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The effects of the combined process of enzymatic bleach clean-up, enzymatic defibrillation and dyeing on the comfort and physical properties of Tencel/cotton knitted fabrics

Sibel Şardağ, Tuba Toprak and Pervin Aniş

Abstract

This study aimed to investigate the comfort and physical properties of raw and finished knitted fabrics made of yarns with different Tencel/cotton blend ratios. For this purpose, Ne 20 yarns were produced with the same twist coefficient on the same production line. Fabric samples were produced on the same knitting machine. The raw fabrics were subjected to two different combined enzymatic pre-treatments and dyeing processes. In the first process, enzymatic defibrillation and dyeing were carried out in the same bath. In the second, enzymatic bleach clean-up, defibrillation and dyeing were conducted in the same bath. The comfort and physical properties of all the raw and finished fabric samples were measured according to the relevant standards. The results were assessed statistically. The results of this study showed that with increased percentage of Tencel in the blend, the water vapor and air permeability, fabric roughness, pilling, thermal absorption and loss of mass values of the fabrics increased, whereas thermal conductivity values decreased. It was observed that the fabrics which were subjected to enzymatic defibrillation and dyeing processes in a single bath gave lower surface roughness and abrasion values but higher air permeability values; while those subjected to enzymatic bleach clean-up, defibrillation and dyeing in a single bath gave higher thermal conductivity and thermal absorptivity values. Comparison of the two processes showed that there were no significant differences in the pilling and the water vapor permeability values obtained from both processes.

Keywords

tencel, cotton, yarn, dyeing, lyocell, finishing, fibrillation, comfort

Today, consumers' expectations from clothing are not limited to covering up or protection. People also want to look good and feel comfortable in their clothes. For a person to be comfortable, their brain should not receive stimuli arising from environmental factors such as temperature, humidity, wind speed or light, and any discomfort that is felt due to these factors will remove the feeling of comfort.[1] The air layer, also called the microclimate, which is between the human skin and clothing, determines a person's feeling of comfort. This microclimate is affected by environmental factors, the wearer's level of activity and the properties of the clothing.[2,3] Fiber type, yarn construction, knitting structure, fabric thickness, finishing processes and treatments applied to the fabric are parameters which determine the properties of clothing.[3] Of the factors that affect the microclimate, in other words, the wearer's comfort, environmental factors, wearer's physical state and physical activity level cannot always be changed as much as desired; therefore, improvement of comfort is achieved by changing the properties of clothing. In other words, changes

Bursa Uludağ University, Textile Engineering Department, Bursa, Turkey

Corresponding author:
Sibel Şardağ, Bursa Uludağ University, Textile Engineering Department, 16059 Bursa, Turkey.
Email: sibels@uludag.edu.tr

made in the properties of clothing affect the microclimate, thus determining the wearer's state of being comfortable.[4]

When compared with synthetic fibers, natural and regenerated cellulosic fibers which are obtained from natural polymers intrinsically have a greater capacity to hold more water in their structure. For this reason, fabrics manufactured from natural polymers are expected to have better comfort properties. Today, since global production of natural fibers is not sufficient to meet the growing demand for them, the main objective has become to produce artificial or synthetic fibers which have similarities to natural fibers in large quantities.

Lyocell, better known under the brand name Tencel, is a regenerated cellulosic fiber which is obtained from natural cellulosic polymers by using organic solvent (N-Methyl-Morpholine-N-oxide),[4,5] and it is generally produced in staple form (1.4–1.7 dtex).[6–9] Tencel is an eco-friendly fiber because a large percentage of the organic solvent used in its production can be recycled. Fabrics obtained from Tencel are also expected to have many favorable properties such as softness, drapability, brightness, breathability, high tensile strength etc.

Tencel fiber (lyocell fiber) has a high degree of molecular orientation and its degree of crystallinity can be as high as 90%.[9–16] This high degree of crystallinity leads to increased dry and wet tenacity of Tencel fibers; however, it also increases breakability and fibrillation properties of the fiber.[4,5] Fibrillation behavior is the most important characteristic of Tencel.[4,9,13,17] Fibrillation can be defined as the longitudinal splitting of a single fiber with high crystalline structure into microfibers. When Tencel fibers are soaked in water, they swell diametrically by 40%, but no change occurs in fiber length. Cracks form on the fiber surface due to the swelling and small fibrils protrude outward from these cracks. When it comes to fabrics, fibrillation is induced by mechanical and frictional processes applied to wet and swollen fabrics.[4,17] If Tencel fabrics are subjected to mechanical processes in a dry state, or if mechanical processes are not applied to them in a wet state, the fibers do not fibrillate. [18] Fibrillation of the fabric surface leads to the formation of ''pills'' ranging from one to four microns in length.[4, 17]

In order to prevent formation of pills on fabric surfaces during normal wear and use, Tencel fabrics need to be subjected to finishing processes which include primary fibrillation, defibrillation and secondary fibrillation. The main aim of the primary fibrillation is to allow as many free fiber ends as possible to protrude from the yarn body toward the outer yarn surface so that optimal yarn fibrillation can be achieved. Defibrillation can be defined as the control of fibrillation with the use of enzymes and the removal of pills from the surface of the fibrillated fabric. The enzyme mechanism in the defibrillation process is known to attack and hydrolyze the microfibrils that form pill structures on the fiber surface.[19] Secondary fibrillation is the application of mechanical processes to the fabrics in a wet state in such a way as to cause another fibrillation at micro level after enzymatic defibrillation finishing treatments.[4,17]

