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Life Cycle Assessment (LCA) of Single Jersey Knitted Fabrics Containing Recycled Cotton Fiber and Fabric Performance

Füsun DOBA KADEM [1,a], **Raziye OZAN** [2,b]

[1]*Cukurova University, Faculty of Engineering, Department of Textile Engineering, Adana, Türkiye*
[2]*Cukurova University, Institute of Natural and Applied Sciences, Department of Textile Engineering, Adana, Türkiye*

[a]***ORCID***: *0000-0002-7764-5910;* [b]***ORCID***: *0000-0003-4070-7679*

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Corresponding Author
Füsun DOBA KADEM
fusunkadem01@gmail.com
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ABSTRACT
This study investigates the life cycle assesment of single jersey knitted fabrics containing recycled cotton and their some performance properties. In the yarn production stage fibers obtained from waste through mechanical recycling (pre-consumer recycle) were used in blends at 10%, 15%, and 20% to produce knitted fabrics. Some performance properties such as fabric stiffness, air permeability, and dimensional change, which are important in the usage properties of jersey knitted fabrics, were compared. Within the scope of the study, the environmental impact of the use of recycled raw materials was evaluated with LCA. According to the Life Cycle Analysis (LCA) results, the use of recycled cotton with contributions ranging from 10% to 20% instead of 100% original cotton demonstrated significant improvements in resource depletion (fossil fuels), global warming, ozone layer depletion, toxic impact on human life, toxic impact on freshwater life, toxic impact on terrestrial life, and total water usage.

Geri Dönüştürülmüş Pamuk Elyafı İçeren Süprem Örme Kumaşların Yaşam Döngüsü Değerlendirmesi ve Kumaş Performansı

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ÖZ
Bu çalışmada geri dönüştürülmüş pamuk içeren süprem örme kumaşların yaşam döngüsü değerlendirmesi yapılmış ve bazı performans özellikleri araştırılmıştır. İplik üretim aşamasında mekanik geri dönüşüm (tüketici öncesi geri dönüşüm) yoluyla atıktan elde edilen lifler %10, %15 ve %20 oranlarında karışım halinde kullanılarak örme kumaşlar üretilmiştir. Süprem örme kumaşların kullanım özelliklerinde önemli olan kumaş sertliği, hava geçirgenliği ve boyut değişimi gibi bazı performans özellikleri karşılaştırılmıştır. Çalışma kapsamında geri dönüştürülmüş hammadde kullanımının çevresel etkisi LCA ile değerlendirilmiştir. Yaşam Döngüsü Analizi (LCA) sonuçlarına göre %100 orijinal pamuk yerine %10 ile %20 arasında değişen katkı oranlarına sahip geri dönüştürülmüş pamuk kullanımı kaynak tükenmesi (fosil yakıtlar), küresel ısınma, ozon tabakasının incelmesi, insan yaşamı üzerindeki toksik etki, tatlı su yaşamı üzerindeki toksik etki, karasal yaşam üzerindeki toksik etki ve toplam su kullanımında önemli iyileştirmeler göstermiştir.

1. INTRODUCTION

The textile industry is one of the sectors with great economic value in the world, but it also has a high environmental impact. Unconscious behaviors in resource use around the world significantly affect economic sectors, especially textiles and clothing. Steps such as choosing reusable products, repairing and reusing products, recyclable product design, using recycled materials, repairing and reusing, and renting can be listed as options to be preferred for resource efficiency in the textile and apparel sector.

In this context, recycling, especially in cotton materials as raw materials in textiles and apparel, has recently gained an important place in the sector with different application stages. If the aim is to add value to the product through high-level recycling, using cotton obtained from pre-consumer/post-consumer waste sources instead of producing cotton from scratch not only ensures the sustainable use of natural resources, but also significantly reduces environmental damage by saving energy and water. When it comes to textile fibers such as cotton, recycling becomes increasingly important when the value of such a valuable material is considered, and obtaining products from 100% recycled fibers becomes important over time.

In this study, in a facility where production wastes generated during yarn production stages are recycled by mechanical methods, knitted fabric yarns were obtained by mixing original cotton fiber with recycled fiber at different rates. With the recycled knitting yarns obtained here, single jersey knitted fabrics were produced at different recycling rates and some performance properties in the use of the fabrics were compared with each other.

