EFFECTS OF HEMP FIBER ADDITION ON DENIM FABRIC PERFORMANCE CHARACTERISTICS

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This study aims to investigate the effect of employing industrial hemp fibers (*Cannabis sativa* L.) as an eco-friendly fiber in denim fabric, which is one of the most extensively used fabrics in today's clothing industry and is popular with all socio-economic groups. In line with this aim, denim fabric samples were developed using conventional and organic cotton ring spun yarns in the warp, and conventional cotton, organic cotton/bamboo/linen, and organic cotton/bamboo/hemp ring, core, and dual-core spun yarns in the weft. The manufactured denim fabric samples' weight, tensile and tearing strength, stiffness, dimensional change, seam slippage, abrasion, and pilling characteristics were analyzed comparatively using statistical analysis techniques. The findings of the statistical analysis indicated that the core component type was the most significant independent variable for almost all fabric characteristics studied. The usage of linen and hemp fibers in the sheath structure of the weft yarn did not cause nearly any change in fabric weight, abrasion, or seam slippage values, but led to a decrease in mechanical properties. In addition, while they increased fabric stiffness, they had a positive effect on pilling and caused it to decrease.

Keywords: denim fabric, organic cotton, bamboo, linen, hemp, hybrid yarn, eco-design

INTRODUCTION

Fiber is an essential component of the clothing industry; the manufacturing process line and design begin with fiber selection. The type and properties of the fiber have a significant impact on the final product's qualities, despite all the technical methods.[1] Cotton has been the most important textile cellulose fiber crop for thousands of years, due to its softness, cool-keeping, good strength, absorbency, and biodegradability properties. It is mostly cultivated and used for producing clothing. According to a market study, the share of cotton fiber in clothing products is 48% on a global level.[2] However, because of the negative environmental effects resulting from its cultivation, the usage of cotton fibers in the clothing industry has become a sensitive topic in recent years.[3] Cotton farming as a whole is associated with several sustainability issues, including degraded land as a result of salinization and erosion; water depletion by excessive use of soil and surface water; natural habitat conversion caused by cutting down forests and dam constructions; eutrophication of surface water; wildlife contamination by pesticides (insects, fish, mammals, and birds); and human health threats caused by direct pesticide intake, primarily by farm workers.[3-6] While researchers continue to look back to natural fibers for the future, the search for substitute materials is ongoing.[7,8] In the recent decade, bamboo,[9,10] Tencel,[11,12] and flax[13,14] fibers have been studied as alternatives to cotton. Hemp fibers may be a greener choice in comparison with cotton fiber, according to some researchers.[7,13,15,16]

Cannabis sativa L., also known as hemp, has been used as a source of fiber for many different industrial and consumer products for ages. In the early twentieth century, however, its significance decreased for a variety of reasons. The main reason and biggest challenge to hemp cultivation is the presence of psychoactive substances (delta9 tetrahydrocannabinol, or THC), which led to the outlawing of its production in many nations.[16] The reborn interest in hemp arose in the early 1980s, but not without reason, owing especially to ecological concerns, environmental safety, and future resource balance.[16,17] Hemp's intensive growth and high yield, while requiring little to no irrigation, little to no fertilizer use, and little to no pesticide use demonstrate its potential for sustainability. In addition to being a desirable rotational crop, hemp can be adaptable to a variety of environmental conditions. Hemp can improve the soil's structure and is extremely competitive with weeds. Hemp also can be used for bioremediation (to remove heavy metals from the soil) and to turn underutilized areas back into productive farmland, without negatively impacting the quantity or quality of the crop.[16,18-20] Above all, hemp fiber is distinguished from other textile fibers by its properties, being aseptic and anti-static, with high absorbency and water vapor permeability, good thermal and electrical properties, protection against UV rays, and non-allergenicity.[8,21-23] As a result of the aforementioned ecological factors and outstanding textile properties, hemp fibers can be an excellent choice for use in the manufacturing of clothing.

Among all traditional fiber materials, denim, a cotton woven fabric, is one of the most extensively used items in today's clothing trends.[24,25] Being popular with all socio-economic groups, denim has evolved from being merely an article of clothing to a status symbol that is flaunted by fashion models. It now represents a vision of modern society.[26] Throughout our overview of the literature, very few studies on the usage of hemp fiber in denim fabric construction have been noted.[13,27] Furthermore, no study has been done on the manufacturing of organic cotton/bamboo/linen and organic cotton/bamboo/hemp-based denim fabric structures. The usage of hemp blended hybrid yarns in denim fabric structure is not only related to determining fabric performance characteristics, but it is also of importance to the denim industry due to new demanding environmental requirements. As a result, it is a key research topic and deserves great attention.