A review of the literature related to Tencel revealed that different studies have been performed in order to investigate the structure[20–22] and fibrillation properties[13,14,17,23,24] of Tencel fiber; the properties and production methods of Tencel yarn,[9,25–27] the dyeing/printing behaviors of Tencel fabrics,[28–41] sewing properties of Tencel fabrics[4,5], and comfort and mechanical properties of Tencel blended woven or knitted fabrics.[42–49] Other studies on different topics related to Tencel are available in the literature.[15,50,51]

From the abovementioned studies, it can be seen that blending Tencel with different fibers has become increasingly common in recent years. The most important reason for this, presumably, is that the advantages of Tencel fiber have been realized in terms of its tenacity and comfort properties. The literature review showed that the inclusion of Tencel into the blend led to improvements in tenacity and comfort properties of fabrics.[42–49] It also showed that the number of studies on defibrillation of Tencel fabrics is quite limited. Tencel fibers, yarns and fabrics have higher fibrillation properties than other cellulose fibers, yarns and fabrics; therefore, the defibrillation process which is applied to Tencel blend fabrics plays a crucial role in determining the surface and comfort properties of these fabrics.

In this study, the comfort properties of Tencel/cotton blend fabrics were examined in detail and, unlike other studies, the effects of the conventional and combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes on the comfort properties of fabrics were investigated. Scouring, peroxide bleaching, enzymatic bleach clean-up and enzymatic defibrillation and dyeing processes were carried out in separate baths in Process 1, referred to as the ''conventional process''. In Process 2, enzymatic bleach clean-up and enzymatic defibrillation and dyeing processes were carried out in a single bath, referred to as the ''combined process''. The effects of the combined process on the comfort properties of the fabrics were examined and the results obtained were compared with those of the conventional process. Savings in time, energy and water could be achieved by carrying out these three processes in a single bath. Evaluation of the two methods at the end of the study in respect of comfort and physical properties showed that although there was a statistically meaningful difference between the two methods, the values obtained

were close to one another. Therefore, depending on area of usage, seasonal conditions and personal preferences, the combined process could be recommended as a more environmentally friendly process for Tencel/cotton blend fabrics.

Experimental

In this study, 100% Tencel, 75/25 Tencel/cotton, 50/50 Tencel/cotton, 25/75 Tencel/cotton and 100% combed cotton yarns were used. All the yarns had the same linear density (Ne 20) and twist value (600 turns per meter). The type of Tencel fiber used in this study was Tencel standard, and the length and the count of the fiber were 38 mm and 1.3 dtex respectively. HVI (high volume instrument) values of the cotton fiber and properties of yarns are given in Table 1 and Table 2, respectively. All the yarns were produced on a ring spinning machine at a spindle speed of 11,000 rpm with C 2HRMT-1 travelers. All the yarns were manufactured on the same production line at Kipaş Holding A.S. yarn production facilities.

Table 1. Properties of cotton fibers (HVI values)

Property	Value
Spinning consistency index	138
Upper half mean length	29.08 mm
Uniformity index	83.3
Short fiber index	7.9
Fiber strength	31.6 g/tex
Elongation	6.7%
Color grade	31–41
Reflectance Rd	76
Yellowness + b	8.1
Trash count	37
Trash % area	0.4%

Source: Bilir and Şardağ.[25]

The yarns were knitted on a single jersey knitting machine with gauge number 20. The properties of the knitted fabrics obtained are given in Table 2.

The raw knitted fabrics were subjected to conventional and combined enzymatic pre-treatment (enzymatic bleach clean-up and defibrillation) and dyeing processes. Cellusoft Combi enzyme (4900 CPU/g) produced by Novozymes was used for defibrillation and removal of residual hydrogen peroxide after bleaching. Ruco-Flow Aio (stabilizer) and Ruco®-Flow BBA (nonionic/anionic) from Rudolf Duraner Company were used in the bleaching process. Drimaren Red HF6BL was used for the dyeing process. Ruco-tex KST 150 (dispersing agent, anionic) and Rucowet Fin Conc (wetting agent, nonionic) were supplied from Rudolf Duraner Company. Laboratory-grade sodium hydroxide, sodium carbonate and sodium chloride (salt) from Merck were used.

A Dyetech Polybath Sample Dyeing Machine was used in all the wet processes. In the scouring process, $2\,g\,L^{-1}$ of sodium carbonate and $1\,g\,L^{-1}$ of wetting agent were used. For this process, the liquor ratio was 20:1. Hydrogen peroxide ($7.5\,mL\,L^{-1}$), sodium hydroxide ($1\,mL\,L^{-1}$) and stabilizer ($2\,mL\,L^{-1}$) were used for peroxide bleaching. Except for the 100% Tencel fabric, bleaching was applied to all the fabric samples. The liquor ratio of the bleaching process was 15:1. For the bleach clean-up, sodium carbonate was used in Process 1, while in Process 2 the fabric was only rinsed after bleaching. In the enzymatic treatment, 1.5% enzyme concentration was used. Tencel and cotton blend

Table 2. Properties of knitted fabrics used in the study

Property of fabric/Blend ratio	100% cotton	75% cotton, 25% Tencel	50% cotton, 50% Tencel	25% cotton, 75% Tencel	100% Tencel
Courses/cm					
Raw fabric	13	12	12	11	11
Finished fabric (1)	12	12	12	11	10
Finished fabric (2)	13	12	12	12	10
Wales/cm					
Raw fabric	11	10	10	11	10
Finished fabric (1)	11	12	12	11	10
Finished fabric (2)	11	11	10	11	11
Fabric thickness (mm)					
Raw fabric	0.75	0.77	0.74	0.66	0.67
Finished fabric (1)	0.70	0.73	0.72	0.67	0.67
Finished fabric (2)	0.86	0.80	0.80	0.76	0.64

fabrics were dyed at 2% o.w.f. dye concentration, and 20:1 liquor ratio was used. The fabric samples were treated with enzyme, dyestuff, dispersing and wetting agents for 10 minutes, followed by the addition of salt (60 g L^{-1}) at 10-minute intervals. The addition of sodium carbonate (30 g L^{-1}) was carried out at 10-minute intervals after the addition of the salt. The washing processes after reactive dyeing consisted of five steps: cold rinse, warm rinse, soaping at 95° C for 30 minutes, warm rinse and cold rinse.

