DEVELOPMENT OF SUSTAINABLE AND ECOLOGICAL HYBRID YARNS: HEMP FIBER IN DENIM FABRIC PRODUCTION

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This study aims to develop and characterize more sustainable and ecological yarns as an alternative to 100% cotton in traditional denim fabric production by using hemp fiber. For this purpose, conventional ring, core-spun and dual core-spun yarns were spun from three blend proportions of organic cotton/hemp fibers as 100:0, 80:20 and 70:30 in percentages. Hemp and organic cotton were used as sheath fiber, and elastane type (Lycra and T400) – as core fiber in the yarn structures. According to the results, the sheath fiber type and blend ratio greatly influenced all yarns' physical characteristics. Using hemp fiber in the yarn structure generally decreased the yarn properties, as expected. However, the best results by using hemp fiber in the yarn structures were achieved by using 20% hemp fiber in the sheath of the yarn structure. Further increasing this rate to 30% worsened the yarn properties considerably, regardless of the core component. When the yarns were evaluated in terms of sustainability and performance, 80/20% organic cotton/hemp blended yarns had the optimum yarn properties.

Keywords: sustainability, hemp, organic cotton, hybrid yarn, denim

INTRODUCTION

Denim is a popular fabric for all seasons and is more of a way of life than just clothing. Cotton is the key raw material for denim production.[1] Classical denim weaving uses indigo-dyed cotton yarn as the warp and undyed cotton yarn as the weft in a warp-faced twill pattern. Natural fibers are regarded as environmentally friendly, in contrast with synthetic fibers. However, each fiber's manufacture has its own sustainability characteristics that should be considered. According to the literature, cotton is grown in 3% of the world's cultivated area.[2] Although cotton is environmentally safe, it uses a large amount of water. It requires using pesticides and fertilizers to produce the desired quality and quantity.[3] According to a data report released by the US Department of Agriculture and the Organic Consumers Foundation, cotton is the most toxic crop on the planet. Cotton utilizes more than 25% of all insecticides and 12% of pesticides globally.[4,5] Most of these insecticides are among the world's most dangerous substances. Birth abnormalities, reproductive diseases, and weakened immune systems are among the health risks associated with pesticide exposure.[6-10] Furthermore, producing 1 kg of raw cotton requires 7–29 tons of water.[11-13] These environmental and health concerns and increased customer awareness drive the denim industry to adopt ecological fibers as an alternative to 100% cotton.

In recent studies, fiber blends, such as bamboo, flax, viscose and Tencel fibers, are used to reduce the amount of cotton in denim and develop fabric properties.[14] The alternative fiber highlighted in this study is hemp, which is more sustainable than cotton and can bring numerous advantages in denim fashion trends. However, the hemp fiber is rigid, and the fiber-to-fiber cohesion is low, which results in difficulties in spinning yarn.[15] To increase the spinnability of blended hemp yarns, a cottonization process can be conducted, which removes the lignin from the fiber structure,[16] which results in hemp fibers binding onto each other and adapting for spinning with other staple fibers, such as cotton or wool.[17]

Hemp is a fast-growing plant that may reach 0.31 m in height in a week, a desirable trait for industrial purposes.[14,18] Compared to cotton, hemp uses significantly less water and requires little or no herbicides or pesticides.[19-21] Cotton has a carbon footprint of 4.2 tons per ton, while hemp has 1.9 tons per ton.[20] Aseptic properties, moisture-wicking, breathability and UV resistance are promising features of hemp fiber.[14,22] It also possesses unique features, being antistatic, antibacterial,[23] non-irritant and hypo-allergenic.[22] These advantageous properties of hemp fiber are encouraging its use as an alternative to 100% cotton in the denim industry. Also, the global demand is for sustainable and ecological natural fibers.

There are some studies in the literature on hemp concerning its harvesting, extraction process, and its use in composites.[24-39] Although a comprehensive literature survey has been conducted, we have not encountered a specific study investigating organic cotton/hemp blended hybrid yarns. Therefore, this study aims to produce hemp-containing sustainable and ecological yarns as an alternative to 100% cotton in denim fabric production to rectify the above-mentioned problems. In line with this aim, conventional ring, core-spun and dual-core spun yarns, with different blend ratios and compositions, were fabricated. Statistical analysis methods were used to examine comparatively the physical properties of the manufactured yarns for the first time.