In this research, 12 different types of denim fabric samples were developed by using 100% conventional and organic cotton ring spun yarns in the warp, and conventional cotton, organic cotton/bamboo/linen, and organic cotton/bamboo/hemp blended hybrid yarns in the weft. The weight, tensile and tearing strength, stiffness, dimensional change, seam slippage, abrasion, and pilling properties of the developed denim fabric samples were evaluated comparatively using statistical analysis methods.

EXPERIMENTAL

Materials

The characteristics of the fibers used in this study for the production of denim fabric samples are provided in Table 1. Additionally, the chemicals used in the production of these samples are as follows: starch (Cottonal KS-Royal, AVEBE U.A., Netherlands) used as a sizing agent, salt as an affinity agent, Glissofil Extra (Royal, AVEBE U.A., Netherlands) as a cross-linker, caustic soda (Likit Kimya San. ve Tic. A.Ş., Turkey) as a bleaching aid and impurity remover, Indigo dye (DYSTAR Indigo Vat 40%) as a colorant, a neutralizing acid and buffering agent (AKASIT PFC, Akkim Kimya, Turkey) as a pH regulator in the washing process, and polyethylene emulsion (REPELLAN NEU, Pulcra Chemicals, Germany) as a chemical finishing agent.

Methods

Production of denim fabric samples

In this study, 12 different types of denim fabric samples were produced, utilizing various fiber blends. Conventional cotton and organic cotton ring-spun yarns, with a linear density of Ne 14/1, were used for the warp. For the weft, conventional cotton, organic cotton/bamboo/linen, and organic cotton/bamboo/hemp ring-spun, core-spun, and dual-core-spun yarns, with a linear density of Ne 18/1, were used. Table 2 lists the production parameters of the warp and weft yarns utilized in the study. All denim fabric samples were woven in 20 picks/cm density, 3/1 Z twill weave pattern on a dobby loom (Picanol Optimax-i 4R-220, Belgium).

Table 1
Characteristics of fibers used in the production of denim fabric samples

Properties	Conventional cotton (C)	Organic cotton (O)	Bamboo (B)	Linen (L)	Hemp (H)	Elastane (E)	Polyester (P)
Length (mm)	28.00	27.85	38.00	33.00	33.00	-	-
Linear density (tex)	0.18	0.18	0.13	0.33	0.39	7.80	5.50
Tenacity (cN/tex)	30.83	30.45	25.90	89.01	45.00	9.23	35.35
Elongation (%)	5.26	5.25	11.60	2.80	2.60	520.00	24.00

Table 2
Spinning parameters of produced warp and weft yarns

Yarn type	Yarn linear density (Ne)	T/m	ae	Lyra drawing	T400 drawing
Warp	14/1	560.00	3.75	-	-
Weft	18/1	760.00	4.50	3.60	1.10

(T/m: Number of twists per meter and ae: Twist coefficient)

Table 3
Properties and denotation of the developed denim fabric samples

Fabric type	Fabric composition	
	Warp yarn	Weft yarn
DC	100.00% conventional cotton	100.00% conventional cotton
DCE		93.40% conventional cotton + 6.60% elastane
DCP		84.80% conventional cotton + 15.20% polyester
DCEP		78.20% conventional cotton + 6.60% elastane + 15.20% polyester
DOBL	100.00% organic cotton	47.00% organic cotton + 33.00% bamboo + 20.00% linen
DOBLE		43.90% organic cotton + 30.82% bamboo + 18.68% linen + 6.60% elastane
DOBLP		39.86% organic cotton + 27.98% bamboo +16.96% linen + 15.20% polyester
DOBLEP		36.75% organic cotton + 25.81% bamboo + 15.64% linen + 6.60% elastane + 15.20% polyester
DOBH		47.00% organic cotton + 33.00% bamboo + 20.00% hemp
DOBHE		43.90% organic cotton + 30.82% bamboo + 18.68% hemp + 6.60% elastane
DOBHP		39.86% organic cotton + 27.98% bamboo + 16.96% hemp + 15.20% polyester
DOBHEP		36.75% organic cotton + 25.81% bamboo + 15.64% hemp + 6.60% elastane + 15.20% polyester

After weaving, a variety of finishing treatments were applied to denim fabrics. These treatments were as follows, in the order of application: singeing (front face: flat; back face: tangent), washing (at 60 °C and pH 5–7.5), chemical finish (polyethylene emulsion to give seam non-slip), and sanforizing (130 °C and 40 m/min). All the materials and conditions used to produce the denim fabric samples were the same, except the twelve different weft yarns. The properties and denotation of the denim fabric samples produced are given in Table 3.

Characterization of fabric samples

The following tests were done to determine the performance characteristics of the denim fabric samples produced. All the specimens were conditioned at standard atmosphere conditions of 65 ± 2% R.H. and 20 ± 1°C for 24 h as per the requirements of ISO 139:2005 before performing the tests. Each test was performed in five replicates and averages of the test results were calculated. Error bars were determined by calculating the coefficient of variation.