Details of these processes are shown in Figures 1 and 2.

The abrasion resistance, pilling resistance, water vapor permeability, air permeability, thermal properties and surface roughness of both the raw and treated fabrics were tested according to the relevant standards. Three fabric samples of each blend ratio were produced for each process, amounting to a total of 45 samples.

Abrasion resistance tests by the Martindale method were carried out according to ISO 12947-3:1998 and the average of three different measurements from each fabric sample was taken for the experiment. The top weight chosen for the abrasion tests was 9 kPa, and the weights of the fabric samples were measured after 20,000 cycles. The pilling resistance values of the fabric samples were measured on an ICI pilling tester according to ISO 12945-1:2000. The fabrics were compared with the standard photographs and numbered from 1 to 5 after 20,000 cycles. Five different tests were carried out for each fabric sample.

Air permeability tests were carried out on an SDL (M021A) Tester according to ISO 9237:1995 at a pressure of 200 Pa and for an area of 20 cm^2. Five different tests were carried out for each fabric sample. The water vapor permeability values were measured using Permetest instruments according to ISO 11092:2014. Five different tests were performed for each fabric sample. Thermal properties were tested using Alambeta instruments according to the Alambeta Users' Guide. Five different tests were performed

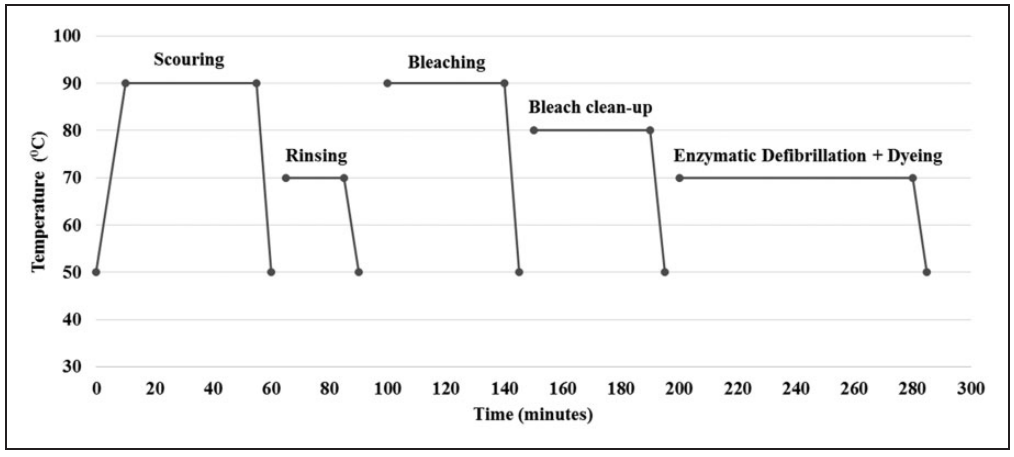


Figure 1. Details of finishing process 1.

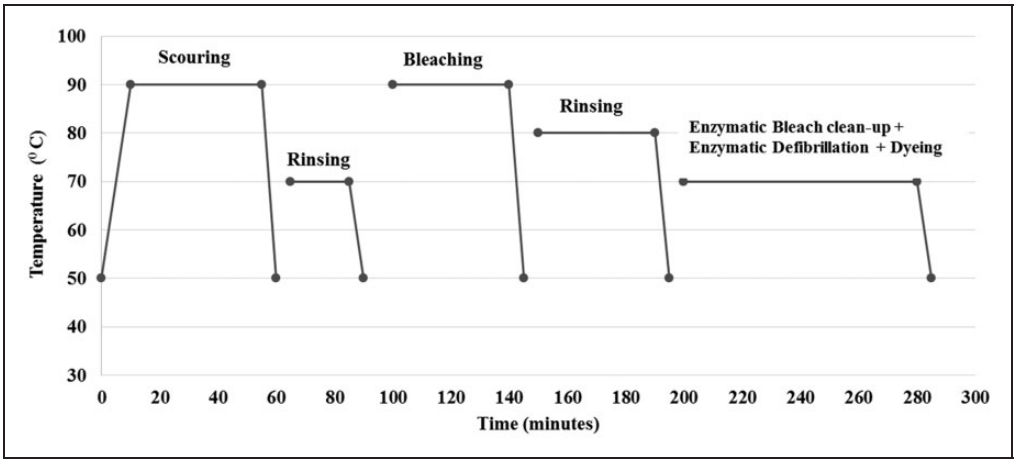


Figure 2. Details of finishing process 2.

