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Investigation of the Physical Properties of Yarns with Varying Recycled Cotton Fiber Content and Cotton/Polyester Blended Knitted Fabrics

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ABSTRACT
The textile industry is a major waste producer due to its high production volume and increasing consumption rates. Therefore, recycling and re-using textile waste for production is crucial for environmental sustainability. This study examines the physical properties of cotton/polyester blended knitted fabrics produced with yarns containing four different recycled cotton fiber ratios. In the first part, yarns with varying recycled fiber content were evaluated for unevenness, tensile strength, and friction properties by changing yarn count and twist. In the second part, rib and interlock fabrics were knitted, and fabric tests for weight, thickness, bending rigidity, bursting strength, air permeability, and pilling were conducted. Reference fabrics were produced using virgin yarn with the same blend ratio as the highest recycled fiber yarns for comparison. The results show that recycled yarns can replace virgin yarns, contributing to reducing environmental impacts through textile waste recycling, and recycled yarn quality significantly affects fabric properties.

Farklı Geri Dönüşüm Pamuk Lifi İçeren İpliklerin ve Pamuk/Polyester Karışımlı Örme Kumaşların Fiziksel Özelliklerinin Araştırılması

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ÖZ
Tekstil endüstrisi, yüksek üretim hacmi ve artan tüketim oranı nedeniyle en fazla atık üreten sektörlerdendir. Çevresel sürdürülebilirlik için, nitelikli tekstil atıklarının geri dönüştürülerek üretimde kullanılmasının önemi giderek artmaktadır. Bu çalışmada, dört farklı oranda geri dönüşüm pamuk lifi içeren iplikler ile bu ipliklerden üretilen pamuk/polyester karışımlı örme kumaşların fiziksel özellikleri incelenmiştir. İlk bölümde, geri dönüşümlü ipliklerin numara ve büküm parametreleri değiştirilerek düzgünsüzlük, kopma mukavemeti ve sürtünme özellikleri açısından performansları değerlendirilmiştir. İkinci kısımda, geri dönüşümlü ipliklerden ribana ve interlok kumaşlar üretilmiş, gramaj, kalınlık, dairesel eğilme, patlama mukavemeti, hava geçirgenliği ve boncuklanma testleri gerçekleştirilmiştir. Sonuçların kıyaslanabilmesi için en fazla geri dönüşüm lif oranına sahip iplikle aynı karışım oranında orijinal iplik temin edilerek referans kumaşlar üretilmiş ve test edilmiştir. Sonuçlar, geri dönüşümlü ipliklerin orijinal iplikler yerine kullanılabileceğini ve tekstil atıklarının geri dönüşümünü teşvik ederek çevresel etkilerin azaltılmasına katkı sağlayacağını göstermektedir.

1. INTRODUCTION

The rapid increase in the world population and the increase in production and consumption caused by the industrialization process led to the depletion of limited natural resources and an increase in environmental pollution problems. For this reason, recycling applications that aim to recover textile waste and reuse it for production are gaining more and more attention and importance every day. The textile industry is one of the largest industries causing global pollution and is second after the petroleum industry in terms of pollution. It generates millions of tons of waste and contributes approximately 1.2 billion tons of greenhouse gas emissions annually. Every year, millions of tons of clothing are produced, worn, and discarded. The textile and apparel industries are also the largest contributors to the microplastic fibers released into oceans [1,2]. In this context, the recycling of textile waste plays a significant role in reducing the negative environmental impacts and supporting the proper use of limited natural resources. If serious precautions are not taken against the environmental damage caused by raw material production, product manufacturing, use, and post-use stages in the textile and apparel sector, the foreseen impact will be significant. If current conditions persist, the textile sector is expected to consume 25% of the world's carbon budget by 2050 [3]. This negative scenario predicts that, by 2050, the non-renewable raw material usage in the textile and apparel sector will reach 300 million tons, and the amount of microplastic waste released into the oceans will be 22 million tons [4].

Materials that are no longer usable and have become harmful to the environment as a result of production and consumption activities are defined as waste materials. The recycling process allows these waste materials to be re-used in the production and consumption cycle by subjecting them to various physical or chemical processes [5]. Textile recycling refers to the recovery of unusable clothing or any material that can be defined as pre-production fiber waste, fabric waste, or textile waste so that they can be used again in production [6-8].

The total annual fiber production in the world is 111 million tons, a striking figure that demonstrates the high level of textile consumption. Given the annual increase in fiber production, this figure is expected to reach 130 million tons by 2025 [9]. This high level of textile and apparel production generates a large amount of solid textile waste, which leads to environmental issues such as the occupation of large landfill areas, contamination, and global warming. In Turkey, it is known that more than 1 million tons of recyclable textile waste are generated each year [10,11]. This situation can be associated with the constant renewal of products in various ways to keep up with changing fashion trends and excessive consumption. As long as consumers continue their purchasing habits in the same way, the production of packaging, clothing, and home textile products, and consequently their waste, will increase, and this problem will continue to grow [12]. Textile recycling provides many advantages, such as preventing environmental pollution, reducing energy and water consumption, and minimizing the use of dyes and chemicals [10,13]. However, only a small portion of textile products that become waste worldwide are recycled. Solving this problem requires more investment and conscious consumer habits. According to a report published by the United States Environmental Protection Agency, 5% of landfill space is made up of textile waste, of which only 15% is recyclable, while the remaining portion is sent to landfills. Therefore, activities related to the recovery of textile waste in Europe and America have focused on collecting and recovering used textile waste [10]. Studies show that only 2% of discarded clothing is recycled, with the remaining 98% either sent to landfills or incinerated [14]. In terms of raw material content, textile waste typically contains cotton, acrylic, and polyester fibers, which are collected, sorted, processed, and converted into reusable products during the recycling process. Synthetic fibers like polyester, acrylic, nylon, and polypropylene account for approximately 60% of global textile production [15]. These synthetic fibers are often used in the production of many textile products in combination with natural fibers like cotton and wool to reduce production costs. Since the 1980s, conscious consumers in developed countries have tended to use textile materials that do not have harmful effects on human health and the environment during production, usage, and after becoming waste. As a result, interest in natural fibers has increased, and cotton fiber has become more and more important [16]. According to the data from the Strategy Development Department of 2020, while Turkey's cotton production met 55% of domestic consumption in the 2019-2020 season, cotton fiber imports increased by approximately 31% compared to the previous season, reaching 996,000 tons, while exports decreased by 26%, falling to 78,000 tons. According to foreign trade statistics for 2021, cotton, cotton yarn, and cotton fabric products ranked 18th among the top 20 imported products with a trade volume of 182.822.000 USD [17]. In a country where cotton consumption is so high, meeting the need for cotton fiber through recycling is an important step in terms of reducing production costs and cotton imports.