EXPERIMENTAL

Materials

Organic cotton and hemp fibers were selected as sheath, while elastane (Lycra) and polyester (T400) fibers were selected as core fibers in the yarn structure. The properties of fibers are described as follows. Sheath fibers: organic cotton (OC, length: 30 mm, fineness: 0.18 tex, strength: 32 cN/tex, elongation: 5.1%, Akkucak Tekstil San. Tic. Ltd. Şti., Turkey); hemp fiber (H, cottonized hemp, length: 33 mm, fineness: 0.39 tex, strength: 45 cN/tex, elongation: 3.42%, La Chanvrière, France). Core fibers: soft core (SCS) - Elastane (L, Lycra®, linear density: 7.8 tex, Lycra, UK); hard core (HCS) - Polyester (T, T400®, linear density: 5.5 tex, Lycra, UK).

Production of hybrid yarns

In this research, conventional ring-spun (RS), core-spun (CS) and dual-core spun (DCS) yarns were produced with the yarn linear density of Ne 10/1 (59 tex) on a conventional ring spinning machine (Marzoli MDS1, Italy), to investigate the effects of hemp ratio and core component type on the physical and performance properties of the yarn (Table 1). The RS yarn was spun on a conventional ring spinning frame. The CS (soft-core (SCS) and hard-core (HCS)) and DCS yarns were spun on the same modified ring spinning frame. Similar to the CS yarn production, during the DCS yarn production, Lycra and T400 core filaments were supplied separately under the control of a positive feed roller system. The filaments were diverted to the V-grooved guide roller (Fig. 1), and both core materials composed of Lycra and T400 filaments were wrapped by organic cotton (OC) and organic cotton/hemp (OC/H) sheath fibers. The production parameters of all yarns are given in Table 2.

Table 1
Notation and contents of yarns produced

Yarn notation	Sheath and blend percentages		Core type	
	Organic cotton	Hemp	SCS-Lycra	HCS-T400
OC*	100	-	-	-
OCL	100	-	✔	-
OCT	100	-	-	✔
OCLT	100	-	✔	✔
OCH1	80	20	-	-
OCHL1	80	20	✔	-
OCHT1	80	20	-	✔
OCHLT1	80	20	✔	✔
OCH2	70	30	-	-
OCHL2	70	30	✔	-
OCHT2	70	30	-	✔
OCHLT2	70	30	✔	✔

*OC: Organic cotton, H: Hemp, L: Lycra, and T: T400

Table 2
Fabrication parameters of yarns

Yarn linear density (Ne)	T/m	α_e	Lyra drawing	T400 drawing
10/1	550	4.4	3.6	1.1

Figure 1: RS, CS and DCS yarn production frame

Characterization

Yarn analysis

RS, CS and DCS yarn specimens were initially conditioned in the laboratory under standard atmospheric conditions (20 ± 1 °C and 65 ± 2% RH) for 24 h, according to TS EN ISO 139. The mean of ten samples from each cop was recorded as the final value of one yarn cop produced. The produced five cops were tested and determined as replications. All yarn analyses were performed according to the TS EN ISO 2062 standard. An Uster Zweigle yarn reel was used to test yarn count. An Uster Tester 5 was used for determining yarn unevenness, imperfections and hairiness at 400 m/min test speed. Hairiness (H) was calculated as the total length in centimeters of all hairs within one centimeter of yarn. The mechanical properties of the yarns were tested on an Uster Tensorapid 4.

Statistical analysis

The data obtained from the experimental study were introduced into the IBM® SPSS 26 statistical software using two-way analysis of variance (ANOVA). The significance of the blend ratio and core component was analyzed in a 95% confidence interval (CI). The mean differences subgroups were also compared by post-hoc Duncan test at 95% CI.

RESULTS AND DISCUSSION

The physical properties, such as unevenness, imperfections, hairiness, and mechanical properties, such as breaking strength and elongation, of RS, CS and DCS yarns were evaluated comparatively in this part.

Yarn unevenness (U%)

The ratio of hemp fiber (p = 0.000) and the core component type (p = 0.000) were statistically significant at a level of 5%. In contrast, the interactive effect of these two parameters (p = 0.424) had no statistically significant effect on the yarn unevenness values, according to the statistical data. The unevenness average values and statistical test results of the yarns produced in this study are depicted in Figure 2, and Tables 3 and 4, respectively. From the U% results, it was determined that yarns with OC/H (70/30%) sheath fiber gave the highest yarn unevenness values (from 14.70 to 15.59), while yarns with the OC (100%) sheath fiber provided the lowest ones (from 9.45 to 9.95). In addition, as the proportion of the hemp fibers in the blends decreased (80/20%), yarn unevenness values (from 10.68-11.28) improved for all yarn types. Yarn unevenness is affected by fiber cohesion, length variations and differences in the number of fibers in the yarn cross-section.[40,41] As known, the elementary hemp fiber is short, and its uniformity difference is poor, so the coefficient of variation of fiber length is high, and fiber cohesion is low.[15] Therefore, the worse U% values of OC/H yarns might be explained by lower fiber-to-fiber cohesion forces and higher fiber length variation values of OC/H sheath fibers, compared with OC sheath fibers. The U% test results indicated that the core component types significantly affected the yarn unevenness. It could be seen from the results that Lycra, an elastic core filament, led to the production of more uneven yarns, while T400, a semi-elastic core filament, gave lower U% values for all yarns (Fig. 2).

