



Effects of Recycled Fiber Usage and Laundering Processes on the Performance Properties of Knitted Fabrics

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Abstract

It is known that in recent years, major textile and apparel companies in the world have shown a great tendency towards recycled clothing within the scope of sustainability and it has been observed that recycled knitted clothes have started to take place in the product range of many big brands. However, the subject of recycled textiles is a topic that has become popular in recent years and the performance of recycled textiles in end use is not yet known. For this purpose, knitted fabrics were produced from Ne 20/1 open-end yarns with %50 recycled cotton/%50 recycled polyester, %50 recycled cotton/%50 virgin polyester and %50 virgin cotton/%50 virgin polyester yarns in this study. All fabrics were then subjected to laundering processes at two different washing temperatures and then dried in two separate ways for 5, 10, and 20 laundering cycles. These selected variables and recycled fiber contents were evaluated for their influence on fabric performance properties before and after predetermined laundering cycles. Comparative analyses supported with statistical analysis of circular bending rigidity, weight loss after laundering, and dimensional stability properties were carried out. Results demonstrated that interlock fabrics exhibit higher circular bending rigidity and dimensional change percentages than the other fabric types. Additionally, yarn type did not affect fabric stiffness. Dimensional changes in the wale direction were significantly affected by the yarn type and laundering cycle. Moreover, fabrics made of %50 recycled cotton–%50 recycled polyester yarn exhibited less weight loss percentages after repetitive laundering processes which proves their endurance that is comparable to commercial yarns and encourages us to use recycled yarns more commonly.

Keywords Recycled cotton · Recycled polyester · Laundering · Drying · Knitted fabrics · Performance properties

1 Introduction

The increase in textile production and consumption results in the exhaustion of natural sources faster than they can be replenished. This situation also emerges a huge amount of textile waste that causes numerous environmental problems. For this reason, countries and national and international organizations that are aware of environmental damage continue intensive studies at the level of consumers and producers to protect nature and to use limited natural resources not only today but also in the future. At this point, it has become extremely important to recycle qualified and economical wastes to use natural resources efficiently and benefit from natural resources for a longer time.

Recycling is the reuse of wastes that emerge after various production and consumption processes and have the quality of reuse and participate in production again by passing through different process steps. The total annual fiber production in the world, with 111 million tons, is a striking figure that shows how high the consumption of textile products is. Considering the annual increase in fiber production, this figure is expected to reach 130 million tons in 2025 [1]. In addition, it is known that nearly 6 million tons in Europe and 15 million tons in the United States are being generated every year [2]. For this reason, it is seen that the best solution for reducing the negative environmental effects of textile waste is recycling them.

Cotton and polyester are the most widely used fibers in the global textile industry. Polyester is one of the most preferred fibers with %60 of usage in the textile industry because of its physical properties, recyclability, and low price. The price advantage of polyester especially has made it essential for the cheap and short lifespan clothing industry

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known as “fast fashion” [3, 4]. Cotton fibers biodegrade rapidly in the environment. However, cultivation requires a water supply that caused the usage of approximately 2.6% of global water and is often associated with considerable applications of fertilizers, herbicides, and insecticides [5]. Recycling seems to be the most effective way to reduce the environmental problems caused by this huge consumption and it also reduces the energy costs and usage quantity of raw materials. Moreover, it is required to blend the recycled cotton fibers with polyester or acrylic fibers to give strength to the yarn and make it easier to spin due to the shorter length of recycled cotton fibers when compared with original cotton fibers. Blending recycled cotton fibers with polyester fibers also decreases the amount of fiber fly generation during weaving or knitting [6]. Thus, in this study, fabrics were produced by blending recycled cotton fibers with both recycled and virgin polyester fibers and how the yarn and fabric properties were affected by various fiber types were analyzed, comparatively.

There are many studies on the use of fibers obtained by recycling from textile wastes and used PET bottles in yarn production by various methods, the effect of production parameters on yarn properties, and examining the physical and mechanical properties of these yarns [7–13]. The yarns to be used within the scope of this study have been selected in the yarn count (Ne 20) which is mostly preferred by the major textile and apparel companies operating in the production of knitted fabrics.

The mechanical properties of single-jersey fabrics produced from original and recycled cotton fibers blended with recycled polyester (PES) such as bursting strength, pilling, and air permeability were previously investigated [14, 15]. The properties of single-jersey knitted fabrics produced from recycled polyester and cotton blended yarns with fabrics produced from the original polyester and cotton blended yarns were also compared in another research [16]. As a result of that study, it was revealed that there is no significant difference between the quality of the recycled fabrics and the quality of the fabrics manufactured by using new materials and that the recycled garments obtained from the fabric scraps can be used in the ready-made clothing industry. It was reported that when a small amount of r-PET (recycled PET) was blended with cotton, no significant change was observed in the properties and quality of interlock knitted fabrics compared to that blended with virgin polyester [17]. The 50/50% recycled cotton/virgin polyester yarn and 100% virgin cotton yarns were used in the production of socks, and their physical and thermal performance properties were investigated. It was concluded that fiber type affected all the performance properties of the socks significantly and recycled yarns could be used in socks production [18–20]. In another research, knitted fabrics made from recycled PET, PET-nylon 6, and original PET were investigated, and

it demonstrated the advantages of using recycled polyester in terms of some physical and mechanical properties [21].

Uyanık [22] found that the rPET fibers provided bursting strength values which were close to that of virgin PET fibers for the knitted fabrics produced from coarse yarns. Thus, it was indicated that rPET fiber was more suitable for knitted fabrics containing coarse yarns rather than fabrics having fine yarns.

Virgin and waste cotton fibers are blended in various ratios for yarn and knitted fabric production. The results of the study showed that the yarns and fabrics produced with up to 75% percent of waste cotton blended yarns show no statistically significant differences on yarn and fabric properties [23].

Textile products are affected by various important environmental conditions and end-use processes such as usage conditions, laundering, dry cleaning, ironing, drying methods, and sunlight. Laundering is regarded as one of the most influential routines in terms of the long-term use of textile products while maintaining the same appearance and performance [24]. The previous research showed that the physical and performance properties of textiles change, and garments show different deformation characteristics after repeated laundering. The importance and the effects of this problem have been investigated by several researchers who focused mainly on the mechanical, tactile, and surface characteristics of fabric that were subjected to the laundering process [25–27].