Recycled yarns are produced from cotton and polyester waste. These yarns have an important role in the recycling chain, helping to reintroduce textile waste into production and thereby minimizing waste. According to data presented by recycled yarn manufacturers, producing a single t-shirt using recycled yarn instead of conventional yarn allows for the saving of 2,700 liters of fresh water and zero chemical consumption in production. Moreover, if recycling is done correctly, production can be achieved without any loss of quality [7,14,18].

There are considerable number of studies in the literature that have been conducted on the use of fibers obtained through recycling textile waste and used PET bottles in yarn production, the effects of production parameters on yarn characteristics, and the physical and mechanical properties of these yarns [19-25]. In these studies, open-end, friction, and ring yarn production systems have been used, particularly for producing thick and medium-thick yarns (yarns thicker than Ne 20). Furthermore, some studies examine the use of yarns made from recycled and original PET fibers in various ratios for producing interlock fabrics and the mechanical properties of these fabrics, such as bursting strength, pilling, and air permeability [26-34].

Goswami and Basu [35], examined the challenges of using mechanically recycled cotton in yarn production, determining optimal blend ratios for ring and rotor spinning and suggesting double or siro yarns to improve quality. Raiskio et al. [36] evaluated the quality and durability of mechanically recycled cotton and linen yarns, assessing their suitability for producing long-lasting knitted fabrics. Doba Kadem and Ozan [37] evaluated the life cycle assessment and performance properties of single jersey knitted fabrics containing 10-20% mechanically recycled cotton, highlighting environmental benefits and comparing key fabric characteristics. In another study conducted by Utebay et al. [38], the effects of conventional wet-finishing processes on knitted fabrics with up to 80% recycled cotton examined and it was demonstrated that fabric quality can be optimized through appropriate finishing techniques. Muthukumara and Thilagavathi [39] produced open-end spun yarns from recycled cotton and r-PET blends in their study and it was found that the 60/40 blend had the best quality and fabrics made from this yarn have properties comparable to commercial fabrics, making them suitable for knitted garments. Sarı et al. [40] investigated the impact of mechanically recycled cotton blended with virgin cotton on the mechanical and fastness properties of knitted fabrics, finding that mechanically recycled cotton can be a viable alternative to virgin cotton with comparable performance. Doba Kadem and Sevgi [41] examined the performance properties of single jersey knitted fabrics containing different ratios of recycled cotton fibers and found that as the recycling rate increases, the bursting strength of the fabrics decreases, air permeability increases, and the fabric becomes softer.

This study aims to investigate the usability of recycled yarns in fabric production, focusing on both yarn and fabric physical properties. However, this study differs from previous research in that it specifically examines cotton/polyester blended single yarns containing recycled cotton fibers in four different proportions, and the physical properties of rib and interlock knitted fabrics produced from these yarns. This two-part study involved the preparation of cotton/polyester blended single yarns (Ne 20) containing recycled cotton fibers in varying proportions, followed by physical testing of the yarns in both their single and two-ply forms. The yarn properties were then analyzed. Subsequently, rib and interlock knitted fabrics were produced from these yarns containing different percentages of recycled cotton fibers. To assess the physical properties of the recycled fabrics, tests were conducted on fabric weight, fabric thickness, air permeability, pilling, bursting strength, and circular bending rigidity. The results of the study revealed that recycled yarns can be effectively used as a substitute for virgin yarns without compromising fabric physical properties.

2. METHOD

2.1. Material

Four types of cotton/polyester blended yarns with different proportions of recycled cotton fibers were purchased from a recycled yarn manufacturer. All yarns were produced using the open-end spinning system at a twist coefficient of 650 turns/m. The average fiber length and fineness of recycled cotton were 26.64 mm and 4.9 mic (1.9 dtex), consequently. 38 mm/1.3 dtex virgin polyester fibers were used in the production of blended yarns. The structural properties of the single-ply yarns are shown in Table 1.

Table 1. Structural properties of the single-ply yarns

Yarn code	Yarn composition	Yarn count
Y1	50% recycled cotton / 50% polyester	Ne 20
Y2	60% recycled cotton / 40% polyester	
Y3	65% recycled cotton / 35% polyester	
Y4	70% recycled cotton / 30% polyester	

2.2. Plied Yarn Production and Yarn Testing

Purchased yarns were twisted into plied yarns using the Saurer Allma plying machine at two different twist levels (150 T/m and 250 T/m) to produce two-ply yarns. The details of the produced two-ply yarns are provided in Table 2.