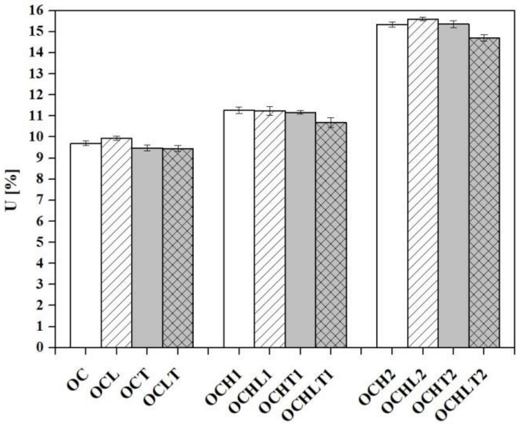

Figure 2: Yarn unevenness values of the yarns fabricated

Table 3
ANOVA findings for yarn unevenness values

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	342.697[a]	11	31.154	281.203	0.000
Intercept	8633.761	1	8633.761	77929.651	0.000
Hemp ratio	338.550	2	169.275	1527.904	0.000
Core type	3.469	3	1.156	10.437	0.000
Hemp ratio * Core type	0.678	6	0.113	1.020	0.424
Error	5.318	48	0.111		
Total	8981.776	60			
Corrected total	348.015	59			

[a] R squared = 0.985 (Adjusted R squared = 0.981)

Table 4
DUNCAN findings for yarn unevenness values

Yarn unevenness	Group			
	N	1	2	3
Hemp proportion		9.644		
0	20			
20	20		11.094	
30	20			15.249
Sig.		1.000	1.000	1.000
Core component				
RS	15		12.105	12.105
SCS	15			12.264
HCS	15		12.001	
DCS	15	11.612		
Sig.		1.000	0.396	0.198

RS: ring, SCS: soft-core, HCS: hard-core, and DCS: dual-core

Yarn imperfections

Yarn imperfections and statistical test results of RS, CS and DCS yarns are indicated in Figures 3-5 and Tables 5-10, respectively. According to the statistical test results, the effect of the hemp ratio on yarn thin places was found statistically significant ($p = 0.00$) at a 5% level. However, core component type ($p = 0.981$) and the interactive effect of these two factors ($p = 1.000$) were statistically insignificant at the 5% level. According to the results, while 100% OC and 80/20% OC/H sheath yarns showed little or no thin places (-50%) imperfection, 70/30% OC/H blended yarns led to a marked rise in thin places. It could be seen from Figure 3 that the core components had almost no contribution to the thin places.

When the thick places of the yarns produced were analyzed statistically, ANOVA results introduced the effects of hemp ratio ($p = 0.000$), core component type ($p = 0.000$), and hemp ratio*core component type (p = 0.000), which were found statistically significant at a 5% level. According to the results, the yarns produced from 70/30% OC/H sheath fibers showed significantly higher thick places than 100% OC and 80/20% OC/H sheath yarns.