Table 3. SNK test results of surface roughness properties, abrasion and pilling resistance of knitted fabrics

Fabric/Factor	Abrasion resistance: loss of mass (%)	Pilling value	Ra (μm) (initial roughness values)
Blend ratio (factor)			
100% cotton (combed)	7.04 (1)	4.5(3)	15.54 (1)
25% Tencel/75% cotton	7.35 (1)	4 (2)	16.03 (1)
50% Tencel/50% cotton	8.04 (1) (2)	4 (2)	16.14 (1)(2)
75% Tencel/25% cotton	8.93 (2)	4 (2)	16.53 (2)
100% Tencel	9.63 (2)	3.5 (1)	17.23 (3)
Process (factor)			
Raw fabric	7.34 (1)	5 (2)	15.99 (1)
Finished fabric 1 (process 1)	7.24 (1)	4–5 (1)	16.02 (2)
Finished fabric 2 (process 2)	10.00 (2)	4 (1)	16.88 (3)

Note: Values 1, 2, 3 and 4 in parentheses denote the effects of Tencel proportion and combined and conventional enzymatic pre-treatments and dyeing processes on the abrasion, pilling resistance and surface roughness of knitted fabrics: 4 denotes the highest rank and 1 the lowest rank.

for each fabric. Surface roughness values of the samples were measured on a Zeiss Surfcom 5000 (travel speed, x: 60 mm/s, z: 200 mm/s; and resolution, x: 0.54 nm, z: 0.31 nm) according to ISO 4287:1997. Five different tests were performed for each fabric sample. All the tests included in this study were carried out according to ISO 139:2005 under standard atmospheric conditions ($20^{\circ}C \pm 2^{\circ}C$ temperature and $65\% \pm 2\%$ moisture).

Scanning electron microscopy (SEM) analysis of 100% cotton, 50/50 Tencel/cotton and 100% Tencel fabric samples was carried out using a Tescan Vega3 SBU to investigate the effects of the two finishing processes on the fibrillation properties and surface morphologies of the fibers. SEM images of each sample were obtained at x500 and x2500 magnification, and a total of 18 images were obtained for the three processes and three blends used in this study. According to the statistical results obtained from this study, the optimum abrasion, roughness, pilling and comfort properties were obtained from the 50/50 Tencel/cotton blend fabrics; therefore, 100% cotton, 50/50 Tencel/cotton and 100% Tencel fabrics were selected for SEM analysis.

The effects of the percentage of Tencel in the blend and of the conventional versus the combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes of the Tencel/cotton knitted fabric samples were evaluated by means of SPSS Statistics and variance analyses, and the Student Newman Keuls (SNK) test was performed at 5% (0.05) level of significance.

Results and discussion

In this section, the effects of Tencel percentage in the blend and the effects of the conventional versus the combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes on the abrasion resistance, pilling resistance, surface roughness, water vapor permeability, air permeability and thermal properties of both the raw and finished fabrics are discussed in terms of the SNK test results given in Tables 3–5 and Figures 3–11.

Surface roughness properties, abrasion and pilling resistance of knitted fabrics

Color change, pilling, hairiness and abrasion-induced loss of mass occur in the appearance of knitted fabrics as a result of rubbing the textile surface over another surface during wearing, use, cleaning or washing processes.[52–54] The changes that occur in the mass and appearance of the fabric due to rubbing are considered to be the measure of fabric resistance against any force.

Surface roughness, pilling and abrasion resistance are greatly affected by fiber properties (length, type and thickness of fibers, blend ratios etc.), yarn properties (production methods, production parameters etc.), fabric properties (knit structure, courses and wales per inch etc.) and finishing and dyeing processes.[1,55] In this study, all parameters were kept constant except blend ratio and defibrillation process. Analysis of the SNK test results given in Table 3 shows that the Tencel percentages of blended yarns and the conventional versus combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes had statistically significant effects on the surface roughness, pilling and abrasion resistance properties of the fabric samples.

The information provided in Figures 3 and 4 shows that as the Tencel percentages of the yarns increased, the surface roughness, amounts of loss of mass and pilling values of the knitted fabrics increased as well.

The greatest surface roughness, loss of mass and pilling values were obtained from 100% Tencel fabrics, whereas the lowest surface roughness, loss of mass and pilling values were obtained from 100% cotton fabrics. The reason for this is that the fibrillation property of Tencel is higher than that of cotton.[4] From the SEM images given in Figures 5–7, it can be seen that no fibrillation took place in 100% cotton fabric samples, whereas the 100% Tencel and 50/50 Tencel/cotton fabric samples showed fibrillation. The statistical results given in Table 3, however, suggest that the best surface roughness, loss of mass and pilling values were obtained from fabrics made of 50/50 Tencel/cotton blend yarn.

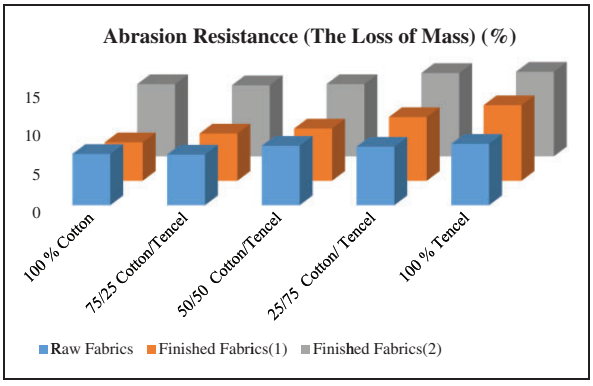


Figure 3. Abrasion resistance of knitted fabrics.