In addition, the effect of the use of recycled raw materials was evaluated with life cycle analysis (LCA) within the scope of the study. The improvement values (%) obtained with LCA for the use of recycled fiber instead of 100% cotton were determined. Life Cycle Assessment is a scientific analysis method used to use resources more efficiently and reduce the consumption of natural resources in a sector where inputs such as energy, raw materials, chemicals, water, etc. are intensive, such as the textile and apparel sectors. Life Cycle Assessment - LCA (Life Cycle Assessment) Life cycle assessment is a scientific analysis method used worldwide, defined and standardized in detail in the ISO 14040 series. It is a tool used to calculate the environmental impacts of a product during the stages of obtaining, producing, transporting, using and disposing of its raw materials (throughout its entire life cycle), to identify problematic points in production and to get to the source of problems. Many environmental impacts can be presented with numerical data using computer software specifically prepared for the subject.

2. LITERATURE

Gün et al. [1] examined the dimensional and physical properties of socks produced from recycled fibers. While the effect of fiber type on air permeability was found to be significant, no significant difference was observed in burst strength between recycled fabrics and original fabrics. Recycled fabrics were found to have lower air permeability and higher pilling tendency. In terms of abrasion resistance, recycled fabrics showed lower mass loss in the evaluation through mass loss, and in terms of color resistance, higher color fastness was observed. Although the quality characteristics of yarns obtained from recycled fibers differ from those of original (virgin) yarns, it has been generally concluded that recycled fabrics can be used comfortably without significant loss of quality.

Doba Kadem [2], in an experimental study on the recycling of cotton waste in the denim sector, compared the strength properties of weft and warp of denim fabric produced by blending recycled cotton in the blend with non-recycled denim fabric. As a result of the study, it was stated that denim fabrics with recycled cotton can be used similarly to non-recycled fabrics.

Wanassi et al. [3], obtained mixed yarns by using fibers obtained after the waste yarn recycling process and mixing these fibers with other fibers. Cotton from Mali, Greece, and Brazil, known for its good length properties, was selected to be mixed with recycled fibers. Mixing ratios were prepared in the form of an experimental plan in different proportions up to 100%. Fiber tests were conducted, and fiber properties were determined, including the flexibility index. When the results were examined, it was seen that the blend made with Mali cotton had the most suitable fiber properties for practical use. Additionally, it was found that these blends could be obtained at a lower cost. It was concluded that the increased proportion of recycled fibers in the yarn led to an increase in thin places, thick places, neps, and roughness of the blended yarn.

Doba Kadem and Özdemir [4] compared some comfort features of denim fabric produced using recycled cotton fibers after consumer use with the original cotton denim fabric of the same construction. Cotton yarns from the same blend were used in the fabric production. The fibers obtained from the post-consumer recycling process were mixed into the warp yarn blend at a rate of 20%, and 79% cotton fibers were selected as the reference denim blend. Both fabrics underwent the same finishing processes. The air permeability, bending strength, and dimensional change after washing of the denim fabrics were determined according to standards. According to the results, it was found that the recycling process in question could be effectively used in denim production.

Kertmen et al. [5], evaluated the selected properties of supreme fabrics woven with various blends of cotton and waste cotton, interpreting the impact of recycling on performance characteristics. In this study, Ne 20/1 open-end yarns were produced using 100% original cotton, 95% original + 5% recycled cotton, and 90% original cotton + 10% recycled cotton blends. Performance tests such as burst strength and pilling were applied to the fabrics produced using the yarns, along with some comfort tests. It was found that the burst strength of the fabric woven from 100% original cotton was higher than that of the knitted fabric with recycled fiber content. The tests indicated that the yarn structure had little effect on thermal comfort.

Jamshad et al. [6], conducted a study to evaluate spinning wastes and transform them into value-added products using different fiber blends recovered from different yarn wastes and fabric cutting machines. The goal was to produce open-end yarns from 100% recycled materials. Cost calculations showed that the yarn cost obtained from recycled fibers was cheaper than the reference yarns. HVI tests revealed that yarn waste had better fiber length and uniformity compared to fabric waste. Yarns produced from blended yarn waste were found to have less yarn irregularity and better tensile strength compared to fabric waste blends.