Table 2. Properties of two-ply yarns

Two-ply yarn code	Yarn twist	Yarn count
Y1-2P	150 T/m	Ne 10
	250 T/m	
Y2-2P	150 T/m	
	250 T/m	
Y3-2P	150 T/m	
	250 T/m	
Y4-2P	150 T/m	
	250 T/m	

Mass variations and yarn defects significantly influence yarn quality and its market value. Measurement of yarn hairiness, which affects the quality of woven and knitted fabrics, has become increasingly important in recent years [42]. Single-ply and two-ply recycled yarns were tested for performance properties, including yarn unevenness, hairiness, tensile strength, elongation, and friction coefficients for yarn-to-yarn and yarn-to-metal interactions. Yarn unevenness, hairiness, and defects such as thick and thin places were measured using Uster Tester 5 Device, in accordance with ISO 16549 standards, with three repetitions. Yarn tensile strength and elongation at break were measured using a Lloyd Yarn Strength Test Device according to TS EN ISO 2062 standards, with ten repetitions. Yarn-to-yarn and yarn-to-metal friction coefficients, as well as lint generation, were tested using a CTT (Constant Tension Transport) Test Device. Lint generation and yarn-to-yarn friction tests were conducted according to ASTM D 3412, while yarn-to-metal friction tests were performed according to ASTM D 3108, each with three repetitions. The lint generation of the yarns was measured with a CTT Lint Generation Tester.

2.3. Production of Knitted Fabrics and Fabric Testing

In the scope of the study, both single yarns with a count of Ne 20 (Table 1) and the two-ply yarns with a twist of 250 T/m, produced by using these single yarns, were used in the production of rib and interlock fabrics. To compare the physical properties of fabrics knitted from recycled yarns, one reference fabric in rib construction and one in interlock construction were also produced by using a virgin yarn with the same blend ratio as the recycled yarn, which has the highest recycled cotton fiber content. Due to the difficulties and issues encountered in fabric production with Ne 10 yarn, as well as the very stiff handle of the fabrics produced from Ne 10 yarn, only Ne 20 single yarn was used in the production of the reference fabrics. All rib and interlock fabrics were produced on a 30” diameter and 18-gauge Fouquet circular knitting machine. Information about the fabrics made from recycled yarns is provided in Table 3, and information about the reference fabrics is presented in Table 4.

Table 3. Information on recycled yarn fabrics

Fabric code	Fabric knit structure	Yarn used in the fabric
R1	Rib	Y1
R2		Y2
R3		Y3
R4		Y4
R5		Y1-2P
R6		Y2-2P
R7		Y3-2P
R8		Y4-2P
I1	Interlock	Y1
I2		Y2
I3		Y3
I4		Y4
I5		Y1-2P
I6		Y2-2P
I7		Y3-2P
I8		Y4-2P

As can be seen in Table 3, a total of 16 types of fabric were produced in the scope of the study, using two different yarn counts, made from yarns with four different recycled cotton fiber ratios and two different knitting structures.

Table 4. Information on reference fabrics

Fabric code	Fabric knit structure	Yarn used in the fabric	Yarn count	Yarn composition
R-Ref	Rib	virgin cotton/polyester yarn	Ne 20	70% cotton/ 30% polyester
I-Ref	Interlock			

The fabric weight, thickness, circular bending, bursting strength, air permeability, and pilling properties of all the produced fabrics were measured. Fabric weight was measured using a Sartorius electronic balance according to TS EN 12127, and fabric thickness was tested on an SDL ATLAS Digital Thickness Gauge following ASTM 1777. Circular bending strength was measured using a Shirley circular bending tester according to ASTM D 4032, while bursting strength was determined with a James Heal Truburst 4 tester following TS EN ISO 13938-2. Air permeability was tested using a Textest FX 3300 device by TS 391 EN ISO 9237, and pilling was tested on a Martindale tester according to TS EN ISO 12945-2.

2.4. Statistical Analysis

The experimental data obtained from the measurements were statistically analyzed and evaluated using SPSS Statistics 25 software. In the statistical analysis, the dependent variables, namely bursting strength, air permeability, and circular bending rigidity were evaluated based on the independent variables, which include fabric knit structure, yarn composition, and yarn count. The bursting strength, air permeability, and circular bending rigidity data of rib and interlock fabrics were grouped based on fabric structure and yarn count parameters. Furthermore, the statistical significance of the effects of yarns containing varying proportions of recycled cotton fiber on the bursting strength, air permeability, and circular bending rigidity of the fabrics was determined. In this regard, the statistical significance of the difference in the physical properties between fabrics produced from virgin yarn and those produced from recycled yarn was assessed. In the statistical analysis of fabrics knitted from yarns containing varying proportions of recycled cotton fiber, a normality test was initially performed to determine the distribution of the data. Based on the Shapiro-Wilk test results, non-parametric tests were applied, as the data did not conform to a normal distribution. The Kruskal-Wallis test was conducted for air permeability, bursting strength, and circular bending rigidity parameters, and the Bonferroni post hoc test was used for pairwise comparisons. In the statistical analysis conducted to compare the recycled yarn fabric samples with the reference fabric samples produced from virgin cotton/polyester yarn, it was determined that the experimental data obtained from the air permeability, bursting strength, and circular bending resistance tests followed a normal distribution, and the independent samples t-test was applied accordingly.

3. RESULTS AND DISCUSSION

3.1. Findings for Single-Ply Yarns

The tensile strength and unevenness values of single-ply yarns, obtained from measurements carried out on the USTER Testing Machine, are presented in Table 5.