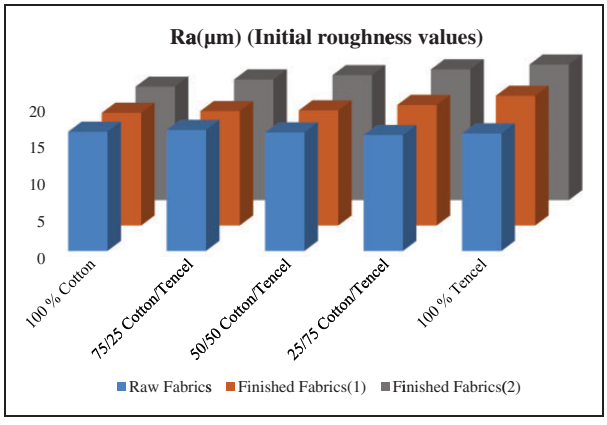


Figure 4. Surface roughness properties of knitted fabrics.

An examination of the defibrillation processes applied to the knitted fabric samples (Figures 3 and 4) revealed that the raw fabrics gave the lowest surface roughness, loss of mass and pilling values after the abrasion tests. The reason for this is that in Tencel blend fabrics, hairiness and fibrillation behaviors take place after the application of mechanical and wet processes. Tencel fiber has high wet and dry strength because of its high degree of crystallinity (up to 90%) and axial molecular orientation; however, Tencel fabrics can swell up to 40% by volume when wetted, as a result of which cracks form on the surface of the fibers and fibrils protrude from these surface cracks. Friction and mechanical processes applied to wet and swollen fabrics cause the fibrils on the fabric surface to become entangled, thereby leading to pill formation.[4,9,13,17,24] Therefore, the surface roughness, abrasion resistance and pilling values of the raw fabrics are expected to be lower than those of the finished fabrics. From the SEM images given in Figure 5, it can also be observed that no fibrillation occurred in raw fabric samples of 100% cotton, 100% Tencel and 50/50% Tencel/cotton blend.

An examination of the results of the conventional and combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes, which were applied to fabrics (Table 3) shows that the loss of mass measured as the abrasion resistance value of Process 2 was higher than that of Process 1. However, both processes provided similar values in terms of pilling and surface roughness. The pilling value of Process 1 was half a point better than that of Process 2 and the surface roughness value of Process 1 was slightly better than that of Process 2. In Process 1, enzymatic defibrillation and dyeing were carried out in a single bath but enzymatic bleach clean-up, enzymatic defibrillation and dyeing were carried out in a single bath in Process 2.

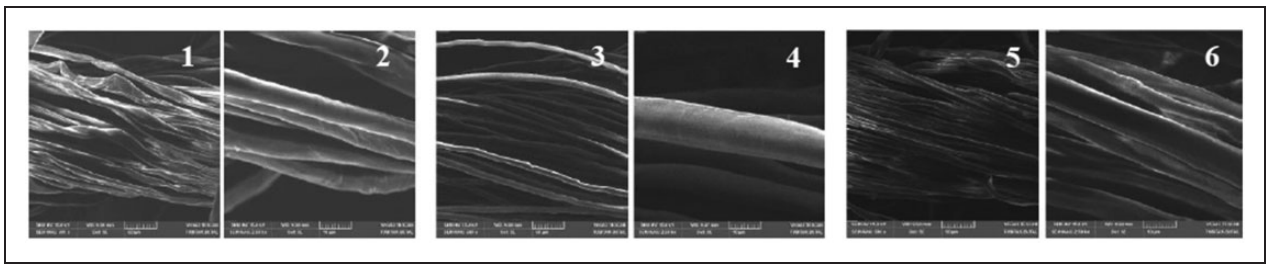


Figure 5. SEM images of raw fabrics: (1 and 2) 100% cotton, (3 and 4) 100% Tencel, (5 and 6) 50/50 Tencel/cotton. Images 1, 3 and 5 at x500 magnification; images 2, 4 and 6 at x2500 magnification.

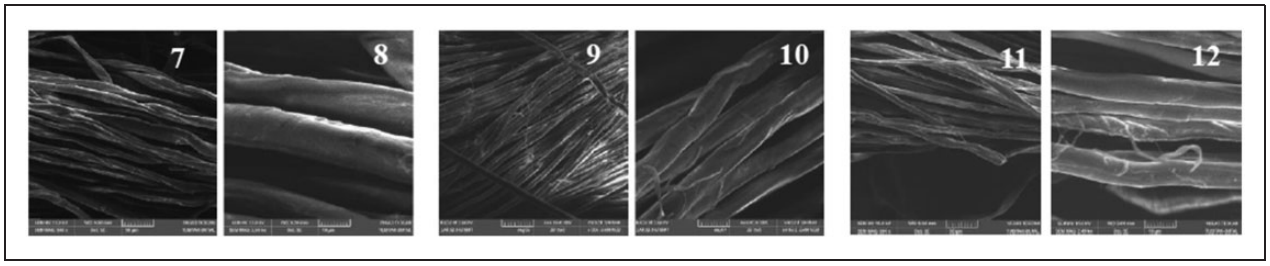


Figure 6. SEM images of finished fabrics from process 1: (7 and 8) 100% cotton, (9 and 10) 100% Tencel, (11 and 12) 50/50 Tencel/cotton. Images 7, 9 and 11 at x500 magnification; images 8, 10 and 12 at x2500 magnification.

Table 4. SNK test results of water vapor permeability and air permeability of knitted fabrics

Yarn/factor	Water vapor permeability (%)	Air permeability ($l/m^2/s$)
Blending ratio (factor)		
100% cotton (combed)	65.58 (1)	1088.47 (1)
25% Tencel/75% cotton	66.70 (1)	1268.53 (2)
50% Tencel/50% cotton	67.83 (1) (2)	1517.33 (3)
75% Tencel/25% cotton	69.73 (2)	1760.67 (4)
100% Tencel	70.89 (2)	2310.0 (5)
Process (factor)		
Raw fabric	63.83 (1)	1759.60 (2)
Finished fabric (Process 1)	70.04 (2)	1688.48 (2)
Finished fabric (Process 2)	70.57 (2)	1318.92 (1)

Note: Values 1, 2, 3, 4 and 5 in parentheses denote the effects of Tencel proportion and combined and conventional enzymatic pre-treatments and dyeing processes on the water vapor permeability (%) and air permeability of knitted fabrics: 5 denotes the highest rank and 1 the lowest rank.