Fabric weight (GSM)

GSM is a globally accepted method for measuring fabric weight in grams per square meter (g/m²). In this study, the ASTM D3776 standard was followed, using a GSM cutting template. A fabric sample was cut into a circular area of 100 cm², weighed in grams using the PRECISA/XT 320 M Tester, and then multiplied by 100 to calculate the final GSM.

Tensile and tearing strength

The tensile strength of the fabrics was tested using a tensile strength tester (SDL Atlas UT350) in accordance with the ASTM D5034 (Grab Test) standard. A rectangular sample measuring 100 mm × 150 mm was placed between the upper and lower jaws of the machine. The machine was operated until the breaking load was displayed on the monitor.

The tearing strength of the fabrics was measured according to the ASTM D1424 (Pendulum Method) standard, using the SDL Atlas M008 Elmendorf Tearing Tester. In this method, the pendulum was first raised to the starting position, with the indicator aligned to the initial reference point (1000).

Then, the center of each prepared sample was positioned and securely clamped in the jaws of the instrument. By releasing the pin holding the pendulum, the sample was partially cut by a blade measuring 20 ± 0.15 mm, initiating the tear. The pendulum was allowed to swing freely until the tearing process was complete. Finally, the tearing strength value was recorded from the instrument's display.

Stiffness

Stiffness was defined using the SDL Atlas SASD-672 tester, following the general guidelines of the ASTM D4032 standard. The test procedure was as follows: fabric samples were prepared near the center of the fabric width, with dimensions of 102 mm × 204 mm, and the shorter edge aligned with the warp direction. The prepared sample was folded in half, with the front side facing up, and placed in the sample chamber of the testing instrument. Air pressure of 3.24 kPa was then applied, and the measurement continued until the sample exited the chamber.

Dimensional properties

The Electrolux FOM71 CLS machine was used to assess dimensional stability according to the AATCC 135 standard. Fabric samples for testing were cut into three pieces, each measuring 500 × 500 mm, leaving at least 50 mm from the edges and maintaining a minimum distance of 350 mm between the samples. The edges were sewn with an overlock stitch. The samples then underwent three cycles of "home laundry washing" for 60 minutes at 60 °C. After washing, the samples were dried and conditioned for 4 hours under standard atmospheric conditions. The marked areas on the conditioned samples were measured using a shrinkage chart, and the shrinkage values in the weft and warp directions were calculated as percentages. If shrinkage occurred, the values were reported with a '-' sign, and if elongation occurred, the values were reported with a '+' sign.

Seam slippage

Seam slippage was determined using SDL ATLAS/UT350 in compliance with ASTM D434. The fabric samples prepared by sewing were placed in the testing machine, with the jaw distance set to 76 ± 1 mm and the measurement speed set to 300 mm/min. During the analysis, the instrument measured the force required to achieve a 6.4 mm stitch pitch. If the specimen or the seam breaks before the specified screw pitch is reached, the analysis result cannot be obtained.

Abrasion and pilling resistance

The SDL Atlas M235 machine was employed to measure abrasion resistance according to the BS EN ISO 12947-2 standard. A weight of 9 kPa was applied for the test, and yarn breakage in the fabrics was monitored at intervals of 1.000 cycles between 0 and 5.000 cycles, 2.000 cycles between 5.000 and 20.000 cycles, 5.000 cycles between 20.000 and 40.000 cycles, and 10.000 cycles after 40.000 cycles. The number of cycles at which yarn breakage occurred was recorded, and finally, the weights of the samples were measured after 25.000 cycles.

Pilling resistance was measured using the SDL Atlas M235 instrument based on the BS EN ISO 12947-2 standard. Fabric samples with a diameter of 140 mm and backing felt with a diameter of 90 mm were prepared. The backing felt was placed on the base of the apparatus, and the fabric sample was positioned on top with the front side facing upwards. To prevent any slippage or wrinkling, an appropriate weight was applied on top, and the stabilizing rings were tightly fastened with screws. Once secured, the weight was removed, the testing device was set to its starting position, and the abrasion table was mounted onto the machine. The machine was paused every 500 cycles, during which the samples were gently brushed. The process continued until 2,000 cycles were completed. At the end of the test, the samples were removed and evaluated for pilling levels using the standard reference photo scale.

Statistical analysis

The data obtained in the study were analyzed using a multilevel categoric design as a statistical analyzing technique with Design Expert software 13. The significance of the sheath fiber type and core component type was determined by using a two-way analysis of variance (ANOVA) at a 95% confidence interval (CI). In the ANOVA table, R^2, df, F, and p mean the proportion of the variance for a dependent variable that is explained by an independent variable in a regression model, the degrees of freedom, variation between the sample means, and whether there is a significant difference between the sample means, respectively.