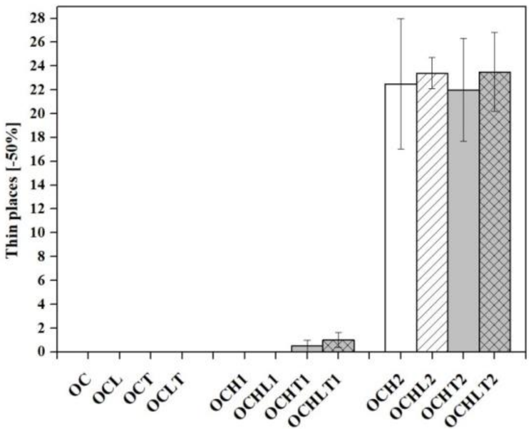

Figure 3: Thin places values of the yarns fabricated

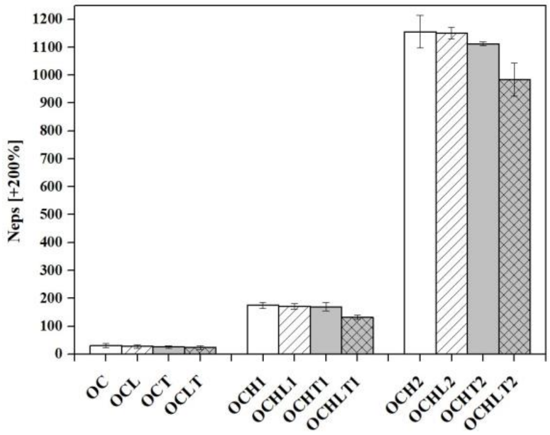

Figure 4: Thick places values of the yarns fabricated

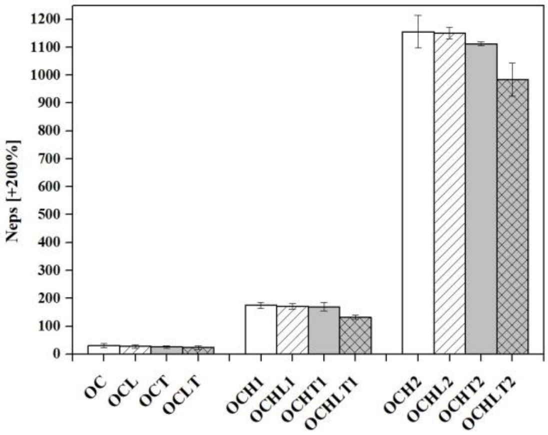

Figure 5: Nep values of the yarns fabricated

Table 5
ANOVA findings for yarn thin places values

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	6860.546[a]	11	623.686	24.266	0.000
Intercept	3596.004	1	3596.004	139.911	0.000
Hemp ratio	6849.258	2	3424.629	133.243	0.000
Core type	4.512	3	1.504	0.059	0.981
Hemp ratio * Core type	6.775	6	1.129	0.044	1.000
Error	1233.700	48	25.702		
Total	11690.250	60			
Corrected total	8094.246	59			

[a] R squared = 0.848 (Adjusted R squared = 0.813)

Table 6
ANOVA findings for yarn thick places values

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	17888683.150[a]	11	1626243.923	388.146	0.000
Intercept	16984632.150	1	16984632.150	4053.829	0.000
Hemp ratio	17502565.725	2	8751282.862	2088.724	0.000
Core type	225366.950	3	75122.317	17.930	0.000
Hemp ratio * Core type	160750.475	6	26791.746	6.395	0.000
Error	201109.200	48	4189.775		
Total	35074424.500	60			
Corrected total	18089792.350	59			

[a] R squared = 0.989 (Adjusted R squared = 0.986)

Table 7
ANOVA findings for yarn nep values

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	13781806.513[a]	11	1252891.501	370.875	0.000
Intercept	11087550.937	1	11087550.937	3282.084	0.000
Hemp ratio	13680092.500	2	6840046.250	2024.758	0.000
Core type	52019.046	3	17339.682	5.133	0.004
Hemp ratio * Core type	49694.967	6	8282.494	2.452	0.038
Error	162153.800	48	3378.204		
Total	25031511.250	60			
Corrected total	13943960.313	59			

[a] R squared = 0.988 (Adjusted R squared = 0.986)

Table 8
DUNCAN findings for yarn thin places values

Yarn thin places		Group	
	N	1	2
Hemp proportion			
0	20	0.000	
20	20	0.375	
30	20		22.850
Sig.		0.816	1.000
Core component			
RS	15	7.500	
SCS	15	7.800	
HCS	15	7.500	
DCS	15	8.1667	
Sig.		0.747	

RS: ring, SCS: soft-core, HCS: hard-core and DCS: dual-core

According to the statistical test results of the yarn nep (+200%) values, the effects of hemp ratio (p = 0.000), core component type (p = 0.004), and hemp ratio*core component type (p=0.038) were statistically significant at a 5% CI level. As the ratio of hemp in the yarn increased from 0% to 30%, nep content per kilometer increased greatly. For the same blend composition, nep count was lower in core-spun and dual-core spun yarns than in conventional ring yarns. It was thought that this situation could be explained by the core component, composed of continuous filaments in the center of the yarns.

When the yarn imperfection results were evaluated collectively, it could be said that the hemp fiber harmed the yarn imperfection values. This effect became more evident when the hemp fiber ratio in blend yarns was increased from 20% to 30%. This could be explained by the characteristic features of hemp fiber such as length, fineness, maturity, uniformity index, trash ratio, coarseness, and low cohesion.