In the literature survey, any study examining the performance properties of knitted fabrics produced from recycled yarns after repeated laundering has not been found. Özkan and Gündoğdu [3] and Frost et.al. [5] investigated only the microfiber release and shedding of recycled and virgin polyester and cotton knitted fabrics after three washing cycles and accelerated laundering, respectively. Thus, all main knitted fabric types (single jersey, rib, interlock) were produced from virgin and recycled PES and cotton blended yarns in this study. Fabric performance properties of these fabrics were examined and analyzed before and after repeated laundering, comprehensively.

2 Experimental

2.1 Materials

Yarns produced from recycled cotton, virgin cotton, recycled polyester, and virgin polyester were supplied from various yarn production companies. 50/50% blended open-end yarns were chosen to compare the fabric performance properties after laundering. The yarn count and twist multiplier of all yarn types were selected as Ne 20 and 3.8, consecutively. The tensile strength and elongation values of yarns

were tested with Zwick Z010 Tester according to the standard TS EN ISO 2062. Unevenness and hairiness tests of the yarns were performed on Uster Tester 5 according to ISO 16549. The properties of yarn samples are given in Table 1. Yarns were coded as shown in the table in the interest of easy expression. According to Table 1, maximum uniformity, maximum irregularity, and the highest nep rate among the yarn samples are observed for yarn type 2. It is followed by yarn types 1 and 3, respectively. On the other side, the tensile strength of yarn types 2 and 3 is similar, and yarn type 1 has the lowest tensile strength value. The percentage of elongation at break is the most for yarn type 1, and the elongation of yarn types 2 and 3 is nearly the same at break. Extension values at the upper yield reveal that yarn type 2 extends more than yarn type 3 and yarn type 1 at the upper yield point. Additionally, the young modulus results of the yarn samples show that yarn type 3 has the highest Young's modulus, while yarn type 2 has the lowest one.

2.2 Knitted Fabric Production

Single jersey fabrics were produced in Mesdan circular laboratory sample knitting machine with the same tightness factors. Rib and interlock structures were produced using a 30 inch Fouquet circular knitting machine (18 E gauge and 36 systems) with constant setting values. All types of fabrics were produced at the same tightness level. The properties of the fabrics are given in Table 2. Performance tests were carried out after all fabric samples were conditioned at standard atmospheric conditions according to TS EN ISO 139. Fabrics are also coded in Table 2 to be used in the comparison of fabric performance properties.

Table 2 Knitted fabric properties

Fabric code	Fabric type	Fabric weight (g/m ²)	Fabric thickness (mm)
1S	Single Jersey	127.5	0.568
2S		124.7	0.570
3S		125.4	0.560
1R	Rib	205.9	0.993
2R		203.0	1.008
3R		201.7	0.992
1I	Interlock	287.1	0.978
2I		287.1	0.980
3I		287.9	0.940

Thickness values of the fabrics and fabric weights were measured according to ASTM 1777 by SDL ATLAS Digital Thickness Gauge and according to TS EN 12,127, consecutively. The fabric weight and thickness values of knitted fabrics produced from various yarn types were found approximately the same for all fabrics in the same fabric category (single jersey, rib, and interlock).

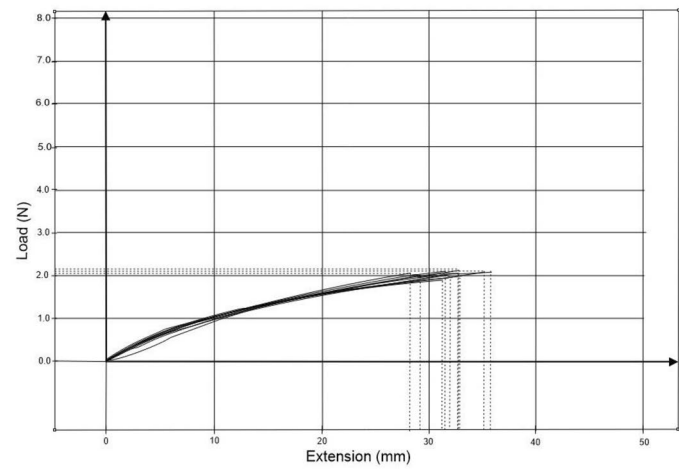
2.3 Laundering Procedure and Performance Tests

All fabrics were subjected to laundering processes for 90 min at two different washing temperatures (30 °C and 60 °C) and then dried in two separate ways (tumble dryer and hanging) in order to investigate the effects of laundering temperature and drying method on knitted fabrics. The fabric samples were tested as unlaundered, and 5, 10, and 20 times washed according to the procedures given below.

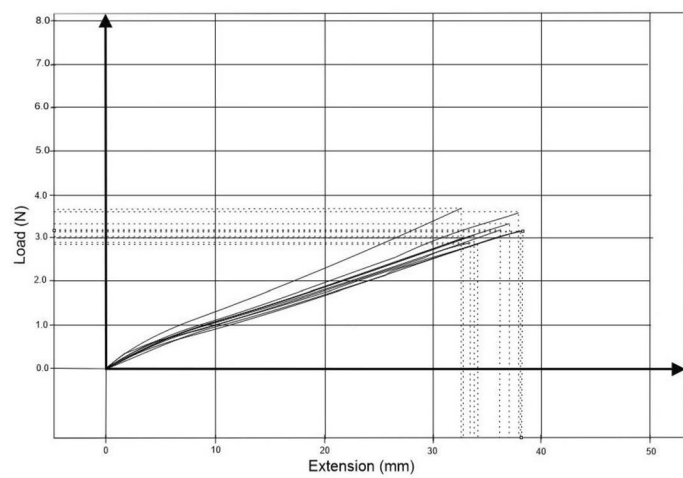
Table 1 Properties of yarn samples

Yarn code	1	2	3
Yarn composition	%50 recycled cotton %50 recycled PES	%50 recycled cotton %50 virgin PES	%50 virgin cotton %50 virgin PES
Measured yarn count, Ne	18.57	19.65	19.61
Tensile strength, <i>N</i>	2.15	3.38	3.47
Elongation at break, %	9.50	9.30	9.26
Extension at upper yield (mm)	32.99	36.00	35.44
Stress at upper yield (MPa)	26.01	40.42	41.03
Young's modulus	536.19	486.23	655.39
Yarn uniformity, U%	11.23	12.53	10.64
Yarn irregularity, CVm	14.45	16.09	13.41
Thin places, − 50%/km	1	10	4
Thick places, + 50%/km	29	45	1
Neps, + 200%/km	968	1436	272
Hairiness, H	5.82	5.66	5.31
Hairiness, sh	1.56	1.53	1.43