RESULTS AND DISCUSSION

Fabric weight

The ANOVA statistics and weight findings of the produced denim fabric samples, which were investigated before and after washing, are provided in Tables 4 and 5 and Figure 1, respectively. The R^2 value was 99.92% before and 99.97% after washing. According to ANOVA statistics, the sheath fiber type, the core component type, and the intersection of these independent variables statistically significantly affected weight values both before and after washing, with a p-value of <0.0001. The independent variable that contributed the most to the weight value, both before (98.28%) and after washing (99.38%), was the core component type. In the analysis performed before washing, the weight value of the fabric containing hemp

(DOBH: 248.00±0.13 g/m^2) was slightly higher than those of the other fabrics (DC: 243.00±0.44 g/m^2 and DOBL: 243.60±0.08 g/m^2), when compared to the results of fabrics that did not contain core components. This might be since hemp fibers have higher fiber density and moisture retention capabilities, and thicker fiber structure, compared to cotton and linen fibers. After washing, the weight of all fabric types without core components decreased by 3.08–7.19%, most likely due to fabric extension.[28] Regardless of the type of core component, the use of core components improved the weight (by 4.52 to 28.40%) of all fabric types before washing. After washing, the use of elastane and dual-core components resulted in an increase in weight for all fabric types, potentially due to shrinking, but the use of polyester resulted in a decrease, most likely due to extension.[28]

Table 4
ANOVA statistics for fabric weight values before washing

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	45128.06	99.92	11	4102.55	5356.98	< 0.0001
Sheath fiber type	362.83	0.80	2	181.42	236.89	< 0.0001
Core component type	44389.68	98.28	3	14796.56	19320.86	< 0.0001
Sheath fiber type*core component type	375.54	0.83	6	62.59	81.73	< 0.0001
Error	36.76	0.08	48	0.77		
Corrected total	45164.82	100.00	59			

Table 5
ANOVA statistics for fabric weight values after washing

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	327189.45	99.97	11	29744.50	12995.96	< 0.0001
Sheath fiber type	1375.417	0.42	2	687.71	300.47	< 0.0001
Core component type	325260.82	99.38	3	108420.27	47370.96	< 0.0001
Sheath fiber type*core component type	553.220	0.17	6	92.20	40.29	< 0.0001
Error	109.860	0.03	48	2.29		
Corrected total	327299.31	100.00	59			

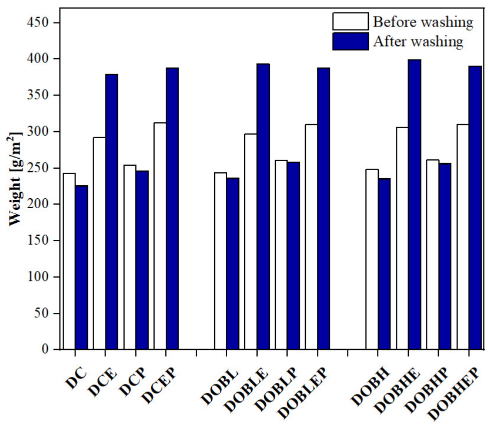

Figure 1: Weight findings of developed denim fabric samples

Shrinkage and extension during washing significantly influence fabric weight. Shrinkage causes a reduction in surface area, which leads to an increase in weight per unit area (g/m²) as the fibers become more compact. In contrast, extension increases the surface area, reducing weight per unit area by spreading the fibers apart. In conclusion, regardless of the core component used, when evaluating all fabric types, hemp-containing fabrics (except for DOBHEP) had higher weight values (0.03-4.56%) compared to the reference and linen-containing fabrics before washing. After washing, they maintained higher weight values (0.67-5.15%) compared to the reference fabrics, although no clear trend was observed when compared to the linen-containing fabrics.

Tensile strength

The ANOVA statistics and tensile strength findings in the weft and warp directions of the developed denim fabric samples are given in Tables 6 and 7, and Figure 2, respectively. The R^2 value was determined to be 99.93% in the warp direction and 98.35% in the weft direction. ANOVA statistics revealed that the sheath fiber type, the core component type, and the intersection of these factors had a statistically significant effect on tensile strength values in both directions of the fabric, with a p-value of <0.0001. The core component type was the most effective independent variable on tensile strength in both the warp (96.50%) and weft (55.00%) directions. When fabrics without core components were evaluated in the warp direction, the linen-containing fabric had the highest tensile strength value (DOBL: 662.57±0.44 N). By contrast, the tensile strength values of hemp-containing and reference fabrics were lower by 2.22% and 4.26%, respectively. In the weft direction, the opposite situation was observed, that is, the fabrics containing bast fibers had a lower tensile strength value (DOBL: 260.36±1.12 N and DOBH: 261.14±2.17 N) than the reference fabric (319.42±1.47 N). This situation could have been caused by using linen and hemp fibers, which have high strength as single fibers, but low cohesiveness in bundles,[29] and bamboo fiber, which has a lower strength value (25.00 cN/tex) compared to conventional cotton fiber (30.83 cN/tex), in the weft composition. In addition, the use of three different fiber blends in the weft yarn's sheath could have increased fiber migration by causing irregularities.[28]