Table 9
DUNCAN findings for yarn thick places values

Yarn thick places	Group			
	N	1	2	3
Hemp proportion				
0	20	46.350		
20	20		264.375	
30	20			1285.425
Sig.		1.000	1.000	1.000
Core component				
RS	15			576.800
SCS	15			570.133
HCS	15			554.433
DCS	15	426.833		
Sig.		1.000	0.379	0.379

RS: ring, SCS: soft-core, HCS: hard-core and DCS: dual-core

Table 10
DUNCAN findings for yarn nep values

Yarn neps	Group			
	N	1	2	3
Hemp proportion				
0	20	26.875		
20	20		162.125	
30	20			1100.625
Sig.		1.000	1.000	1.000
Core component				
RS	15		453.333	
SCS	15		449.900	
HCS	15		435.900	
DCS	15	380.167		
Sig.		1.000	0.440	

RS: ring, SCS: soft-core, HCS: hard-core and DCS: dual-core

Yarn hairiness

The amount of freely moving fiber ends or fiber loops protruding from the yarn surface is called yarn hairiness.[42] Yarn hairiness and statistical test results for the hybrid yarns are indicated in Figure 6, Tables 11 and 12, respectively. ANOVA results showed that hemp ratio ($p = 0.072$) and hemp ratio*core component type ($p = 0.056$) did not statistically affect the yarn hairiness values. However, the core component type ($p = 0.000$) had a statistically significant effect on the H hairiness values of the hybrid yarns. According to Figure 6, the yarn hairiness values of OC/H blended yarns seemed almost the same or slightly lower than that of the 100% OC yarns. It can be due to the sheath fibers used having almost similar fiber lengths. As for the effect of the core components, CS and DCS yarns had lower yarn hairiness values than the conventional ring-spun ones. On the other hand, the yarns with Lycra core filament produced lower hairiness values than the yarns containing T400 core filament.

Yarn tenacity

Tenacity is a measure of the strength of the yarn, defined as the ultimate breaking force of the yarn divided by the tex.[43] Yarn tenacity values and statistical test results for the OC/H blend yarns and 100% OC as benchmark were displayed in Figure 7, Table 13 and Table 14, respectively. According to ANOVA results, the hemp ratio ($p = 0.000$) and core component type ($p = 0.001$) demonstrated statistically significant effects on yarn tenacity values. However, the interaction of these parameters had no statistically significant effect on the yarn tenacity values ($p = 0.152$).

Table 11
ANOVA findings for yarn hairiness values

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	3.683[a]	11	0.335	5.141	0.000
Intercept	3686.525	1	3686.525	56608.358	0.000
Hemp ratio	0.362	2	0.181	2.778	0.072
Core type	2.448	3	0.816	12.529	0.000
Hemp ratio * Core type	0.873	6	0.146	2.235	0.056
Error	3.126	48	0.065		
Total	3693.334	60			
Corrected total	6.809	59			

[a] R squared = 0.541 (Adjusted R squared = 0.436)

Table 12
DUNCAN findings for yarn hairiness values

Yarn hairiness	Group			
	N	1	2	3
Hemp proportion				
0	20		7.942	
20	20	7.820	7.820	
30	20	7.754		
Sig.		0.417	0.139	
Core component				
RS	15			8.153
SCS	15	7.609		
HCS	15	7.733	7.733	
DCS	15		7.860	
Sig.		0.190	0.178	1.000