As a result of this, more protruding fibers were removed by defibrillation in Process 1 (Figure 6), indicating that the fabrics subjected to Process 1 underwent a more effective defibrillation.

Water vapor and air permeability properties of knitted fabrics

Water vapor and air permeability of fabrics are affected by a number of factors such as fiber properties, yarn properties, fabric structure properties (thickness, porosity and pattern) and finishing processes applied.[56] In this study, different blend ratios as well as two different combined enzymatic pre-treatments and dyeing processes were employed, whereas all other parameters were kept stable. Table 4 shows that the blend ratios and combined enzymatic pre-treatments and dyeing processes applied had statistically significant effects on the water vapor and air permeability values of the fabric samples.

When water is absorbed by textile materials it is transferred through the structure of the material by diffusion and is allowed first to pass through air spaces between fibers and yarns and then through the fibers themselves. Hydrophilic fiber molecules attract and consequently absorb water molecules, as a result of which the fibers become swollen. The swelling of fibers decreases the volume of the air spaces in the fabric and slows down the diffusion process, thereby leading to evaporation of water from the fabric surface. Water is not absorbed by fabrics made of synthetic fibers. Instead, it passes through capillary spaces between fibers and yarns and is released from the external surface of the fabric.[57]

Tencel fiber has a high water absorption capability but, unlike other cellulosic fibers, it consists of crystalline nanofibrils. The fibrils themselves do not absorb water; water absorption only occurs in the capillaries between the fibrils. Therefore, a single Tencel fiber will behave like an ideally wetting bundle of nanofibrils with nanometric size pores. The structural property of Tencel fiber aids the human body to achieve an optimum temperature by regulating the absorption and transfer of moisture.[18,20,29,58] Figure 8 shows that the water vapor permeability values of the fabric samples increased as Tencel percentages of the blends increased, and a blend with 50% Tencel was sufficient to achieve the optimum water vapor permeability.

When the raw fabrics are compared with the finished fabrics in terms of water vapor permeability, it can be seen that the raw fabrics had the lowest water vapor permeability values, as shown in Table 4. The reason for this can be attributed to the fact that raw fabrics are not subjected to scouring process. Pre-treatment processes, especially scouring, leads to increased wettability of cellulosic fabrics and consequently their water vapor permeability values are expected to increase as well. In our study, the water vapor permeability values of Tencel blend fabrics subjected to Process 1 and 2 were close to one another, and the differences between the values of the two processes were not statistically significant.

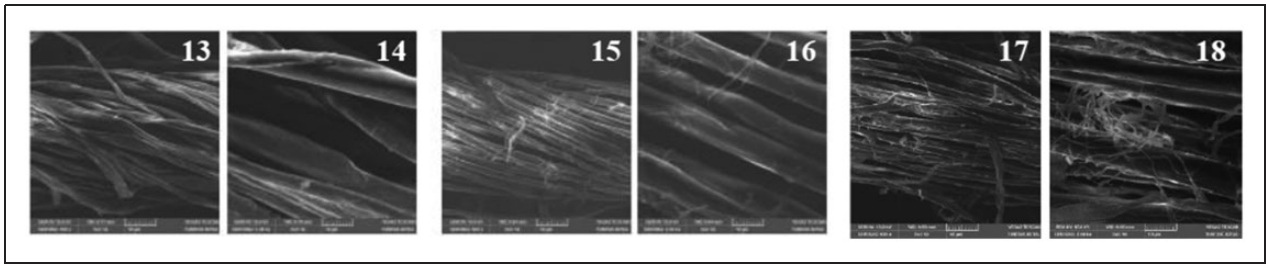


Figure 7. SEM images of finished fabrics from process 2: (13 and 14) 100% cotton, (15 and 16) 100% Tencel, (17 and 18) 50/50 Tencel/cotton. Images 13, 15 and 17 at x500 magnification; images 14, 16 and 18 at x2500 magnification.

As shown in Figure 9, the amount of air that passed per unit time increased with an increase in the proportion of Tencel in the blend. The best results were obtained from 100% Tencel fabrics. Since Tencel fiber has a round cross-section and a smooth uniform surface (Figure 5), Tencel-containing fabrics may have higher porosity, and consequently greater air permeability when compared with cotton-containing fabrics.[4–6,26,29,50,59] Findings of other studies support our finding that the air permeability properties of Tencel fabrics are better than those of viscose and cotton fabrics.[51,60,61]

An examination of the effects of the finishing processes applied (Figure 9) showed that the raw fabrics had higher air permeability values than finished fabrics. It is necessary for Tencel fabrics to undergo fibrillation and defibrillation finishing processes in order to prevent the formation of fibrils on the surface of the fabric during normal wear and use. Fibrillation of a Tencel-containing fabric occurs when mechanical processes are applied to the fabric in a wet and swollen state.[4,17] When mechanical processes are not applied to wet Tencel-containing fabrics or are applied to dry Tencel-containing fabrics, the fibers and fabrics do not fibrillate.[18] Raw fabrics do not undergo fibrillation; therefore, their porosity, and consequently air permeability, values are expected to be higher than those of finished fabrics. From the SEM images given in Figures 5, 6 and 7, it can be seen that the raw fabric samples did not exhibit fibrillation while finished ones did.