Table 5. Single-ply yarn properties

Yarn code	Y1	Y2	Y3	Y4
Tensile strength (N)	3.38	1.85	3.70	2.58
Elongation at break (mm)	35.30	34.13	31.23	25.48
Yarn uniformity (U%)	12.53	12.53	10.01	11.92
Yarn unevenness (CVm)	16.09	16.21	12.74	16.32
Thin places (-50%/km)	10	11.7	0.0	8.3
Thick places (+50%/km)	45	64.2	9.2	142.5
Neps (+200%/km)	1436	2977	368.3	1865
Hairiness (H)	5.66	8.38	6.16	5.88
Hairiness (sh)	1.53	2.32	1.65	1.62

It was observed that the tensile strength values of single-ply yarns varied according to the recycled cotton fiber content, as shown in Table 5. Specifically, the tensile strength values were lower for yarns made from 60% recycled cotton/40% polyester and 70% recycled cotton/30% polyester. This is believed to be due not only to the recycled cotton fiber content but also to the presence of high neps and thick-place defects, which negatively affect the yarn's tensile strength. The lowest unevenness values were obtained for the yarn made from 65% recycled cotton and 35% polyester. Similarly, this yarn also exhibited the fewest defects. When examining the yarn hairiness values, the lowest hairiness values were observed for the yarns made from 50% recycled cotton/ 50% polyester and 70% recycled cotton/ 30% polyester. The yarn-to-yarn, yarn-to-metal friction coefficients, and the lint amount of the single-ply yarns, measured using the CTT test device, are presented in Table 6.

Table 6. CTT results for single-ply yarns

Yarn code	Y1	Y2	Y3	Y4
Yarn-to-metal friction coefficient (μ)	0.52	0.58	0.60	0.59
Yarn-to-yarn friction coefficient (μ)	0.18	0.19	0.21	0.20
Lint amount (mg/1000m)	6	12	11	26

It is expected that the yarn-to-yarn and yarn-to-metal friction coefficients of the yarns be as low as possible [43]. As seen from the CTT results provided in Table 6, the yarn with the lowest yarn-to-yarn and yarn-to-metal friction coefficients is the 50% recycled cotton/ 50% polyester blend yarn. This result can be explained by the fact that the friction coefficient is closely related to yarn hairiness [44]. As the recycled cotton fiber content in the yarn structure increases, it has been observed that the yarn-to-metal friction coefficient increases slightly, and this value is found to be similar for the other three yarns (Y2, Y3, and Y4). The yarn-to-yarn friction coefficients are generally close to each other. The lint amount is significantly affected by the increase in recycled cotton content. While 6 mg of lint was detected in the 50% recycled cotton / 50% polyester blend yarn, this amount increased to 26 mg in the 70% recycled cotton / 30% polyester yarn.

3.2. Findings for Two-Ply Yarns

The tensile strength and elongation at break values of two-ply yarns with 150 T/m and 250 T/m twist levels are presented in Table 7.

Table 7. Tensile strength and elongation at break results of two-ply yarns

Yarn code	Yarn twist (T/m)	Tensile strength (N)	Elongation at break (mm)
Y1-2P	**150**	6.75	32.56
	250	7.19	33.03
Y2-2P	**150**	4.82	37.04
	250	5.44	39.74
Y3-2P	**150**	7.22	38.45
	250	6.82	33.28
Y4-2P	**150**	5.46	25.36
	250	6.75	27.68

When the tensile strength of two-ply yarns is compared, an increase in strength has been observed in all blended yarns with higher twist levels, as expected. The increase in the proportion of recycled cotton fiber has generally led to a slight decrease in yarn strength, although this reduction is not considered significant. When evaluating the elongation at break values of two-ply yarns, the highest elongation was observed in the yarn made from a 60% recycled cotton/40% polyester blend. The lowest elongation value was found in the 70% recycled cotton/30% polyester yarn, which is similar to the result observed for single-ply yarn. The unevenness test results of the two-ply yarns are presented in Table 8. Generally, the unevenness values are quite similar, and the lowest irregularity was observed in the 65% recycled cotton/35% polyester yarn. In particular, the neps count for this yarn (Y3-2P) was significantly lower compared to the others.

Table 8. Yarn unevenness results for two-ply yarns

Yarn code	Y1-2P		Y2-2P		Y3-2P		Y4-2P	
Yarn twist (T/m)	**150**	**250**	**150**	**250**	**150**	**250**	**150**	**250**
Yarn uniformity (U%)	8.68	8.84	9.00	9.12	7.07	7.15	8.87	8.96
Yarn unevenness (CVm)	11.10	11.09	11.54	11.68	8.97	9.03	11.99	11.99
Thin places (-50%/km)	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0
Thick places (+50%/km)	5.8	5.0	3.3	4.2	0.8	0.0	31.7	33.3
Neps (+200%/km)	180.8	235.0	492.5	538.3	29.2	17.5	382.5	396.7
Hairiness (H)	7.10	6.61	8.37	7.77	7.24	7.44	7.47	7.32
Hairiness (sh)	1.56	1.55	2.00	2.05	1.67	1.82	1.72	1.85

The results of the yarn-to-yarn, yarn-to-metal friction, and lint generation tests conducted to evaluate the performance of two-ply yarns during the production process are presented in Table 9. According to Table 9, the yarn-to-yarn and yarn-to-metal friction coefficients of two-ply yarns are generally higher compared to those of single-ply yarns. However, the amount of lint generated by two-ply yarns was found to be lower, likely due to the effect of yarn twist. The use of plied yarns has led to a decrease in lint generation for all yarn types.

Table 9. CTT test results for two-ply yarns

Yarn code	Y1-2P		Y2-2P		Y3-2P		Y4-2P	
Yarn twist (T/m)	**150**	**250**	**150**	**250**	**150**	**250**	**150**	**250**
Yarn-to-metal friction coefficient (μ)	0.67	0.69	0.65	0.66	0.62	0.69	0.58	0.60
Yarn-to-yarn friction coefficient (μ)	0.25	0.27	0.28	0.27	0.26	0.25	0.26	0.26
Lint amount (mg/1000m)	5	5	16	15	7	5	13	11