RS: ring, SCS: soft-core, HCS: hard-core and DCS: dual-core

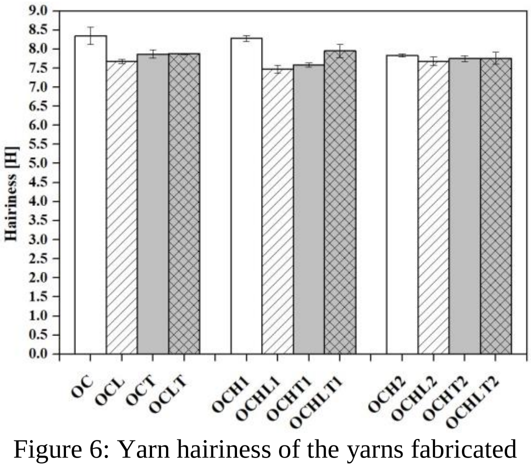

Figure 6: Yarn hairiness of the yarns fabricated

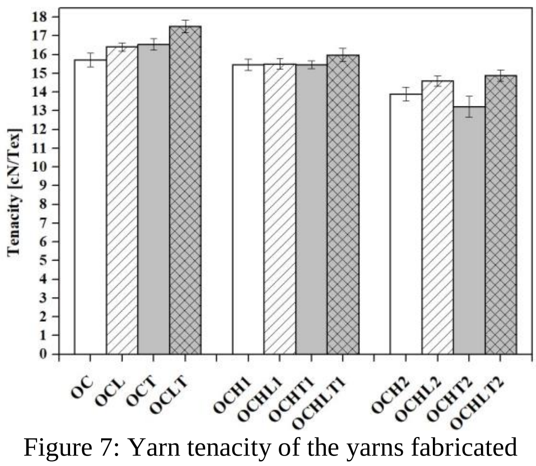

Figure 7: Yarn tenacity of the yarns fabricated

When the tenacity results of the spun yarns were analyzed, the yarns produced with OC/H sheath fibers had slightly lower tenacity than OC sheath yarns. The yarn-breaking tenacity values decreased as the percentage of hemp in the OC/H blends increased. Although the tenacity of hemp fiber was higher than that of organic cotton, the tenacity of yarns produced from OC/H sheath fibers was lower. Hemp fibers' low cohesion could explain this due to their surface, which decreases the fiber-to-fiber friction. Also, the irregularity of the yarns covered with OC/H fibers, compared to the yarns covered only with OC, could speed up the migration of the fibers.[43] In a CS yarn, sheath fibers contribute more to the tensile properties of the yarn, since the sheath part of the yarn carries more of the load compared to the core component. Therefore, the tensile properties of the CS yarns changed depending on the sheath fiber types. A similar pattern was also observed for the DCS yarns. When the influence of the core component on yarn tenacity was investigated, it was discovered that both core components had a slight beneficial effect on yarn tenacity. It could be said that this situation resulted from a low core component ratio in the yarn structure and a uniformly covered core filament by sheath fibers.

Table 13
ANOVA findings for yarn tenacity values

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	75.802[a]	11	6.891	12.075	0.000
Intercept	14283.242	1	14283.242	25027.621	0.000
Hemp ratio	58.573	2	29.287	51.317	0.000
Core type	11.546	3	3.849	6.744	0.001
Hemp ratio * Core type	5.682	6	0.947	1.659	0.152
Error	27.394	48	0.571		
Total	14386.438	60			
Corrected total	103.195	59			

[a] R squared = 0.735 (Adjusted R squared = 0.674)

Table 14
DUNCAN findings for yarn tenacity values

Yarn tenacity	Group			
	N	1	2	3
Hemp proportion				
0	20			16.544
20	20		15.600	
30	20	14.143		
Sig.		1.000	1.000	1.000
Core component				
RS	15	15.025		
SCS	15	15.503		
HCS	15	15.071		
DCS	15		16.117	
Sig.		0.108	1.000	

RS: ring, SCS: soft-core, HCS: hard-core and DCS: dual-core

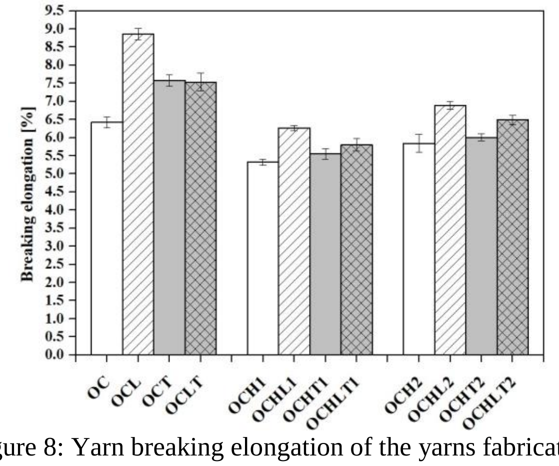

Figure 8: Yarn breaking elongation of the yarns fabricated

Yarn breaking elongation

Hemp ratio (p = 0.00), core component type (p = 0.000), and the interaction of these parameters (p = 0.000) had statistically significant effects on yarn-breaking elongation values (Table 15). The yarn-breaking elongation findings are shown in Figure 8. Yarn-breaking elongation values decreased as the hemp fibers ratio in sheath increased, as expected. This could be explained by the breaking elongation and fiber-length characteristics of OC and H fibers. The Lycra core filament type gave significantly higher elongation values than the T400 core filament. A probable reason for this could be the fiber-breaking elongation feature of the core filaments. As stated, Lycra is a polyurethane fiber, which led to higher elongation values than in the case of the semi-elastic T400 polyester filament.