Fidan's study investigates the contribution of the use of organic cotton fiber to the environmental impact of denim fabric, instead of conventional cotton fiber. As a result of this LCA study, all environmental impacts of denim fabric decreased with the use of organic cotton. The LCA application was implemented using Simapro 8.5.2 software. A significant reduction in fresh aquatic ecotoxicity of 96% was achieved compared to the use of conventional cotton. Moreover, in terrestrial ecotoxicity and photochemical oxidation potentials, quite remarkable improvements were gathered with 90% and 57%, respectively. [7]

Doba Kadem and Sevgi [8] conducted a study in which waste material generated during the yarn production stages (such as combing waste, carding waste, and other production waste referred to as pre-consumer waste) was mechanically recycled and blended with original cotton fibers in different proportions to obtain recycled fiber. Knitted yarns with recycled content were produced from these recycled blend yarns, and supreme knitted fabrics were manufactured. Although there was an increase in yarn irregularity, especially as the recycling ratio increased, generally, for all the tested properties, supreme knitted fabrics with 10%, 15%, and 20% recycling ratios showed similar values in terms of air permeability, burst strength, and fabric stiffness. Similar studies conducted previously have also observed that the use of recycled fibers in fabric production is acceptable in terms of performance characteristics. It is suggested that increasing the usage ratio of recycled cotton fiber can contribute significantly to raw material resource conservation without compromising product performance.

In the Doba Kadem study, changes in selected performance properties of fabrics woven in plain weave with different weft densities and different raw materials (cotton, linen and cotton/linen blended) weft yarns were examined and the positive contribution of linen fiber to the fabric was revealed in the study. When evaluated in terms of life cycle analysis, fabrics using 5% linen have 2% better resource depletion, 3% better toxic effect on human life and 1% better effect on freshwater life. When 20% linen is used, resource depletion is 9% better, 10% better effect on terrestrial life, 10% better toxic effect on human life and 9% better effect on freshwater life [9].

Zervent Ünal and Baylak [10] conducted a study on pre-consumer yarn production using fibers obtained through the recycling of indigo-dyed waste yarns used as the weft yarn in denim fabric production. In the study, fibers obtained from recycled indigo-dyed yarns were blended with the blend at a ratio of 30%, and yarn production was carried out. The physical properties of the produced yarns were compared with yarns produced using original cotton fibers of the same number. It was found that the U% and CVm values of the yarns containing pre-consumer fibers were, on average, 1% higher for all yarn numbers, and the increase in irregularity due to the use of recycled fibers was quite low. As a result of the study, it was determined that fibers obtained through the recycling of indigo-dyed yarns, despite a slight increase in irregularity and a loss in strength, could be reused in denim fabric production, which is an essential part of denim fabric manufacturing.

In another paper, within the framework of increasing contributions to sustainable development goals and reducing the water footprint, the sustainable production potential of a factory producing denim fabrics was studied in association with the sustainable development goals. As a result of the evaluations, it emerged as a more dominant view that the factory's contribution to sustainable development goals should be evaluated according to the total production capacity. The sustainability evaluation made according to the total production capacity determined that the factory contributed approximately 12% to Sustainable Development Goal 12 in the period examined, according to both the life cycle assessment and material input per service method. Although there is inconsistency in the life cycle assessment and material input per service method results, it was predicted that there are economic and environmental gain potentials related to Sustainable Development Goals 13, 14, and 15, and the sustainable production potential of the factory can be increased [11].

In Sabır et al.'s study, the life cycle analysis (LCA) of finished fabrics produced as denim and sportswear products from soy protein fiber, an innovative natural fiber, was examined. In the study, 8 different blends consisting of cotton, soy fiber and cotton/soy blend yarns were used in the weft of woven fabrics selected from the denim and sportswear product groups. The soy fiber ratio in the blend was selected as 10%, 30% and 50%, and the other blend material was cotton. Weft yarns were produced in two different yarn counts, Ne10 and Ne16. The warp yarn is the same in all fabrics and is 100% cotton material. Fabrics produced using these yarns were woven as 8 different fabrics, four of which were denim and four were sportswear. Anti-bacterial activity, color fastness and some fabric performance tests were applied to the sample fabrics. It was observed that the soy fiber content did not negatively affect the fastness and performance of the woven fabrics. All fabric samples in the study were analyzed separately for denim and sportswear lines with the Life Cycle Analysis (LCA) study. The best result in the life cycle analysis study of soybean fiber was obtained in fabrics using 90% cotton-10% soybean fiber yarn in the weft for denim fabric and 50% cotton-50% soybean fiber yarn in sportswear fabric production [12].