3.3. Findings for Knitted Fabrics

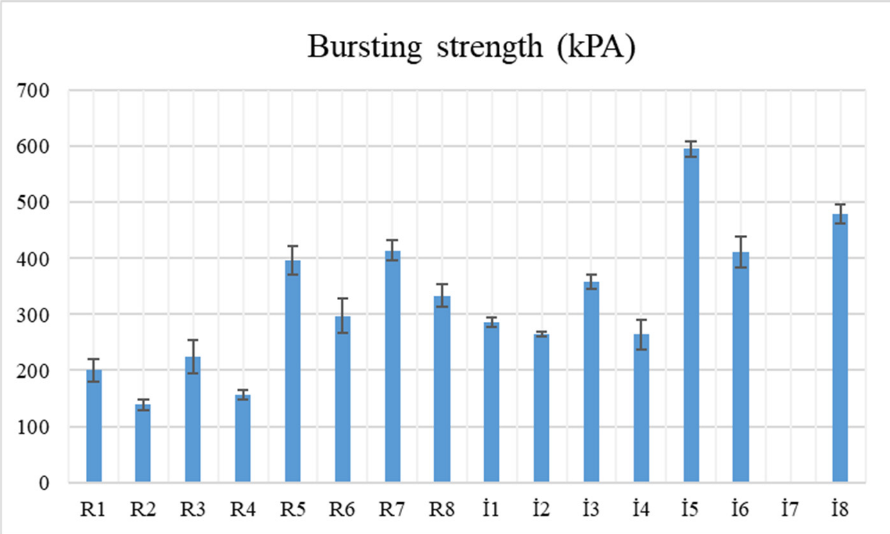
The average fabric weight and thickness values of fabrics produced from recycled yarn and reference fabrics are provided in Table 10.

Table 10. Fabric weight and thickness values of recycled and reference fabrics

Fabric code	Fabric weight (g/m²)		Fabric thickness (mm)	
	Mean	**St. Dev.**	**Mean**	**St. Dev.**
R-1	188.13	7.68	1.08	0.03
R-2	163.50	3.67	1.13	0.04
R-3	196.07	9.32	1.15	0.04
R-4	178.17	4.88	1.16	0.01
R-5	370.20	11.63	1.50	0.03
R-6	342.07	6.62	1.39	0.14
R-7	392.77	16.36	1.46	0.01
R-8	359.60	9.30	1.45	0.14
R-Ref	209.93	2.14	1.10	0.02
I-1	257.90	3.92	1.20	0.01
I-2	240.10	6.51	1.14	0.04
I-3	272.67	1.90	1.17	0.04
I-4	249.57	5.51	1.14	0.01
I-5	544.33	3.93	1.53	0.03
I-6	600.23	5.08	1.65	0.01
I-7	609.30	10.37	1.44	0.16
I-8	584.23	3.80	1.57	0.02
I-Ref	280.20	6.20	1.18	0.02

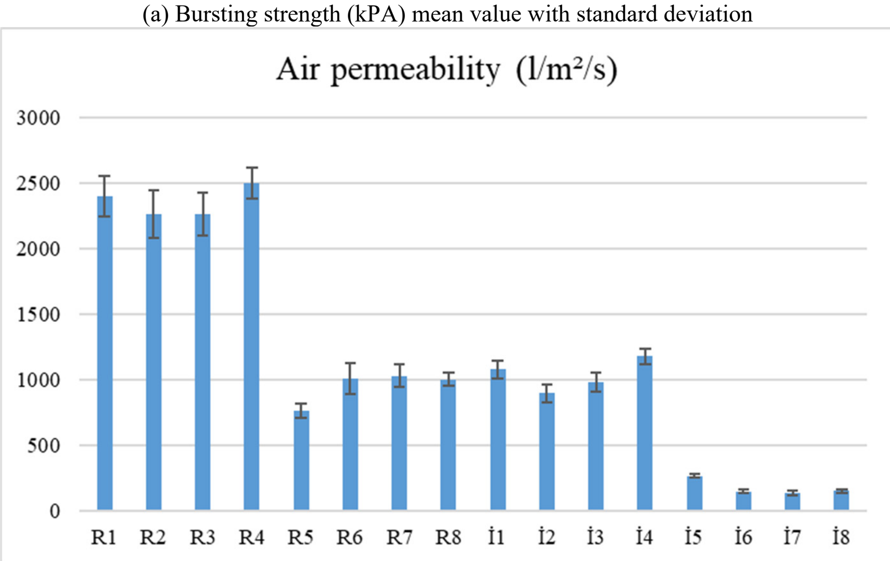
As seen in Table 10, the fabric weight of rib fabrics knitted from the same yarn number is lower compared to interlock fabrics. As the yarn thickness increases, the fabric weight also increases proportionally. When rib and interlock fabrics are evaluated separately, the values are close to each other despite some differences. The thicknesses of fabrics knitted from the same yarn number are also similar for rib and interlock fabrics. However, as the yarn thickness increases, the fabric thickness increases as expected. Moreover, the reference fabrics knitted from Ne 20 yarn are observed to have higher fabric weights for both rib and interlock structures compared to the fabrics knitted from recycled yarns (R1-R4 and I1-I4). However, the thickness values are found to be quite similar.

The experimental results of the bursting strength, air permeability, circular bending rigidity tests for fabrics knitted from recycled yarns and reference fabrics are presented in Figure 1, and pilling values of fabrics are given in Table 11. The statistical analysis data on the physical properties of fabrics knitted from recycled yarns are provided in Table 12. The statistical analysis results comparing the bursting strength, air permeability, and circular bending rigidity values of reference fabrics knitted from virgin yarns with those of fabrics knitted from recycled yarns are provided in Table 13.