Table 15
ANOVA findings for yarn breaking elongation value

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	57.317[a]	11	5.211	42.120	0.000
Intercept	2570.745	1	2570.745	20780.835	0.000
Hemp ratio	36.520	2	18.260	147.606	0.000
Core type	16.936	3	5.645	45.635	0.000
Hemp ratio * Core type	3.861	6	0.643	5.201	0.000
Error	5.938	48	0.124		
Total	2634.000	60			
Corrected total	63.255	59			

[a] R squared = 0.906 (Adjusted R squared = 0.885)

Table 16
DUNCAN findings for yarn breaking elongation values

Yarn tenacity	Group			
	N	1	2	3
Hemp proportion				7.599
0	20			
20	20		6.305	
30	20	5.734		
Sig.		1.000	1.000	1.000
Core component				
RS	15	5.861		
SCS	15			7.338
HCS	15		6.377	
DCS	15		6.606	
Sig.		1.000	0.080	1.000

RS: ring, SCS: soft-core, HCS: hard-core and DCS: dual-core

CONCLUSION

In this study, hybrid yarns containing organic cotton and hemp in different blend ratios (100:0, 80:20, and 70:30) were produced for the first time. The data obtained by testing the physical properties of the produced yarns were evaluated statistically. The results are summarized below:

- As previously indicated, the type, properties, blend ratio, and blend homogeneity of the sheath fiber significantly affected the yarn's physical qualities.
- The use of 20% hemp fiber in the yarn structure slightly worsened all yarn properties, except hairiness, and this became more evident when the hemp content was increased from 20% to 30%, regardless of the core component.
- Contrary to expectations, tenacity values decreased as the hemp fiber content in the yarn structure increased.
- As for the effect of the core material, no clear trend in the values was observed, and the results varied depending on the sheath fiber type and blend ratio used.

The results revealed that, from the viewpoint of yarn properties, 20% hemp-containing yarns can be used instead of 100% cotton yarns in denim fabric production.

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REFERENCES

1 S. S. Muthu, "Sustainability in Denim", United Kingdom, Elsevier, 2017
2 T. A. Hackett, Master's Thesis, University of Kentucky, Lexington, 2015