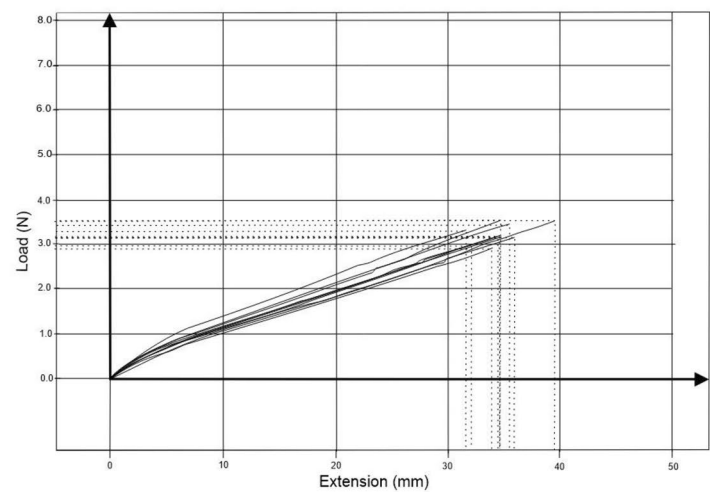
Fig. 1 Load and extension curves of yarn samples; **a** yarn type 1, **b** yarn type 2, and **c** yarn type 3



(a)



(b)



(c)

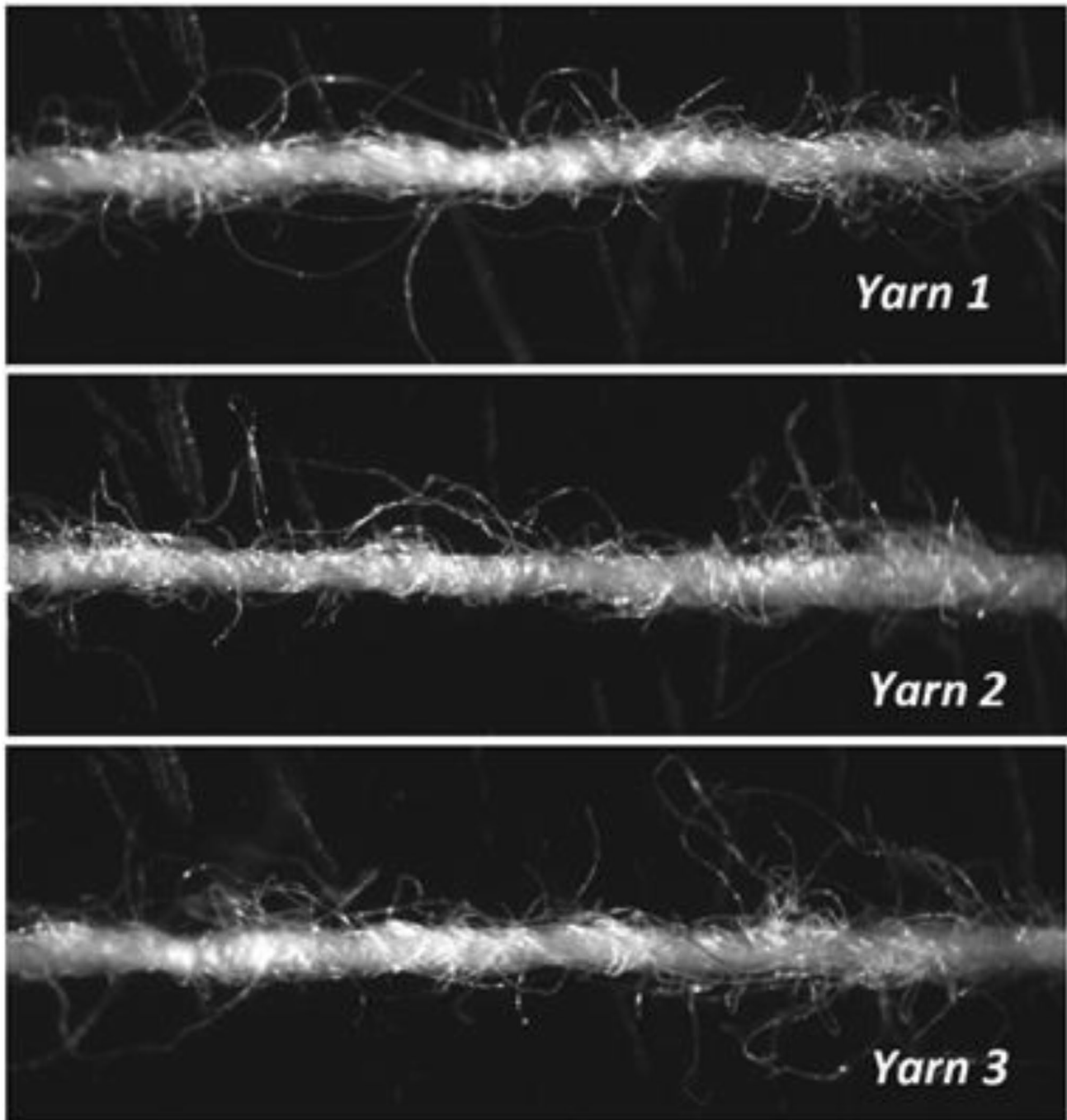


Fig. 2 Magnified images of yarns under microscope

SDL Atlas Digital Pneumatic Stiffness Tester was used to measure circular bending rigidity values of knitted fabrics according to ASTM D 4032 standard. The principle of measurement consists of determining the maximal force of a mandrel causing a simultaneous multidirectional fabric strain by pushing a sample through the tester table hole [28].