Karagöl et al.'s study conducted on denim fabrics were produced using weft yarns obtained from mechanically recycled fibers after consumer use, and the breaking strength, tearing strength, thermal resistance, water vapor permeability, air permeability, and fabric stiffness of these fabrics were determined according to the standards and the results were interpreted. With this study, it was aimed to reveal the importance of more environmentally friendly denim fabric production by increasing the recycled fiber ratio, and the impact of denim fabrics on the life cycle in terms of sustainability was evaluated. A life cycle analysis of the recycled denim fabrics was made using the SimaPro software program, and the environmental effects of the production were also revealed. Within the scope of the study, it was observed that the structural properties of the fabrics produced and the composition of recycled cotton used affect the performance and comfort properties of the fabric. The effect of the cotton recycling rate on the recycled denim fabrics was evaluated by LCA (life cycle analysis). As a result of the LCA evaluation, with the use of cotton with a high percentage of recycling additives instead of conventional cotton, as in the reference fabric, resource depletion (fossil fuels), global warming, depletion of the ozone layer, the toxic effect on human, freshwater and terrestrial life, the total water use, and other categories were observed to undergo a significant improvement [13].

In this study, production wastes called pre-consumer in yarn production stages were recycled by mechanical method and recycled fiber was obtained by mixing with original cotton fiber in different ratios. Single jersey knitted fabrics were produced with the recycled knitting yarns obtained from here at different recycling ratios and some performance properties were compared in the use of fabrics. In addition, the effect of using recycled raw materials was evaluated with LCA within the scope of the study. The improvement values (%) obtained with LCA for the use of recycled fiber instead of 100% cotton were determined.

3. MATERIAL AND METHOD

In the study, single jersey knitted fabrics were produced with Ne 20/1 open-end yarns, which are obtained by mixing recycled cotton fiber with original cotton fiber. Knitted fabrics were obtained by mixing the cotton fiber obtained from the recycling process into the pure cotton mixture at the rates of 10% (90% virgin cotton), 15% (85% virgin cotton) and 20% (80% virgin cotton). The properties of the recycled blended yarns used in the study are given in Table 1.

When Table 1 is evaluated in general, it can be said that as the recycling rate increases, yarn evenness and some yarn defects (thin place, thick place, neps) increase, but yarn strength (Rkm) value is not adversely affected.

Table 1. The properties of the recycled blended yarns

Properties of yarns	Samples			
	100 % virgin cotton (reference)	10% recycled cotton 90% virgin cotton	15% recycled cotton 85% virgin cotton	20% recycled cotton 80% virgin cotton
Rkm	10,74	10,65	10,57	10,04
% U	10,45	10,49	10,88	11,12
% CVm	13.17	13,21	13,7	14,01
Breaking elongation (%)	3,56	3,59	3,79	3,43
Thin places (-50)	3,2	3,5	6	8
Thick places (+50)	12,5	12	31,5	29
Neps (+280) (sayı/km)	0,46	0,5	6	8
Hairiness (H)	4,75	5	5,31	5,15

Single jersey fabrics were produced on a Pilotelli circular knitting machine (Pus/Fein 32/22 inch). Since the fabrics are knitted fabrics, they were kept in laboratory conditions (at 20º C and 65% relative humidity) for at least 48 hours since there would be a size change after leaving the knitting machine. The tests were carried out in a conditioned laboratory environment in accordance with the standards. In this way, before starting the test measurements, the treatment was done with a rested fabric.

Table 2. Structural properties of knitted fabrics

Structural properties	Knitted fabric cotton blend ratio			
	Reference (RS)	10% recycled	15% recycled	20% recycled
Course/cm	17,00	16,40	16,80	16,40
Wale/cm	12,00	11,40	11,00	10,80
Stitch density (wpc*cpc)	204	186,96	184,8	177,12
Loop shape factor (cpc/wpc)	1,41	1,43	1,52	1,51

The structural properties of the knitted fabrics obtained from the yarns were measured in accordance with the standards. The results with the structural properties are given in Table 2. The fabrics were tested before and after home washing.