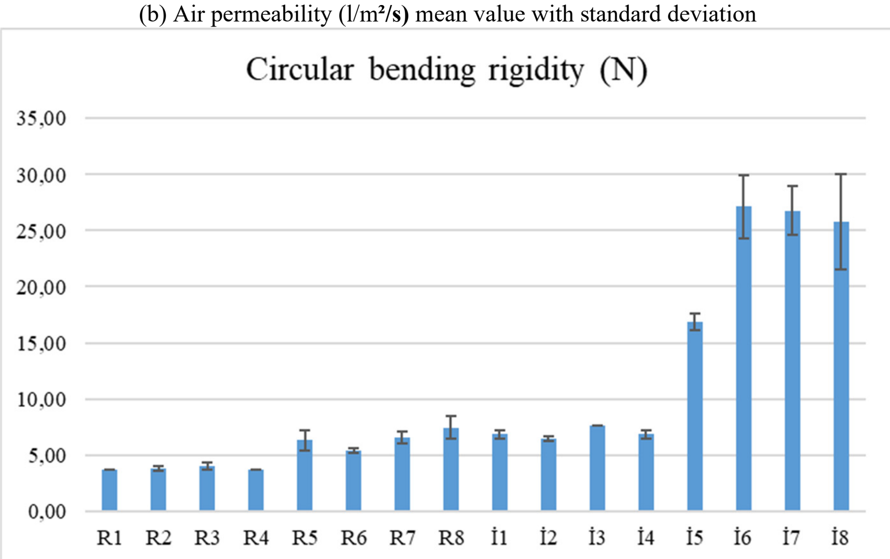


**The bursting strength value of the fabric coded I7 could not be measured*

(a) Bursting strength (kPA) mean value with standard deviation



(b) Air permeability (l/m²/s) mean value with standard deviation



(c) Circular bending rigidity (N) mean value with standard deviation

Figure 1. Physical properties of knitted fabrics

Table 11. Pilling values of knitted fabrics

Fabric code	**R-1**	**R-2**	**R-3**	**R-4**	**R-5**	**R-6**	**R-7**	**R-8**	**R-Ref**
Pilling level	2	2	2	2	3	2-3	3	2-3	3-4
Fabric code	**I-1**	**I-2**	**I-3**	**I-4**	**I-5**	**I-6**	**I-7**	**I-8**	**I-Ref**
Pilling level	2-3	2-3	2	2	3-4	3	3-4	3	2-3

According to Figure 1, a difference is observed in the bursting strength values of fabrics knitted from yarns containing varying proportions of recycled cotton fibers. The highest bursting strength values are exhibited by rib fabrics knitted from yarns with a composition of 65% recycled cotton/ 35% polyester, for both Ne10 and Ne20 yarns. This result can be related to the tensile strength test results of single and two-ply yarns (Table 5 and Table 7). Yarn composed of 65% recycled cotton and 35% polyester exhibits the highest tensile strength and the lowest unevenness and defect rates. Fabrics knitted from yarns with a 50% recycled cotton and 50% polyester blend rank second in terms of bursting strength values for both yarn counts. This result is also significant when evaluated with the yarn tensile strength test results. The lowest bursting strength value is exhibited by fabrics knitted from yarn containing 60% recycled cotton and 40% polyester. On the other hand, when the results of fabrics knitted from Ne 20 recycled yarns (R1-R4 and I1-I4) are compared separately for rib and interlock knit structures with reference fabrics, it was found that the bursting strength of the R-Ref coded reference rib fabric is 21.90% and 12.34% lower than R3 and R1 coded fabrics, respectively, which exhibit the highest bursting strength. The bursting strength of the R4-coded fabric, produced from recycled yarn with the same blend ratio as the reference fabric, was found to be 10.85% lower than that of the reference fabric.

For interlock fabrics made from Ne 20 recycled yarns, the highest bursting strength was achieved by fabrics knitted with yarn containing 65% recycled cotton and 35% polyester, while the lowest values were exhibited by fabrics produced from Y4 and Y2 coded yarns, respectively. When evaluating the bursting strength values of fabrics produced from Ne 10 yarns, the fabrics are ranked from highest to lowest bursting strength as those knitted from Y1-2P, Y4-2P, and Y2-2P coded yarns. However, the bursting strength of the fabric knitted from Y3-2P coded yarn could not be measured. as it could not burst within the standard time frame. When examining the bursting strength of the interlock reference fabric, knitted from the virgin yarn, it was found to be 20.62% higher than the I4-coded fabric, which was knitted from yarn with the same blend ratio of recycled fibers. However, the interlock reference fabric exhibited a bursting strength that was 7.74% lower than the I3-coded fabric, which had the highest bursting strength. Variations in the ratio of recycled fibers or virgin polyester fibers in the fabric significantly affect the bursting strength results. However, the tensile strength of yarn containing recycled fibers plays a key role in the fabric's bursting strength. The results show that knitted fabrics made from cotton/polyester yarn containing recycled cotton fibers can exhibit bursting strength properties that are at least as good as those made from virgin cotton/polyester yarn. This also highlights the importance of properly managing the production process of recycled yarn correctly to produce high-strength and high-quality yarn.

Within the scope of the study, the data obtained from the experimental tests of fabrics knitted from recycled yarns were first grouped based on the fabric knit structure and then according to the yarn count parameters and examined statistically (Table 12). In the statistical analysis, no significant difference was found between the rib knit fabrics produced from yarns containing varying proportions of recycled fibers (p_b=0.178). Similarly, no statistically significant difference was found in the bursting strength values of interlock fabrics knitted from yarns containing different proportions of recycled fibers (p_b =0.201). As seen in Table 12, in the statistical analysis of the samples grouped according to different yarn counts, no statistically significant difference was found between the bursting strength values of fabrics knitted from yarns with Ne 20 and Ne 10 yarn counts, respectively (p_b=0.200; p_b=0.093). When Table 13 is examined, it is observed that the bursting strength values of fabrics knitted from recycled yarns are lower than those of fabrics knitted from virgin yarns, both for rib and interlock knit structures. In the statistical analysis performed, it was determined that the difference between the bursting strength values of recycled and virgin fabrics was significant for both rib and interlock knit structures ($p<0.05$). However, in light of the experimental results, it can be stated that recycled fabrics exhibit a bursting strength similar to the fabrics knitted from virgin yarn.