The air permeability values of the fabrics subjected to finishing Process 2 were lower than those of the fabrics subjected to finishing Process 1. The comparison of finishing Process 1 with finishing Process 2 showed that the defibrillation involved in finishing Process 1 was more efficient in removing fibrils from the fabric surface, which can be seen in the SEM images given in Figures 6 and 7; therefore, the porosity and air permeability values of the fabrics which underwent finishing Process 1 were higher than those of the fabrics which underwent finishing Process 2. The surface roughness and abrasion resistance values we obtained also confirmed this finding. Furthermore, when the Tencel ratio in the blend increased above 50%, the finished fabrics showed greater increases in air permeability values than the raw fabrics, and this was because the effectiveness of the defibrillation processes was enhanced as the ratio of Tencel in the blend increased above 50%.

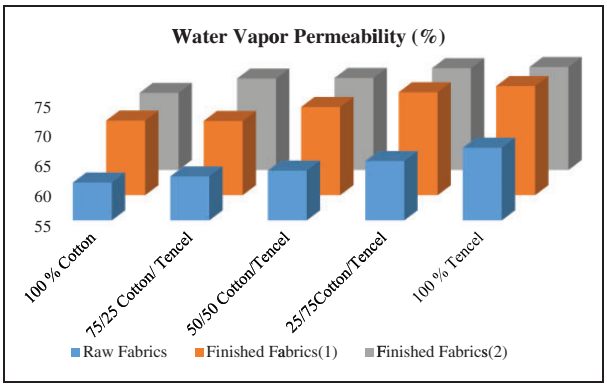


Figure 8. Water vapor permeability of knitted fabrics.

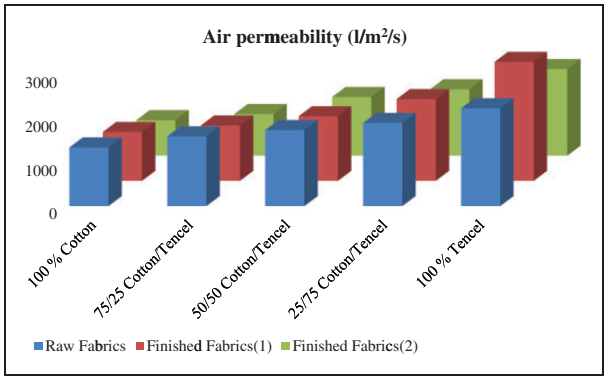


Figure 9. Air permeability properties of knitted fabrics.

Thermal properties of knitted fabrics

Human body temperature can increase as a result of normal daily activities; therefore, the human body

Table 5. SNK test results of thermal properties of knitted fabrics

Yarn/factor	Thermal conductivity ($W/mK*10^{-3}$)	Thermal absorptivity ($Ws^{1/2}m^{-2}K^{-1}$)
Blend ratio (factor)		
100% cotton (combed)	51.11 (5)	144.11 (1)
25% Tencel/75% cotton	48.60 (4)	147.11 (1)
50% Tencel/50% cotton	47.06 (3)	148.33 (1)(2)
75% Tencel/25% cotton	45.57 (2)	153 (2)
100% Tencel	44.18 (1)	155.56 (2)
Process (factor)		
Raw fabric	44.83 (1)	141.20 (1)
Finished fabric (Process 1)	48.03 (2)	146.87 (2)
Finished fabric (Process 2)	49.05 (3)	160.80 (3)

Note: Values 1, 2, 3, 4 and 5 in parentheses denote the effects of Tencel proportion and combined and conventional enzymatic pre-treatments and dyeing processes on the thermal properties of knitted fabrics: 5 denotes the highest rank and 1 the lowest rank.

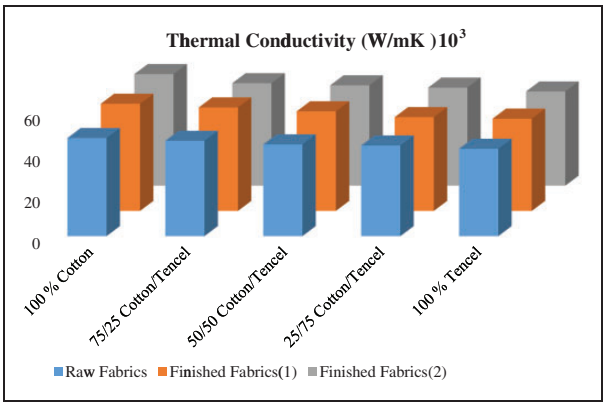


Figure 10. Thermal conductivity of knitted fabrics. W/mK: Watts per meter-Kelvin.

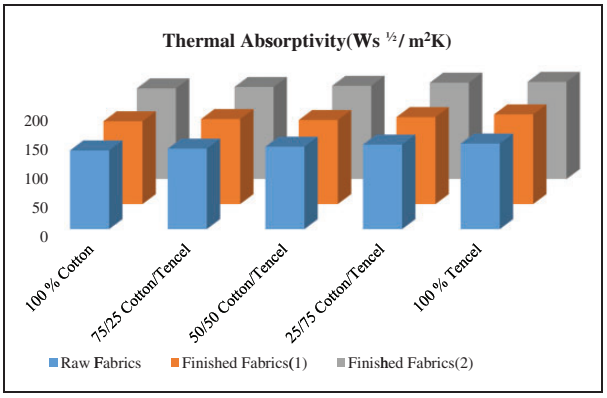


Figure 11. Thermal absorptivity of knitted fabrics. Thermal absorptivity: $Ws^{1/2}/m_{2K}$.

needs to rid itself of the excess heat and a good balance needs to be established between heat gain and heat loss so that bodily comfort can be attained. Therefore, the thermal conductivity and thermal absorptivity of fabrics play an important role in balancing the wearer's heat loss and gain.[62] The SNK test results given in Table 5 reveal that the ratio of Tencel in the blend and the finishing processes which were applied to the fabrics had statistically significant effects on the thermal conductivity and absorptivity of the fabrics.