Dimensional change measurements after laundering were carried out using the marking method at a certain distance given in the literature [24, 29]. Dimension markings were done in the wale and course directions. For each washing cycle, distances between the marked points were measured and dimensional changes (%) of samples were determined according to Eq. (1).

Table 3 Circular bending rigidity (N) results

Knitted fabric type	Temp. (°C)	Drying method	Yarn type	Laundering cycles			
				Unlaundered	5	10	20
Single Jersey	30	Tumble dry	1	3.98	4.20	6.20	5.65
			2	4.10	4.08	4.53	5.75
			3	3.88	3.77	5.42	4.65
		Line dry	1	3.98	4.10	5.43	5.32
			2	4.10	4.30	5.32	4.97
			3	3.88	3.77	4.75	4.65
	60	Tumble dry	1	3.98	4.00	5.42	5.10
			2	4.10	4.32	4.88	4.53
			3	3.88	3.98	5.77	4.32
		Line dry	1	3.98	3.88	4.98	5.10
			2	4.10	4.00	5.32	4.32
			3	3.88	3.77	4.65	4.20
Rib	30	Tumble dry	1	4.20	6.77	6.98	9.32
			2	4.20	5.77	5.77	8.30
			3	4.43	5.30	5.88	7.43
		Line dry	1	4.20	5.98	7.65	7.88
			2	4.20	5.77	5.87	7.22
			3	4.34	5.20	6.42	6.65
	60	Tumble dry	1	4.20	6.87	7.65	8.65
			2	4.20	6.22	6.67	7.20
			3	4.43	5.00	6.30	6.88
		Line dry	1	4.20	5.98	6.67	7.55
			2	4.20	5.53	6.43	7.32
			3	4.34	5.20	5.88	6.42
Interlock	30	Tumble dry	1	9.65	18.87	26.33	38.78
			2	9.22	16.32	21.77	29.00
			3	10.75	17.87	19.43	23.77
		Line dry	1	9.65	16.65	23.12	29.22
			2	9.22	15.87	20.20	24.10
			3	10.75	17.32	18.08	24.45
	60	Tumble dry	1	9.65	23.10	27.57	38.10
			2	9.22	18.10	23.78	26.88
			3	10.75	16.33	19.77	26.55
		Line dry	1	9.65	20.43	24.55	31.00
			2	9.22	16.20	21.78	27.22
			3	10.75	16.32	18.77	22.55

$$\text{Dimensional change(\%)} = \frac{L_0 - L_1}{L_0} \times 100, \quad (1)$$

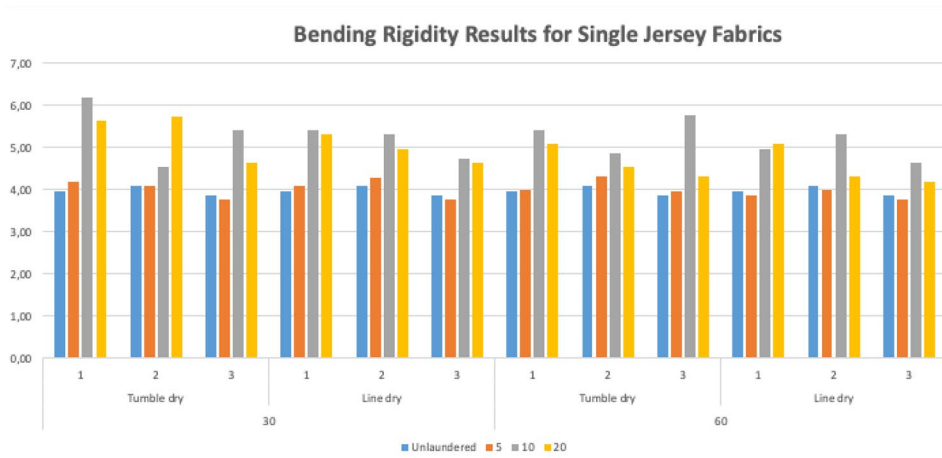
where L_0 is the distance between marked points on the fabric before laundering and L_1 is the distance between marks after laundering cycles.

Weight loss percentages after consecutive washing periods were also investigated and the effects of fiber type, washing temperature, and drying method on these properties were analyzed. Fabric weights were measured before and after washing cycles and weight loss percentages (%) were calculated according to Eq. (2).

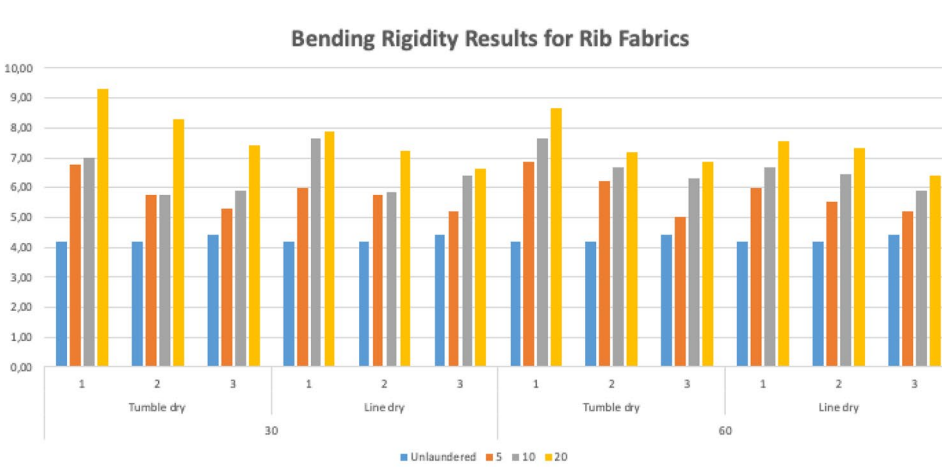
$$\text{Weight loss percentage(\%)} = \frac{W_0 - W_1}{W_0} \times 100, \quad (2)$$

where W_0 is the fabric weight before laundering and W_1 is the fabric weight after a certain number of laundering cycles.