Loop line and bar count were determined according to TS EN 14971 standard [14], weight (mass per unit area) was determined according to TS 251 [15], fabric thickness was carried out according to TS 7128 EN ISO 5084 [16], air permeability was determined according to TS 391 EN ISO 9237 standard [17], fabric hardness was carried out according to ASTM D 4032-94 standard [18], and dimensional change after washing was performed according to TS EN ISO 5077 standard [19] respectively.

4. RESULTS AND DISCUSSION

The fabric weight values of the reference and recycled cotton-added fabrics before and after washing are given in Figure 1, and the fabric thickness results are given in Figure 2. The loop structures of the fabrics approaching each other after washing (gathering of the fabric) caused an increase in grammage and fabric thickness.

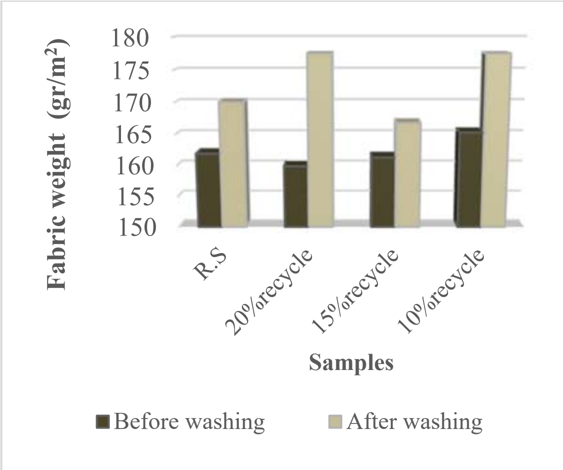

Figure 1. Fabric weight of reference fabric and recycled cotton fabrics

Spirality, which is determined as the deviation value of the angle between the loop row and the loop column from 90 degrees, is an undesirable situation in the fabric and the maximum acceptable value in knitted fabrics is 5 [8]. Figure 3 shows that the spirality before and after washing is within the acceptable limit.

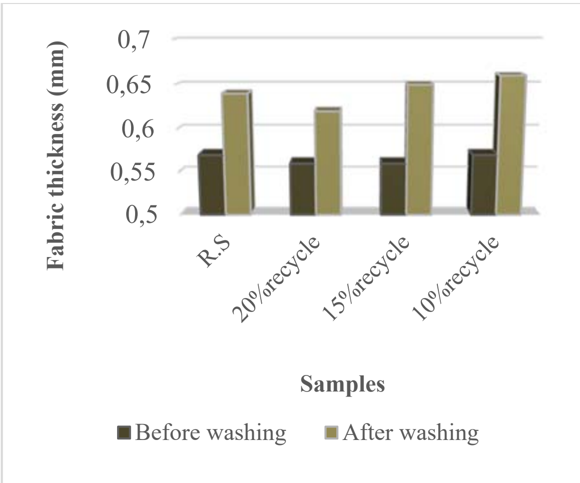

Figure 2. Fabric thickness of reference fabric and recycled cotton fabrics

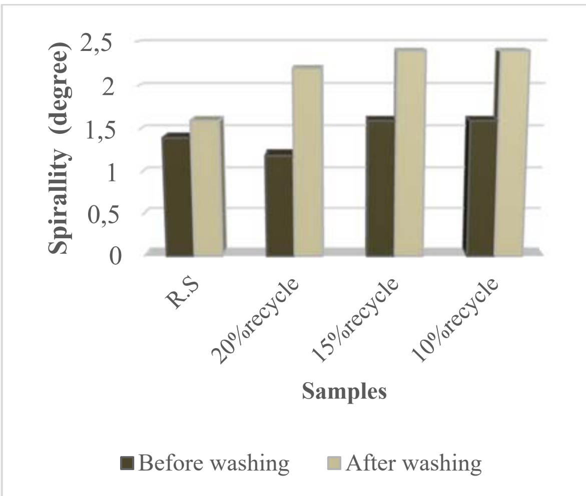

Figure 3. Fabric spirality of reference fabric and recycled cotton fabrics

In addition to the difference in the recycling rates of knitted fabrics, it was observed that the spirality results were close to each other due to the similarity of features such as knitting structure (serial jersey knitting), yarn twist (the twist of the fabrics is 680 t/m), loop density and rod density effective in warp rotation. In order for this value not to be high, knitting in balanced knitting structures (e.g. 1x1 rib) is generally preferred.