The air permeability of a fabric varies depending on the fibers, yarns, and finishing processes used in its production. The structural parameters of the fabric are also influenced by factors such as environmental conditions, viscosity, raw materials, yarn properties, fabric type, knit structure, fabric thickness, and fabric porosity [45]. When Figure 1 is examined, it can be observed that the air permeability values of rib fabrics are higher than interlock fabrics. This is an expected result due to the dense knit structure and the higher fabric thickness of interlock fabrics [46, 47]. The air permeability values of the fabrics were also found to differ based on their yarn composition. The fabric knitted from Y4 yarn, consisting of 70% recycled cotton and 30% polyester, exhibits the highest air permeability. The closest result is shown by the fabric knitted from Y1 yarn, which contains 50% recycled cotton and 50% polyester. The lowest air permeability values are found in the fabrics knitted from Y2 yarn (60% recycled cotton/ 40% polyester) and Y3 yarn (65% recycled cotton/ 35% polyester). As the yarn hairiness increases, the fabric's air permeability decreases [48]. When the hairiness rates of single-ply yarns (Table 5) are evaluated, it is observed that the experimental results are consistent. Fabrics knitted from yarns with the lowest hairiness values demonstrate the highest air permeability values. On the other hand, the air permeability values of fabrics knitted using two-ply yarn (Ne10) and single-ply yarn (Ne20) are quite different from each other as expected. Particularly for interlock fabrics, there is a significant difference in air permeability values between fabrics knitted from Ne20 yarn and Ne10 yarn. According to the statistical analysis results given in Table 12, no significant difference was found between the air permeability values of rib fabrics with different yarn compositions (p_a=0.340). However, significant differences were observed between the air permeability values of interlock fabrics based on yarn content (p_a =0.020) (Table 12). Statistically significant differences were found between interlock fabrics knitted from yarns with different amounts of recycled fiber content, specifically between Y1-Y2 (p=0.014), Y2-Y4 (p=0.050), and Y1-Y3 (p=0.016) yarns. Furthermore, when the fabrics were grouped according to yarn count, significant differences in air permeability values were found among fabrics knitted from Ne20 count yarns (p=0.019), particularly between Y2 and Y4 coded yarns. Nevertheless, for fabrics knitted from Ne10 yarn, changes in yarn composition do not affect the air permeability of the fabric (p_a =0.974). When the fabric sample knitted from the virgin yarn is compared with the same blend ratio as the recycled yarn coded Y4, it is observed that the rib reference sample exhibits 1.3% lower air permeability than the R4 coded fabric, and the interlock reference sample exhibits 5.94% lower air permeability than the I4 coded fabric (R4 and I4 coded fabrics exhibit the highest air permeability values). In the statistical analysis (Table 13), no significant difference was found between the air permeability of rib fabrics knitted from recycled yarn and virgin yarn (p=0.657). However, the difference between the recycled and reference interlock fabrics is significant (p=0.031). According to the evaluations made regarding the fabrics' air permeability properties, it was observed that the air permeability values of samples knitted from recycled yarn were relatively higher for both rib and interlock fabrics (Table 14). The results of the study conducted by Doba Kadem and Sevgi [7] also support this finding. Therefore, it is believed that using recycled yarns instead of virgin yarns is more appropriate for producing rib and interlock fabrics due to their higher air permeability. When the experimental data obtained from the circular bending rigidity test of the fabrics are examined (Figure 1), it is observed that there is a significant increase in the circular bending rigidity when the fabric structure changes from rib knit structure to interlock knit structure. Similarly, fabrics knitted from Ne20 and Ne10 yarns show different circular bending rigidity values, with Ne10 yarns exhibiting higher stiffness. This is an expected outcome, as both the increased fabric density and thicker yarn contribute to higher circular bending resistance [49]. Within the scope of the study, the experimental data on circular bending rigidity were statistically analyzed according to fabric structures. No significant difference was found between rib (p_c=0.812) and interlock (p_c=0.577) fabrics with varying recycled fiber content (Table 12). Similarly, as a result of the statistical analysis performed according to yarn counts, it was determined that there was no significant difference between the fabric groups containing different proportions of recycled fiber for both Ne10 and Ne20 yarns (p_c =0.666; p_c =0.521). The data obtained from fabrics knitted from recycled yarn with the same blend ratio were also compared with those from the reference fabrics knitted from virgin yarn. According to the experimental results, the circular bending rigidity of the reference fabrics knitted from virgin yarn was found to be relatively higher for both rib and interlock fabrics. According to this result, it could be suggested that fabrics knitted from recycled yarns may be preferred instead of fabrics knitted from virgin yarn in terms of handle properties. However, the statistical analysis shows that this difference is not statistically significant (Table 13).

Table 12. Statistical analysis data of the physical properties of fabrics knitted from recycled yarns

Fabric and yarn parameters		Bursting strength (kPa)		Air permeability (l/m²/s)		Circular bending rigidity (N)		Sig.
		Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	
Rib	R1/R5	298.30	109.17	1581.45	849.14	4.98	1.57	p_b=0.178 p_a=0.340 p_c=0.812
	R2/R6	217.85	88.81	1637.20	663.21	4.59	0.92	
	R3/R7	319.77	106.13	1644.85	645.65	5.27	1.46	
	R4/R8	245.00	97.76	1751.95	774.79	5.55	2.17	
Interlock	I1/I5	440.98	169.88	670.30	420.46	11.87	5.50	p_b= 0.201 **p_a=0.020*** p_c=0.577
	I2/I6	338.03	82.13	519.85	388.45	16.77	11.48	
	I3/I7	179.08	196.36	555.15	437.50	17.22	10.57	
	I4/I8	371.45	119.49	662.45	530.62	16.32	4.37	
Ne20	R1/I1	243.32	48.89	1739.65	689.34	5.26	1.78	p_b= 0.200 **p_a=0.019*** p_c=0.521
	R2/I2	201.90	69.30	1581.35	716.17	5.09	1.46	
	R3/I3	291.58	30.97	1620.40	669.47	5.82	2.02	
	R4/I4	210.27	61.22	1840.00	685.44	5.26	1.78	
Ne10	R5/I5	495.97	110.92	512.10	257.86	11.59	5.82	p_b=0.093 p_a=0.974 p_c=0.666
	R6/I6	353.98	67.95	575.50	450.18	16.27	12.02	
	R7/I7	207.27	227.32	579.60	463.58	16.67	11.17	
	R8/I8	406.18	81.54	574.40	440.17	16.61	10.41	

