N, Nallathambi G. Enzymatic biopolishing of cotton fabric with free/immobilized cellulase. *Carbohydrate Polymers*. 2018; 191:95-102. doi: 10.1016/j.carbpol.2018.02.067.
- [16] Guo Y, Sun Z, Guo X, Zhou Y, Jiang L, Chen S, Ma J. Study on enzyme washing process of hemp organic cotton blended fabric. *International Journal of Clothing Science and Technology*. 2019; 31(1):58-64. doi: 10.1108/IJCS-08-2017-0117.