Using core components improved the tensile strength values of all fabric types in the warp direction, regardless of the type of core component. As in the weight results, the least increase was seen in the use of polyester. The tensile strength values were lowered in the range of 8.11 to 14.07% in all fabric types where elastane was used in the weft direction, but raised when polyester or dual-core components were utilized. This might be a result of the lower strength value of elastane (9.23 cN/tex) compared to other fibers (between 25.00 and 35.35 cN/tex).

Table 6
ANOVA statistics for tensile strength values in the warp direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	13975.68	99.93	11.00	1270.52	6222.94	< 0.0001
Sheath fiber type	323.66	2.31	2.00	161.83	792.64	< 0.0001
Core component type	13496.33	96.50	3.00	4498.78	22034.83	< 0.0001
Sheath fiber type*core component type	155.69	1.11	6.00	25.95	127.09	< 0.0001
Error	9.80	0.07	48.00	0.20		
Corrected total	13985.48	100.00	59.00			

Table 7
ANOVA statistics for tensile strength values in the weft direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	618.09	98.35	11	56.19	259.94	< 0.0001
Sheath fiber type	198.46	31.58	2	99.23	459.05	< 0.0001
Core component type	345.64	55.00	3	115.21	532.99	< 0.0001
Sheath fiber type*core component type	73.99	11.77	6	12.33	57.04	< 0.0001
Error	10.38	1.65	48	0.22		
Corrected total	628.47	100.00	59			

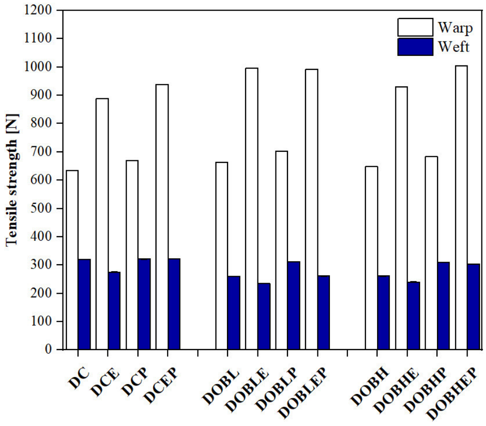

Figure 2: Tensile strength findings of developed denim fabric samples

However, its warp tensile strength values grew dramatically, most likely because of the fabric's compactness and the yarn's elasticity.[28]

To summarize, the tensile strength values of all fabric types in the warp direction were higher than those in the weft direction. This could happen since the warp density of the fabrics (28 ends/cm) was higher than the weft density (20 picks/cm). Regardless of the core component usage, when evaluating all fabric types, the tensile strength values of hemp-containing fabrics in the warp direction were 2.09–6.54% higher than the reference fabrics, but 2.22–6.64% lower than those of linen-containing fabrics (except DOBLEP). In contrast, in the weft direction, the trend reversed: hemp-containing fabrics showed 3.72–18.24% lower tensile strength than the reference fabrics, but 0.30–13.97% higher than linen-containing fabrics (except DOBLP).

Tearing strength

The ANOVA statistics and tearing strength findings of the developed denim fabric samples, which were investigated in both warp and weft directions, are shown in Tables 8 and 9, and Figure 3, respectively. The R^2 value was found to be 94.51% in the warp and 98.66% in the weft. According to ANOVA test results, sheath fiber type, core component type, and sheath fiber type*core component type, all had a statistically significant effect on tear strength values in both directions, with a p-value of <0.0001. The core component type, just like the results for tensile strength, was the factor that had the highest influence on tearing strength in both the warp (81.16%) and weft (73.52%) directions. When fabrics that did not contain core components were evaluated, the reference fabric had the highest value for tearing strength in both the warp (DC: 49.91±0.56 N) and weft directions (DC: 29.42±0.95 N), but the fabric composed of hemp had the lowest value (DOBH, warp: 46.70±1.98 N and weft: 23.66±3.92 N). These results were thought to be due to the same reasons noted for the tensile strength results. While the use of elastane and dual-core components in all fabric types in the warp direction had a positive effect on tearing strength values, the use of polyester had a negative effect, except for the DOBLP sample. Using the core component in the weft direction increased tear strength values by a range of 12.72-42.57%, regardless of the type of core component. Furthermore, the use of dual-core components in all fabric types increased the tear strength the most.