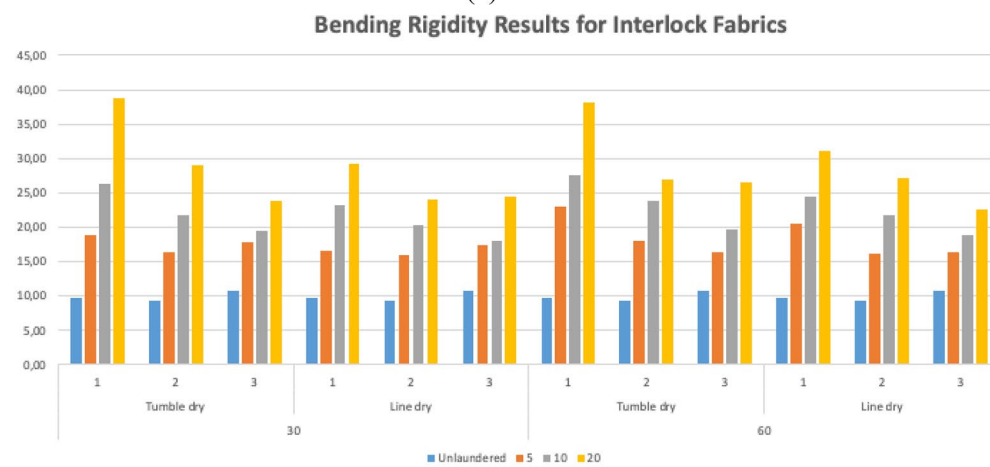
SPSS 25.0 Statistical Software was used for statistical analyses of the results. First, a normality test was conducted to expose whether the data of circular bending rigidity, dimensional change, and fabric weight loss is in a normal distribution. Kolmogorov–Smirnov was used as a normality test method.



(a)



(b)



(c)

Fig. 3 Circular bending rigidity results for knitted fabrics; **a** single-jersey fabrics, **b** rib fabrics, **c** interlock fabrics

Table 4 Descriptive statistics of circular bending rigidity (*N*)

Parameters		Mean	Standard error (\pm)
Knitted fabric type	Single Jersey	4.53	0.06
	Rib	6.04	0.12
	Interlock	19.55	0.64
Yarn type	1	11.17	0.81
	2	9.70	0.63
	3	9.24	0.57
Temperature (°C)	30	9.96	0.54
	60	10.12	0.57
Drying method	Tumble dry	10.43	0.59
	Line dry	9.65	0.51
Laundering cycles	5	9.20	0.61
	10	11.28	0.77
	20	13.64	1.07

According to the results of the Kolmogorov–Smirnov test, it was determined that the data was not in a normal distribution. Therefore, non-parametric tests were used for statistical evaluation. Mann–Whitney test method was used for parameters; temperature (30 °C and 60° C) and drying method (tumble dry and line dry) and the Kruskal–Wallis test method was used for parameters; fabric type (single jersey, rib, and interlock), yarn type (%50 recycled cotton – %50 recycled PES, %50 recycled cotton – %50 virgin PES, and %50 virgin cotton – %50 virgin PES), and laundering cycle (5, 10 and 20). Significance values for pairwise comparisons were obtained with Bonferroni post hoc tests.

3 Results and Discussion

3.1 Yarn Properties

Figure 1 presents the load and extension curves of yarn type 1 to yarn type 3, respectively. Each graphic shows the repeated measurements of the related yarn. It is seen from the figure that yarn type 1 (%50 recycled cotton – %50 recycled PES) has the lowest load value. Yarn type 2 (%50 recycled cotton – %50 virgin PES) and yarn type 3 (%50 virgin cotton – %50 virgin PES) have closer load values that are higher than yarn type 1. Likewise, the extension values of yarn types 2 and 3 are similar and more than the extension of yarn type 1.

Microscope images of yarn samples were taken with Leica S8APO microscope. The magnification ratio was 20X. Magnified microscope images of yarns are given in

Fig. 2. As it is seen from the Fig. 2, hairiness of the yarns is similar as it was supported by the Uster results.

3.2 Circular Bending Rigidity

Circular bending rigidity tests were carried out to evaluate and compare the fabric stiffness of produced knitted fabrics. Table 3 and Fig. 3 exhibit the circular bending rigidity results of knitted fabrics made from %50 recycled cotton – %50 recycled PES (yarn type 1), %50 recycled cotton—%50 virgin PES (yarn type 2), and %50 virgin cotton – %50 virgin PES (yarn type 3) yarns before and after predetermined laundering cycles. Figure 3 demonstrates that tumble drying leads to higher bending rigidity values, especially after 10 and 20 washing cycles for all fabric types. When fabrics washed at 30 °C were compared, the circular bending rigidity results were found close to each other for unlaundered and 5 times washed fabrics for all fabric types. However, it is apparent from the figures that fabrics knitted with %50 recycled cotton – %50 virgin PES (yarn type 2), and %50 virgin cotton – %50 virgin PES (yarn type 3) yarns have significantly different bending rigidity results than fabrics knitted with %50 recycled cotton – %50 recycled PES (yarn type 1) yarns after 10 washing cycles.

Statistical analysis was also carried out to evaluate the circular bending rigidity test results. Effects of the fabric type, yarn type, and laundering cycle on the circular bending rigidity of fabrics were evaluated with a non-parametric Kruskal–Wallis test. Descriptive statistics of circular bending rigidity (%) of fabrics are given in Table 4.

From the results, it was evidenced that interlock knitted fabrics show higher circular bending rigidity among other fabric types. The interlock fabrics also exhibit the highest increase in circular bending rigidity results after laundering cycles (Table 3). These results indicated that the stiffness of interlock fabrics is affected more than single jersey and rib fabrics regardless of yarn type. Furthermore, statistical analyses showed that fabric type has a significant effect on circular bending rigidity, and post hoc tests established that significant differences exist between all fabric types ($p \leq 0.001$).