[3] Y. Zhang, X. Liu, R. Xiao and Z. Yuan, *Int. J. Life Cycle Assess.*, **20**, 994 (2015), http://dx.doi.org/10.1007/s11367-015-0889-4
[4] S. Yafa, "Cotton: The Biography of a Revolutionary Fiber", USA, Penguin Books, 2006
[5] W. Allen, https://cottonusa.org/, (accessed 15 June 2022)
[6] F. Mancini, A. H. C. Van Bruggen, J. L. S. Jiggins, A. C. Ambatipudi and H. Murphy, *Int. J. Occup. Environ. Health*, **11**, 221 (2005), http://dx.doi.org/10.1179/107735205800246064
[7] F. A. Esteve-Turrillas and M. D. L. Guardia, *Resour. Conserv. Recycl.*, **116**, 107 (2017), http://dx.doi.org/10.1016/j.resconrec.2016.09.034
[8] M. Khan and C. A. Damalas, *Crop. Prot.*, **77,** 45 (2015), http://dx.doi.org/10.1016/j.cropro.2015.07.014
[9] E. M. Liu and J. Huang, *J. Dev. Econ.*, **103**, 202 (2013), http://dx.doi.org/10.1016/j.jdeveco.2012.12.005
[10] B. M. Maumbe and S. M. Swinton, *Soc. Sci. Med.*, **57**, 1559 (2003), http://dx.doi.org/10.1016/S0277-9536(03)00016-9
[11] D. M. Oosterhuis and J. T. Cothren, https://www.cotton.org/foundation/upload/flowering-and-fruiting-in-cotton.pdf (accessed 13 June 2022)
[12] USDA, http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26737 (accessed 13 March 2016)
[13] E. M. Kalliala and P. Nousiainen, *AUTEX Res. J.*, **8**, 20 (1999)
[14] A. G. D. Schumacher, S. Pequito and J. Pazour, *J. Clean. Prot.*, **268**, 1 (2020), https://doi.org/10.1016/j.jclepro.2020.122180
[15] Y. Liu, R. C. Xu and Y. P. Zhang, *Adv. Mat. Res.*, **332-334**, 667 (2011), https://doi.org/10.4028/www.scientific.net/AMR.332-334.667
[16] https://moviecultists.com/what-is-cottonized-hemp (accessed 13 June 2022)
[17] K. Shereyans, https://www.linkedin.com/pulse/what-cottonisation-hemp-shreyans-kokra/ (accessed 13 June 2022)
[18] A. Oliver, https://www.doc-developpement-durable.org/file/Culture/Culture-plantes-a-fibres/chanvre-textile/Industrial%20Hemp%20Factsheet.pdf (accessed 13 June 2022)
[19] L. Mwaikambo, *Afr. J. Sci. Tech.*, **7**, 121 (2006)
[20] M. Ahirwar and B. K. Behera, *J. Text. Inst.*, **113**, 934 (2022), https://doi.org/10.1080/00405000.2021.1909799
[21] S. Rana, S. Pichandi, S. Parveen and R. Fangueiro, in "Roadmap to Sustainable Textiles and Clothing", edited by S. Muthu, Springer, 2014, Singapore, pp. 1-35
[22] M. Kostic, B. Pejic and P. Skundric, *Bioresour. Technol.*, **99**, 94e99 (2008), https://doi.org/10.1016/j.biortech.2006.11.050
[23] B. A. Khan, P. Warner and H. Wang, *BioResources*, **9**, 3642 (2014), https://doi.org/10.15376/biores.9.2.3642-365
[24] S. Behera, R. K. Gautam and S. Mohan, *J. Compos. Mater.*, **56**, 929 (2022), https://doi.org/10.1177/00219983211066991
[25] P. Machová and J. Šál, *Con. Series: Mater. Sci. Eng.*, **960**, 1 (2020)
[26] R. Joffe and J. Andersons, in "Natural Filler and Fibre Composites: Development and Characterisation", edited by S. Syngellakis, WIT Press, 2015, pp. 13-26
[27] E. Twite-Kabamba, A. Mechraoui and D. Rodrigue, *Polym. Comp.*, **30**, 1401 (2009), https://doi.org/10.1002/pc.20704
[28] X. M. Guo and Y. P. Qiu, *Adv. Mat. Res.*, **332**, 121 (2011), https://doi.org/10.4028/www.scientific.net/AMR.332-334.121
[29] T. Väisänen, P. Batello, R. Lappalainen and L. Tomppo, *Ind. Crop. Prod.*, **111**, 422 (2018), https://doi.org/10.1016/j.indcrop.2017.10.049
[30] D. M. Panaitescu, R. C. Fierascu, A. R. Gabor and C. A. Nicolae, *J. Mat. Res. Tech.*, **9**, 10768 (2020), https://doi.org/10.1016/j.jmrt.2020.07.084
[31] H. C. Han and X. L. Gong, *Polym. Comp.*, **37**, 385 (2016), https://doi.org/10.1002/pc.23191
[32] Z. L. Yan, H. Wang, K. T. Lau, S. Pather, J. C. Zhang *et al.*, *Compos. Part B: Eng.*, **46**, 221 (2013), https://doi.org/10.1016/j.compositesb.2012.09.027
[33] P. Anand and V. Anbumalar, *Polym. (Korea)*, **39**, 46 (2015), https://doi.org/10.7317/pk.2015.39.1.46
[34] A. Rachini, G. Mougin, S. Delalande, J. Y. Charmeau, C. Barrès *et al.*, *Polym. Degrad. Stabil.*, **97**, 1988 (2012), https://doi.org/10.1016/j.polymdegradstab.2012.03.034
[35] M. A. Sawpan, K. L. Pickering and A. Fernyhough, *Compos. Part A: Appl. Sci. Man.*, **43**, 519 (2012), https://doi.org/10.1016/j.compositesa.2011.11.021
[36] M. Szostak, N. Tomaszewska and R. Kozlowski, in "Advances in Manufacturing II", edited by B. Gapinski, M. Szostak and V. Ivanov, Springer, 2019, pp. 495-506
[37] L. Stelea, I. Filip, G. Lisa, M. Ichim, M. Drobotă *et al.*, *Polymers*, **14**, 481 (2022), https://doi.org/10.3390/polym14030481

[38] A. T. Michel and S. L. Billington, *Polym. Degrad. Stabil.*, **97**, 870 (2012), https://doi.org/10.1016/j.polymdegradstab.2012.03.040
[39] M. Pracella, D. Chionna, I. Anguillesi, Z. Kulinski and E. Piorkowska, *Compos. Sci. Technol.*, **66**, 2218 (2006), https://doi.org/10.1016/j.compscitech.2005.12.006
[40] S. H. Ç. Aydoğdu and D. Yilmaz, *Cellulose Chem. Technol.*, **54**, 381 (2020), https://doi.org/10.35812/CelluloseChemTechnol.2020.54.39
[41] O. Demiryürek and A. Kılıç, *Ind. Text.*, **235**, 1 (2018), https://doi.org/10.35530/IT.069.03.1302
[42] G. K. Tyagi, in "Advances in Yarn Spinning Technology", edited by C. A. Lawrance, Woodhead Publishing, 2010, pp. 119-154
[43] S. A. S. Abdullah, N. Z. M. Zuhudi, K. M. Aris, M. N. Roslan and M. D. Isa, *J. Mech. Eng. Sci.*, **14**, 7622 (2020), https://doi.org/10.15282/jmes.14.4.2020.26.0600