In conclusion, just like the tensile strength results, the tear strength values of all fabric types in the warp direction were higher than in the weft direction. Additionally, regardless of core component usage, when evaluating all fabric types, hemp-containing fabrics generally showed slightly lower tearing strength values in both the warp and weft directions compared to both the reference and linen-containing fabrics.

Stiffness

The ANOVA statistics and stiffness results for the fabricated denim fabric samples are presented in Table 10 and Figure 4, respectively. The R^2 value was calculated to be 93.59%. The results of the ANOVA test showed that all factors had a statistically significant effect on the stiffness values, with a p-value of less than 0.05. The core component type was the independent variable with the highest contribution rate at 74.85%. When the stiffness values of fabrics that did not contain core components were compared, the reference fabric (DC: 0.37±14.35 kg) had a lower stiffness value than fabrics involving linen and hemp (DOBL: 0.45±8.47 kg and DOBH: 0.41±9.13 kg). This could be due to the high bending stiffness of the fabrics containing linen or hemp.[18] The use of core components increased the stiffness values of all fabric types in the range of 2.67-133.65%, excluding the DOBLP sample, regardless of the core component type.

The most significant increase was noticed in the utilization of elastane and dual-core components. The fact that elastane has more elasticity than other core components made the fabrics more compact after washing, which led to an increase in the stiffness value of the fabrics.[28]

To summarize, when fabrics containing no core components were evaluated, the stiffness value of the hemp fabric (DOBH: 0.41±9.13 kg) was higher than that of the reference fabric (DC: 0.37±14.35 kg), while it was negligibly lower than the linen fabric (DOBL: 0.45±8.47 kg).

Table 8
ANOVA statistics for tearing strength values in the warp direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	2823374.58	94.51	11	256670.42	75.12	< 0.0001
Sheath fiber type	197330.83	6.61	2	98665.42	28.88	< 0.0001
Core component type	2424434.58	81.16	3	808144.86	236.53	< 0.0001
Sheath fiber type*core component type	201609.16	6.75	6	33601.53	9.83	< 0.0001
Error	164000.00	5.49	48	3416.67		
Corrected total	2987374.58	100.00	59			

Table 9
ANOVA statistics for tearing strength values in the weft direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	12045945.00	98.66	11	1095085.91	320.51	< 0.0001
Sheath fiber type	2032367.50	16.65	2	1016183.75	297.42	< 0.0001
Core component type	8977308.33	73.52	3	2992436.11	875.83	< 0.0001
Sheath fiber type*core component type	1036269.16	8.49	6	172711.53	50.55	< 0.0001
Error	164000.00	1.34	48	3416.67		
Corrected total	12209945.00	100.00	59			

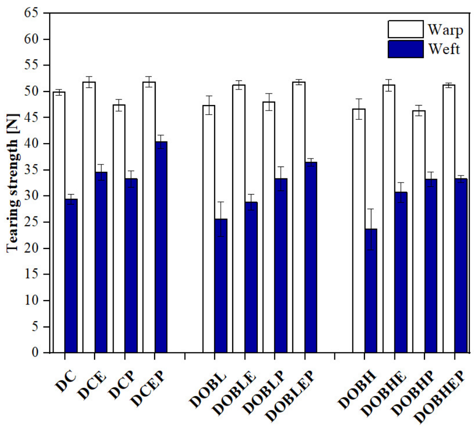

Figure 3: Tearing strength findings of developed denim fabric samples

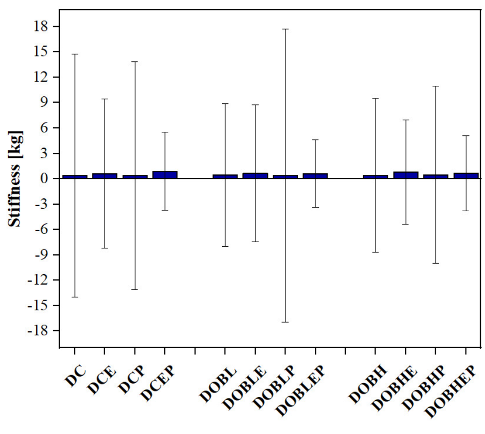

Figure 4: Stiffness findings of developed denim fabric samples

Table 10
ANOVA statistics for stiffness values

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	1.52	93.59	11	0.14	63.68	< 0.0001
Sheath fiber type	0.03	2.04	2	0.02	7.64	0.0013
Core component type	1.22	74.85	3	0.41	186.88	< 0.0001
Sheath fiber type*core component type	0.27	16.63	6	0.05	20.75	< 0.0001
Error	0.10	6.41	48	0.00		
Corrected total	1.63	100.00	59			

When fabrics containing core components were evaluated, hemp fabrics with elastane (DOBHE: 0.78±6.15 kg) and polyester (DOBHP: 0.46±10.47 kg) had higher stiffness values.