When results were evaluated to compare the effect of yarn content on the bending rigidity of fabrics, the unlaundered fabrics knitted from three different yarns, in the same fabric type, gave close results. These results showed that usage of recycled cotton and PES does not affect the unlaundered fabric stiffness (Table 3). On the other side, Table 4 puts forward that the stiffness of the fabric made of yarn type 1 was a bit more than fabrics made of yarn 2 and 3. However, the

Table 5 Results of dimensional change percentages (%) for width and length of the fabrics

Knitted fabric type	Temp (°C)	Drying method	Yarn type	Laundering cycles					
				5		10		20	
				Course	Wale	Course	Wale	Course	Wale
Single Jersey	30	Tumble dry	1	0.00	14.67	2.33	13.00	2.33	17.33
			2	0.67	11.67	2.67	15.00	3.67	17.67
			3	1.67	7.67	2.00	8.67	4.00	12.33
		Line dry	1	1.67	9.67	1.33	9.67	3.33	11.67
			2	0.33	6.33	1.33	7.33	0.67	10.33
			3	1.67	1.67	2.00	4.00	2.33	4.00
	60	Tumble dry	1	2.00	12.33	2.00	14.33	1.00	17.33
			2	0.67	12.33	3.33	12.33	2.00	9.53
			3	3.33	8.00	3.67	9.33	2.33	14.67
		Line dry	1	0.67	15.00	0.67	16.33	3.00	17.67
			2	2.33	13.33	0.33	12.67	1.00	14.00
			3	1.67	9.00	2.67	5.67	0.67	12.67
Rib	30	Tumble dry	1	4.67	14.00	5.67	15.33	4.67	18.00
			2	3.33	14.33	4.00	15.33	4.00	17.00
			3	4.00	13.67	2.33	14.33	5.67	14.33
		Line dry	1	4.00	10.67	5.67	13.00	3.33	12.00
			2	2.00	11.00	2.00	12.33	0.33	15.67
			3	3.00	8.33	3.67	10.33	1.00	12.33
	60	Tumble dry	1	2.33	16.00	6.67	17.00	4.67	18.33
			2	7.33	14.67	4.33	17.00	4.00	18.67
			3	2.67	13.67	2.33	16.33	1.00	17.33
		Line dry	1	4.00	14.33	3.33	14.33	0.67	15.67
			2	3.33	14.67	3.67	15.00	1.33	15.00
			3	2.33	13.33	7.00	11.67	1.67	13.00
Interlock	30	Tumble dry	1	4.67	16.33	3.33	18.67	7.33	19.00
			2	4.67	15.00	2.67	17.00	4.00	16.67
			3	6.00	15.33	6.33	17.00	2.67	20.00
		Line dry	1	1.67	13.67	4.00	15.33	3.00	18.33
			2	4.67	9.67	1.00	15.00	2.67	16.33
			3	4.00	12.00	2.33	13.00	4.00	15.00
	60	Tumble dry	1	4.67	17.67	4.67	19.33	4.33	20.33
			2	6.00	15.33	2.00	17.33	6.00	16.67
			3	4.00	15.67	8.00	17.00	5.33	20.00
		Line dry	1	4.00	18.00	1.67	19.33	3.67	20.00
			2	3.67	16.00	1.33	17.33	7.33	14.67
			3	5.00	16.67	4.47	18.00	1.00	19.67

effect of yarn type was not statistically significant ($p=0.170$) according to the statistical analysis.

For single-jersey fabrics, the stiffness values were in the range of 4.20–5.65 N after 20 washing cycles. The stiffness values were between 6.42 and 9.32 N for rib fabrics and between 22.55 and 38.78 N for interlock fabrics after 20 washing cycles (Table 3). Table 4 shows that fabric stiffness increases due to the increase in the laundering cycle and

the statistical analysis supports the experimental results. It was found that the laundering cycle has a significant effect on circular bending rigidity ($p \leq 0.001$). When Bonferroni post hoc tests were evaluated for the laundering cycle, it was observed that a significant difference exists between the laundering cycles 0th–5th ($p=0.014$), 0–10th, 0–20th, and 5–20th ($p \leq 0.001$), and 5–10th ($p=0.005$). There was no significant difference found between the 10th and 20th

Table 6 Descriptive statistics of dimensional change percentages (%) of fabrics

Parameters		Mean \pm standard error	
		course	wale
Knitted fabric type	Single Jersey	2.13 \pm 0.13	11.56 \pm 0.33
	Rib	3.70 \pm 0.17	14.39 \pm 0.20
	Interlock	4.07 \pm 0.16	16.73 \pm 0.19
Yarn type	1	3.38 \pm 0.17	15.66 \pm 0.23
	2	3.19 \pm 0.17	14.36 \pm 0.23
	3	3.34 \pm 0.16	12.66 \pm 0.35
Temperature (°C)	30	3.20 \pm 0.13	13.11 \pm 0.25
	60	3.40 \pm 0.14	15.34 \pm 0.20
Drying method	Tumble dry	3.83 \pm 0.14	15.46 \pm 0.19
	Line dry	2.78 \pm 0.12	12.99 \pm 0.26
Laundering cycles	5	3.30 \pm 0.17	12.82 \pm 0.27
	10	3.30 \pm 0.17	14.02 \pm 0.29
	20	3.31 \pm 0.17	15.83 \pm 0.27

laundering cycles ($p > 0.05$). Therefore, it can be statistically said that the stiffness of fabrics is similar after the 10th washing cycle.

The washing temperature seems to affect the bending rigidity of the fabrics regardless of yarn type. Thus, the fabrics laundered at 60 °C had higher stiffness values than fabrics laundered at 30 °C in general. The drying method was also found effective on bending rigidity according to the experimental test results. The stiffness of the fabrics dried by a tumble dryer was observed higher than the stiffness of the fabrics dried by line drying. This increasing trend in stiffness values, depending on the drying type, was found to be valid for all fabric types. On the other side, the statistical results obtained by Mann–Whitney tests, established that there are no significant differences between laundering temperatures and drying methods in terms of the circular bending rigidity of fabrics, respectively ($p = 0.761$, $p = 0.384$).

3.3 Dimensional Changes of Fabrics

Dimensional change test was applied to specimens to determine shrinkage or elongation from the length and width after the laundering process. Dimensional change percentage values in the wale and course directions for different washing temperatures and drying methods are given in Table 5.

Additionally, the effects of the parameters such as fabric type, yarn type, and laundering cycle on the dimensional change of the fabrics were statistically evaluated both in the course and wale directions. Descriptive statistics of

dimensional change percentages (%) of fabrics are given in Table 6.