p_b: p-value for bursting strength
p_a: p-value for air permeability
p_c: p-value circular bending rigidity
*Statistically significant (p<0.05)

Table 13. Comparison of the physical properties of the reference fabric and the recycled yarn fabric

Fabric code	Bursting strength (kPa)		Air permeability (l/m²/s)		Circular bending rigidity (N)		t	Sig.
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.		
R-Ref	175.73	3.44	2470.00	188.92	3.98	0.33	t_b=-3.349	**p_b=0.029***
R4	156.67	9.24	2502.00	120.26	3.65	0.01	t_a=0.452	p_a=0.657
							t_c=-1.77	pc=0.151
I-Ref	332.43	12.20	1112.00	66.63	7.1	0.51	t_b=-4.159	**p_b=0.014***
I4	263.87	25.82	1178.00	59.22	6.87	0.38	t_a=2.341	**pa=0.031***
							t_c=-0.640	pc=0.557

t_b : t-value for bursting strength
t_a: t-value for air permeability
t_c: t-value circular bending rigidity
*Statistically significant (p<0.05)
p_b: p-value for bursting strength
p_a: p-value for air permeability
p_c: p-value circular bending rigidity

The pilling values of fabrics knitted from recycled and virgin yarns are presented in Table 11. According to Table 11, it is observed that the pilling degrees of the fabrics are relatively close to each other, and fabrics knitted from recycled yarns exhibited lower pilling, especially those with an interlock knit structure made from Ne10 yarn. It is known that the fabric's tendency to pill increases as the yarn becomes finer and the fabric density decreases [50]. The finding that fabrics knitted from Ne10 yarn show less pilling compared to those knitted from Ne20 yarn was also reported in the study by Uyanık and Kaya Nacarkahya [51]. When the reference fabrics are compared with the recycled yarn fabrics, it is seen that the reference rib fabric tends to pill less than the fabrics knitted from recycled yarn. In interlock fabrics, although the difference is not as obvious as in rib fabrics, the reference interlock fabric has shown less pilling compared to the recycled yarn fabric. The reason why fabrics knitted from recycled yarns generally tend to show more pilling compared to those made from virgin yarns is due to the low average fiber length and the higher proportion of short fibers in the structure of recycled yarns [52].

4. CONCLUSION

In this study, various physical properties of knitted fabrics made from cotton/polyester blend yarns containing different proportions of recycled cotton fiber were evaluated by comparing them with reference fabrics. Therefore, the focus was initially placed on the yarn properties. In single-ply yarns, as the proportion of recycled fiber increases, the tensile strength of the yarns decreases for Y2 and Y4-coded yarns. However, it was observed that the Y3 yarn with a 65% recycled cotton/ 35% polyester blend exhibited the highest tensile strength. This was attributed to the lower unevenness of the yarn and its low defect rate. The yarns with a 60% recycled cotton/ 40% polyester blend exhibited the lowest strength due to high neps and thick places, which directly affected the fabric's mechanical properties.

When comparing the bursting strength values of fabrics knitted from recycled yarns with reference fabrics, it was found that the reference fabrics made from virgin yarns with the same blend ratio exhibited higher bursting strength. However, the effect of increasing the proportion of recycled fiber in the yarn content on the bursting strength of the fabrics is entirely related to the yarn properties. Fabrics made from yarns with a 65% recycled cotton/ 35% polyester blend exhibited the highest bursting strength values, which were higher than those of the reference fabric made with a 70% cotton/ 30% polyester blend. The findings show that the use of recycled yarns significantly affects fabric properties, and with the proper yarn production process, recycled yarns can perform at least as high performance as fabrics produced from virgin yarns.

It was observed that the air permeability values of fabrics knitted from recycled yarns were generally at similar levels. However, the air permeability value of the fabric made from recycled yarn with the same blend ratio as the reference fabric was found to be higher for both rib and interlock fabrics. This result suggests that recycled yarns can be used in fabrics expected to have high air permeability. Circular bending rigidity values of reference fabrics knitted from virgin yarns are higher than fabrics knitted from recycled yarns, both rib and interlock fabrics. This can be considered as an advantage of recycled yarns in terms of fabric handle properties. Fabric pilling tendency was found to be higher due to the high short fiber content of recycled yarns.

In this study, the yarns used in fabric production were supplied ready-made. Although the use of recycled yarns led to a slight decrease in fabric properties such as bursting strength and pilling compared to virgin yarns, it is clear that these yarns have the potential for sustainable fabric production. The findings of the study indicate that the proportion of recycled fibers in the yarn content can negatively affect the fabric's mechanical performance. However, with the optimal yarn blend and processing methods, recycled yarns can be improved to a level that rivals virgin yarns in terms of quality. At this point, optimizing the proper parameters in the production process of recycled yarns is critical for improving both the yarns' and the fabrics' physical properties. As a result, it can be said that the use of recycled yarns in fabric production, when supported by proper yarn selection and production parameters, can exhibit properties comparable to those of fabrics made from virgin yarns.

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