Dimensional properties

The results of ANOVA and shrinkage, which were analyzed in the warp and weft directions of the produced denim fabric samples, are given in Tables 11 and 12, and Figure 5, respectively. The R^2 value in the warp and weft directions was found to be 99.95% and 100.00%, respectively. The most effective independent variable on fabric shrinkage properties was the sheath fiber type (57.13%) in the warp direction, while the core component type (99.67%) was in the weft direction. The ANOVA statistics demonstrated that all independent variables had a statistically significant influence ($p<0.0001$) on shrinkage values in both the warp and weft directions. When the dimensional change properties of the fabrics without core components were evaluated in the warp direction, the DC (2.40±2.23%) and DOBH (3.40±1.10%) samples had an extension, whereas the DOBL (-0.80±4.83%) sample shrank to some degree. In the weft direction, all fabric samples had extensions (from 1.20±3.12 to 2.00±2.68%). The shrinkage values up to 3% for rigid fabrics are within acceptable limits, per international standards (ASTM-D 4235-01). As a result, except for the DOBH sample in the warp direction, all fabric samples were within acceptable limits.

Table 11
ANOVA statistics for shrinkage values in the warp direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	173.44	99.95	11	15.77	8577.02	< 0.0001
Sheath fiber type	99.13	57.13	2	49.56	26960.66	< 0.0001
Core component type	30.40	17.52	3	10.13	5512.88	< 0.0001
Sheath fiber type*core component type	43.91	25.30	6	7.32	3981.21	< 0.0001
Error	0.09	0.05	48	0.00		
Corrected total	173.53	100.00	59			

Table 12
ANOVA statistics for shrinkage values in the weft direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	8621.54	100	11	783.78	360080.99	< 0.0001
Sheath fiber type	12.43	0.00	2	6.22	2855.359	< 0.0001
Core component type	8593.41	99.67	3	2864.47	1315989.712	< 0.0001
Sheath fiber type*core component type	15.70	0.18	6	2.62	1201.845	< 0.0001
Error	0.10	0.00	48	0.00		
Corrected total	8621.64	100.00	59			

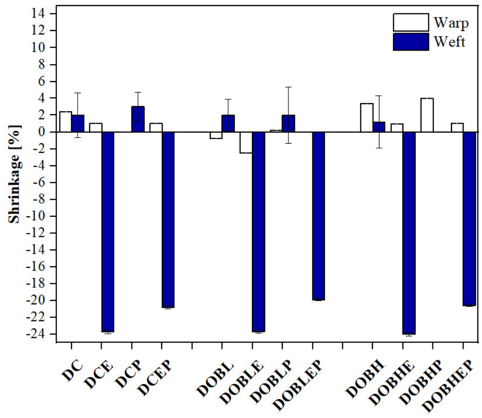

Figure 5: Shrinkage findings of developed denim fabric samples

When fabric samples containing core component were analyzed, some elongation was detected in both the reference and hemp-containing fabrics in the warp direction, regardless of core component type. In the weft direction, fabric samples with elastane and dual-core components shrank more noticeably (between -24.00 and -19.9%) due to the use of elastane and dual-core components in the weft yarn's core. The use of polyester in the core of the weft yarn, on the other hand, produced a few extensions in the reference and linen-containing fabrics, but almost no difference in the hemp-containing fabric.

To conclude, hemp-containing fabrics exhibited an elongation of 1.00-4.00% in the warp direction. However, in the weft direction, except for DOBH, they showed shrinkage ranging from -0.004% to -24.00%, which could be attributed to the use of core components.

Seam slippage

The fabricated denim fabric samples' ANOVA statistics and seam slippage analysis results in both fabric directions are shown in Tables 13 and 14, and in Figure 6. The R^2 value was found to be 88.85% in the warp and 82.78% in the weft. According to ANOVA statistics, all independent variables in both warp and weft directions had a statistically significant effect on fabric seam slippage values with $p<0.05$. While the core component type (68.29%) had the greatest impact on seam slippage in the warp direction, in the weft direction, it was the sheath fiber type*core component type (61.13%). A higher load means the fabric is more resistant to seam slippage.[30] When the seam slippage properties in the warp direction of the fabrics without core components were evaluated, the reference fabric (DC) was the fabric with the highest resistance (23.05±2.68 kgf). Looking in the weft direction, the fabric with the highest resistance was the one containing linen (22.70±1.27 kgf). When considering how the usage of core components affected seam slippage, elastane enhanced it, whereas polyester and double-core components either lowered or did not affect it. In the weft direction, no specific trend was observed. As a result, the seam slippage values in the warp direction are generally higher than or equal to those in the weft direction, except for the DOBHE sample.