The experimental results showed that the dimensional changes in the wale direction are higher than the course direction for all fabric types (Table 5). Similarly, the non-parametric Kruskal–Wallis test output proved that significant differences were found between dimensional change percentages (%) of fabrics in the course and wale direction according to the fabric type ($p \leq 0.001$). As it is seen in Table 6, maximum dimensional changes occurred on interlock fabrics which were followed by rib and single-jersey fabrics, respectively. According to the pairwise comparisons, significant differences were observed between single jersey–rib and single jersey–interlock fabric types ($p \leq 0.001$).

When the effects of yarn type and laundering cycle were evaluated respectively, it is seen from Table 6 that the values are very close to each other for course direction. After all, no significant difference was found in dimensional change percentages of fabrics in course direction in terms of yarn type and laundering cycle ($p = 0.571$; $p = 0.970$). On the other side, a significant difference was found for dimensional change percentages of fabrics in the wale direction according to yarn type and laundering cycle ($p \leq 0.001$). It was also determined with post hoc tests that significant differences exist between all groups for yarn type. The maximum dimensional change percentage was observed for yarn type 1 (%50 Recycled Cotton – %50 Recycled PES), while the minimum dimensional change percentage occurred for yarn type 3 (%50 Virgin Cotton – %50 Virgin PES). On the other hand, significant differences were found between 5 and 10th cycles ($p = 0.003$), 5 and 20th cycles ($p \leq 0.001$), and 10 and 20th cycles ($p \leq 0.001$) for laundering. Accordingly, it can be said that dimensional changes in the wale direction are significantly affected by the yarn type and laundering cycle.

Results showed that high washing temperatures cause higher dimensional change percentages of the fabrics in the wale direction (Table 6). Mann–Whitney test results related to laundering temperature also demonstrated that there is no significant difference in dimensional change percentages of fabrics in the course direction ($p = 0.507$). On the contrary, it was found a significant difference between dimensional change percentages of fabrics in the wale direction ($p \leq 0.001$).

Finally, it was observed that tumble drying has a negative effect on the dimensional change of the fabrics when compared to the line dry method. When Table 6 was evaluated, it was seen that the dimensional change percentages of the fabrics exposed to line drying are less than tumble-dried fabrics and statistical results supported the observations. It was found a significant difference between the dimensional

Table 7 Results for percentages of weight loss (%)

Knitted fabric type	Temp. (°C)	Drying method	Yarn type	Laundering cycles		
				5	10	20
Single Jersey	30	Tumble dry	1	1.17	2.60	4.93
			2	1.48	2.55	4.03
			3	1.49	3.20	5.64
		Line dry	1	1.35	2.24	3.46
			2	1.18	1.79	2.63
			3	1.48	2.57	4.02
	60	Tumble dry	1	1.12	2.62	4.80
			2	1.56	2.85	3.98
			3	1.22	2.47	3.95
		Line dry	1	1.38	1.96	3.21
			2	1.52	2.06	3.06
			3	1.19	1.68	2.29
Rib	30	Tumble dry	1	1.77	2.92	4.47
			2	1.98	3.25	4.70
			3	1.54	2.61	3.91
		Line dry	1	1.50	2.47	3.44
			2	2.16	3.32	4.49
			3	1.26	2.00	2.61
	60	Tumble dry	1	1.72	2.83	4.16
			2	2.48	3.83	4.96
			3	1.68	2.63	3.88
		Line dry	1	1.51	2.18	3.05
			2	2.73	3.60	4.58
			3	1.66	2.23	2.97
Interlock	30	Tumble dry	1	0.80	2.02	3.72
			2	2.04	3.99	6.71
			3	1.30	2.53	3.68
		Line dry	1	1.14	2.06	2.83
			2	1.92	3.50	4.79
			3	1.17	2.57	3.83
	60	Tumble dry	1	0.84	1.92	3.35
			2	2.56	4.31	6.26
			3	1.33	2.58	4.08
		Line dry	1	1.38	2.09	2.81
			2	2.42	3.50	4.64
			3	1.38	2.90	3.64

change percentages of fabrics in the course and wale directions, according to the Mann–Whitney test results related to the drying method ($p \leq 0.001$).

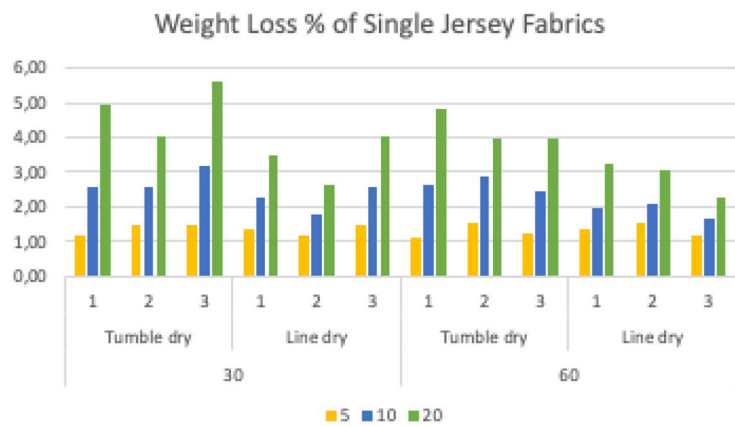
3.4 Weight Loss of Fabrics

Weights of the same fabric specimens were measured after each predetermined laundering cycle to determine the weight loss of fabrics arising from repetitive washings. Table 7 and Fig. 4 present the fabric weight loss percentages of fabrics obtained from experimental tests in terms of.

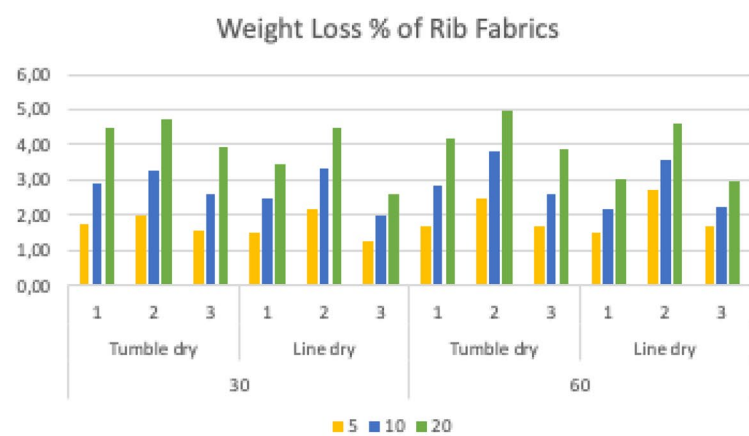
It was concluded from Fig. 4 that tumble drying caused higher weight loss than line drying in general. Thus, the highest weight loss percentages were calculated for fabrics that were tumble-dried after laundering at both washing temperatures (30 °C and 60 °C).