The thermal conductivity value of a fabric is closely related to the thermal conductivity coefficients of its fibers and the amounts of air trapped in the fabric. Since the thermal conductivity coefficient of air is very low ($\lambda = 0.026\,W/mK$), fibers which can trap a large amount of air within them and fabrics made from these fibers are expected to have low thermal conductivity coefficients.[63,64]

As could be seen from Table 5 and Figure 10, the thermal conductivity decreased with an increase in the Tencel proportion of the blend. The highest thermal conductivity values were obtained from 100% cotton fabrics while the lowest were from 100% Tencel fabrics. Tencel fiber consists of nanofibrils and nanochannels that manage the moisture produced by the body as perspiration, and Tencel fiber has a higher water absorption property than natural cellulose or synthetic fibers, as a result of which it can also hold more air. This property of Tencel makes it thermally resistive.[43] This finding was confirmed in a study by Frydrych et al.[65] Tencel also has a significantly smoother fiber surface than cotton.[4, 5,26,29,50,59] For this reason, the porosity of the fabric and, consequently, the amount of air held within the fabric increase as the ratio of Tencel in the blend increases.

An examination of the finishing processes revealed that the lowest thermal conductivity values were obtained from the raw fabrics while the highest values were obtained from the fabrics subjected to Process 2. The reason the raw fabrics showed the lowest thermal conductivity values was that they were more porous and consequently able to hold more air in themselves compared with the defibrillated fabrics. Process 1 proved more effective than Process 2 in defibrillation of fabrics (Figures 6 and 7), and for this reason they had lower thermal conductivity values.

Thermal absorptivity is an indicator of warm or cool feeling. Warm or cool feeling means the feeling experienced when the human skin briefly touches any object, such as fabric, leather or any polymer used in clothing, furniture or carpets, and this feeling strongly affects consumers' choices of people when buying garments.[66] Thermal absorptivity can also be regarded as the numerical definition of heat transfer rate between skin and clothing. While low thermal absorptivity gives rise

to a warmer sensation, high thermal absorptivity leads to a colder sensation.[67] Figure 11 shows that thermal absorptivity, namely ''cool feeling'', increased with the increasing ratio of Tencel in the blend. When the relative humidity of the environment increases, the moisture content of the Tencel fiber also increases, as a result of which the Tencel fiber feels cooler to the touch and the ''cool feeling'' increases. This behavior of Tencel fiber is much more pronounced than that of cotton fiber because the increase in water content with increasing environmental humidity is much higher for Tencel than for cotton. Therefore, the ''cool feeling'' is increased in high temperature and high humidity environments in which the human body needs coolness.[63, 68] No statistically significant differences were obtained from the fabrics with blend ratios of 50% Tencel or more, and 50/50 Tencel/cotton fabrics gave the best results. An examination of the effects of different defibrillation processes employed in this study showed that the raw fabrics had the lowest values of thermal absorptivity, that is, ''warm feeling'', while the finished fabrics subjected to Process 2 had the highest values of thermal absorptivity, that is, ''cool feeling''.

Conclusions

The purpose of this study was to investigate the effects of the conventional and combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes on the comfort and physical properties of fabrics. The effects of blend ratios of Tencel on these properties of the fabrics were also examined in detail. The following results were obtained from the study:

1. Fabric surface roughness, pilling and abrasion-induced mass loss values increased with the increase of Tencel percentage of blend yarns.
2. With the increase in proportion of Tencel fiber in the blend, the air permeability, water vapor permeability and thermal absorptivity values of the fabrics increased, but their thermal conductivity values decreased.
3. According to the statistical results obtained, the optimum abrasion, roughness, pilling and comfort properties were obtained from the 50/50 Tencel/cotton blend fabrics.
4. Examination of the effects of the conventional and combined processes of enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes on the comfort and physical properties of knitted fabrics shows that Process 1, which involves performing defibrillation and dyeing in a single bath, should be preferred when it is desired for the fabrics to have higher air permeability properties; however, Process 2, which involves performing enzymatic bleach clean-up, enzymatic defibrillation and dyeing in a single bath, should be preferred when it is desired for the fabrics to have higher thermal conductivity and absorptivity properties. The processes do not cause any significant effects on other properties of fabrics.

Based on the findings of this study, it seems quite difficult to decide which process is better because the comfort properties expected from these fabrics vary depending on areas of usage, seasonal conditions and personal preferences. The findings obtained from Process 2 were very close to those obtained from Process 1. In Process 2, enzymatic bleach clean-up, enzymatic defibrillation and dyeing processes of Tencel/cotton blended fabrics were carried out in a single bath, thus leading to savings in water consumption and heat energy. Considering all these aspects, Process 2 could be recommended as a more environmentally friendly process for Tencel/cotton blend fabrics.

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ORCID iDs

Sibel Şardağ https://orcid.org/0000-0001-9177-0059
Tuba Toprak https://orcid.org/0000-0001-8475-3197
Pervin Aniş https://orcid.org/0000-0002-6295-637X

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