Table 13
ANOVA statistics for seam slippage values in the warp direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	179.06	88.85	11	16.28	34.76	<0.0001
Sheath fiber type	29.10	14.44	2	14.55	31.07	<0.0001
Core component type	137.64	68.29	3	45.88	97.97	<0.0001
Sheath fiber type*core component type	12.32	6.11	6	2.05	4.39	0.0013
Error	22.48	11.15	48	0.47		
Corrected total	201.54	100.00	59			

Table 14
ANOVA statistics for seam slippage values in the weft direction

Source	Sum of squares	Contribution (%)	Degrees of freedom	Mean square	F value	p-value
Model	70.90	82.78	11	6.45	10.23	<0.0001
Sheath fiber type	12.18	14.22	2	6.09	9.66	0.0003
Core component type	6.37	7.44	3	2.12	3.37	0.0260
Sheath fiber type*core component type	52.36	61.13	6	8.73	13.85	<0.0001
Error	14.75	17.22	48	0.63		
Corrected total	85.65	100.00	59			

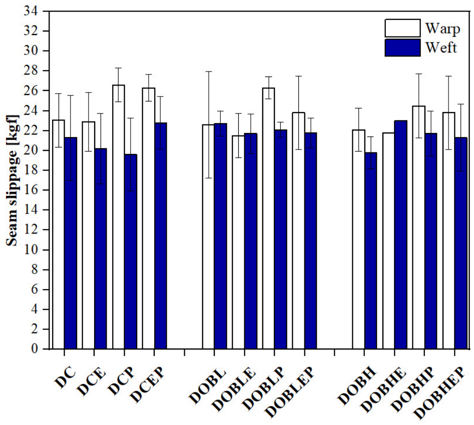

Figure 6: Seam slippage findings of developed denim fabric samples

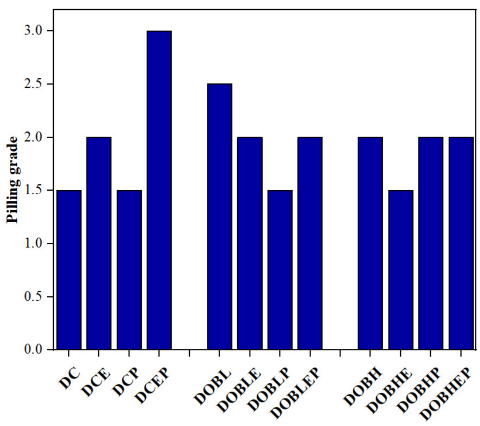

Figure 7: Pilling grade findings of developed denim fabric samples

When fabrics without core components were evaluated, the hemp-containing fabric (DOBH) exhibited lower seam slippage values in both the warp (2.21-4.12%) and weft (7.04-12.78%) directions, compared to the reference and linen-containing fabric. However, when fabrics with core components were evaluated, no clear trend was observed.

Abrasion

No yarn breakage was observed after 25000 rubbings on all fabric types. Abrasion resistance is generally considered to be high in fabrics that can endure rubbing for around 25,000–30,000 times. As a result, all the developed denim fabric types had high abrasion resistance.

Pilling grade

The pilling resistance results of the developed denim fabric samples are given in Figure 7. The ANOVA table could not be obtained since there was no difference between the test replication results. Evaluating the pilling results of fabrics without core components, the pilling grades of fabrics containing bast fibers (DOBL: 2.5±0.0, DOBH: 2±0.0) were better than that of the reference fabric (DC: 1.5±0.0). This might be attributed to the coarser and more durable fiber structure of bast fibers, which reduces the likelihood of pilling. There was no evident tendency to the findings, when it came to the effect of the core components.

CONCLUSION

The key objective of this research has been to clarify the possibilities of using hemp fiber, a fiber known for being environmentally friendly, in denim fabric structures. To achieve this, twelve different denim fabric samples were developed using conventional cotton and organic cotton ring spun yarns in the warp, and conventional cotton, organic cotton/bamboo/linen, and organic cotton/bamboo/hemp blended hybrid yarns in the weft. The weight, tensile and tearing strength, stiffness, dimensional, seam slippage, abrasion, and pilling features of the manufactured denim fabric structures were evaluated comparatively using statistical analytic methods. The findings were as follows:

- R^2 values were determined in the range of 93.59%-100%, which means that the independent variables largely explained the dependent variables analyzed;

- ANOVA results revealed that sheath fiber type, core component type, and their intersection had a statistically significant effect ($p<0.005$) on all dependent variables studied;
- According to the results of the statistical study, the core component type was the most effective independent variable on almost every fabric feature evaluated;
- When the properties of hemp-containing fabrics were evaluated, the DOBHP fabric exhibited the best performance in terms of weight, stiffness, dimensional stability, seam slippage, abrasion resistance, and pilling. On the other hand, the DOBHEP fabric showed the best performance in tensile and tearing strength.

As a result, hemp-containing denim fabric structures can be used in the garment industry instead of fabrics produced with 100% conventional cotton.

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