According to Table 7, it was seen that the percentages of weight loss increased due to the increase in laundering cycles. The Kruskal–Wallis test output also supported the data that laundering cycles have an important effect on fabric weight loss ($p \leq 0.001$), and a significant difference exists between all cycles ($p \leq 0.001$).

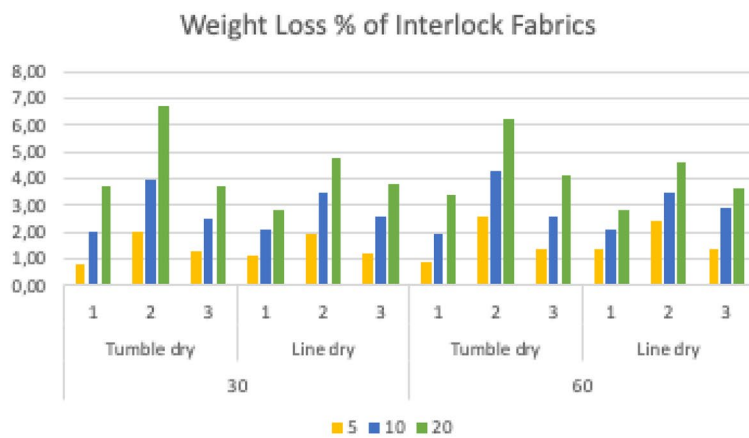
Fig. 4 Weight loss percentages of knitted fabrics; **a** single-jersey fabrics, **b** rib fabrics, **c** interlock fabrics



(a)



(b)



(c)

Table 8 Descriptive statistics of weight loss percentages (%) of fabrics

Parameters		Mean \pm standard error
Knitted fabric type	Single Jersey	2.52 \pm 0.12
	Rib	2.87 \pm 0.10
	Interlock	2.85 \pm 0.15
Yarn type	1	2.44 \pm 0.11
	2	3.26 \pm 0.14
	3	2.53 \pm 0.11
Temperature (°C)	30	2.76 \pm 0.11
	60	2.73 \pm 0.10
Drying method	Tumble dry	2.98 \pm 0.12
	Line dry	2.51 \pm 0.08
Laundering cycles	5	1.57 \pm 0.05
	10	2.68 \pm 0.07
	20	3.99 \pm 0.11

various parameters

Descriptive statistics of the weight loss percentages (%) of fabrics are given in Table 8. Table 8 shows that the maximum weight loss percentage occurred for rib fabrics. In a similar vein, fabric type had a significant effect on fabric weight loss according to statistical analysis results ($p=0.032$). Nevertheless, a significant difference was found only between single jersey and rib fabrics ($p=0.029$). On the other hand, fabrics made of yarn type 2 exhibited the maximum fabric weight loss (Table 8). Similarly, yarn types had a significant effect on fabric weight loss percentages, and a significant difference was found between yarn types 1 and 2, and yarn types 2 and 3 ($p<0.001$). It was observed that the fabrics which were made of yarn type 1 have the minimum weight loss percentage, while the fabrics that were made of yarn type 2 (%50 Recycled Cotton %50 Virgin PES) have the maximum weight loss percentage.

Mann Whitney test results established that there is a significant difference between drying methods ($p=0.006$). The fabric weight loss percentage of fabrics exposed to tumble drier was found more than fabrics that were line dried. Experimental results showed that the weight loss of fabrics washed at 30 °C and 60 °C are close to each other. Nevertheless, the effect of laundering temperature on fabric weight loss was not found statistically significant ($p=0.890$).

4 Conclusion

In this study, the mechanical properties of yarns and the performance properties of three different types of knitted fabrics produced from virgin and recycled cotton and polyester fibers were investigated and compared before and after

repetitive laundering and drying processes. This contribution reveals the effects of recycled yarn usage, knitted fabric structure, and washing parameters on circular bending rigidity, weight loss, and dimensional stability properties of knitted fabrics after multiple laundering cycles.

The output of the study presents that fabric structure and laundering cycle affect the circular bending rigidity. Nevertheless, the fabric stiffness does not change after a certain laundering cycle. It was found that yarn type and fabric stiffness are not significantly related. Consequently, recycled yarns can be preferred instead of virgin yarns in this case.

On the other hand, dimensional change percentages of the fabrics are affected by knitted fabric structure. Additionally, it was observed that fabrics made of full recycled cotton-pes yarns show more dimensional change percentages than fabrics made of semi-recycled and virgin yarns. For this reason, if the dimensional change percentages of the fabric in the wale direction are important and want to be less, semi-recycled yarns can be used. The drying method was also seen to affect the dimensional change percentages of fabrics in both directions. For this reason, line drying should be preferred for less dimensional change.

Fabric structure, drying method, and yarn type were found effective on the fabric weight loss parameter. It was determined that if less fabric loss is required, tumble drying should not be preferred. On the other side, fabrics made of full recycled cotton-pes yarns showed better performance in terms of fabric weight loss than semi-recycled and virgin yarns. In conclusion, it was indicated that the selected performance properties of recycled cotton/virgin polyester fabrics gave quite similar results to the properties of virgin cotton/virgin polyester fabrics, and it was suggested that the usage of recycled cotton fibers in the production of knitted fabrics would not adversely affect the performance properties. Thus, recycled fibers seem most suitable for use in the manufacture of all basic structures of knitted fabrics such as sweatshirts, and t-shirts.

This study was limited to the evaluation of the performance properties of knitted cotton and polyester fabrics produced from recycled and virgin fibers. Therefore, further research using other recycled fiber types in the production of knitted fabrics and research investigating the properties of woven fabrics produced from recycled yarns are planned to be investigated.

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Data availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no conflict of interest.

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