Figure 4 shows the dimensional changes in the transverse and longitudinal directions of knitted fabrics after washing.

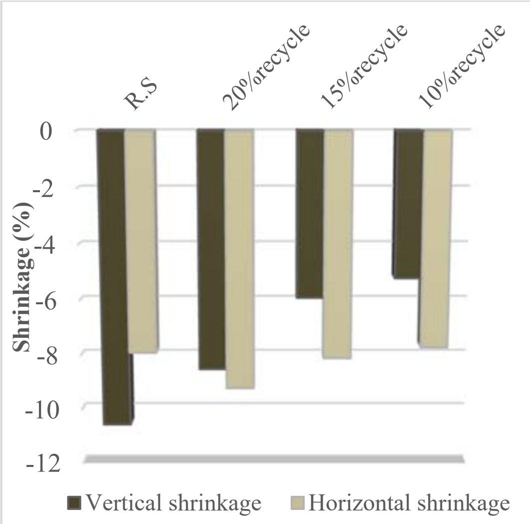

Figure 4. Fabric shrinkage of reference fabric and recycled cotton fabrics

When the test results were evaluated as fabric stiffness (Figure 5), when three fabrics with recycled cotton additives were evaluated together, the handle of the knitted fabric with 10% recycled cotton additive was determined to be harder than the others. As the recycling rate increased, it was observed that the handle of the fabric was softer both before and after washing. The fact that the frequency of the 10% recycled knitted fabric was higher than the others and that it was thicker caused the stiffness value of this fabric, which has a higher grammage, to be higher. This is an expected situation.

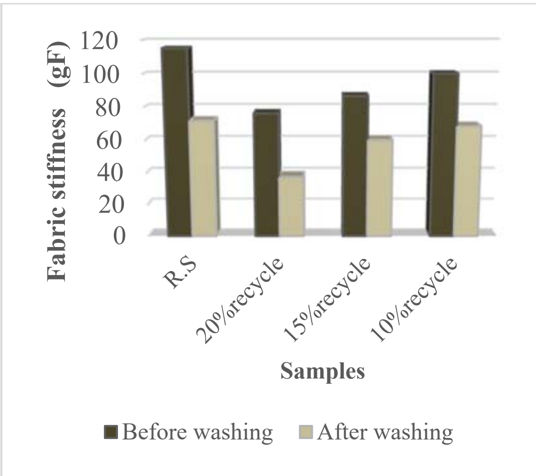

Figure 5. Fabric stiffness of reference fabric and recycled cotton fabrics

It is seen in Figure 6 that air permeability in knitted fabrics is higher in 100% cotton fabric (R.S.). Considering the fact that the effect of fiber type on air permeability is important, since the fabrics tested in the study were cotton and recycled cotton additives, since the fiber type was the same, no negative difference was observed between the fabrics in terms of the effect of recycled cotton additive on air permeability.

However, it is thought that recycled fabrics have a more porous structure than the original fabric and this situation has a slightly increasing effect on air permeability, especially after washing.

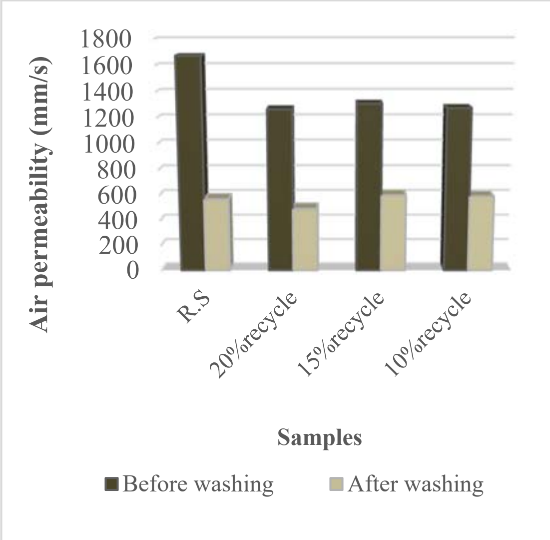

Figure 6. Fabric air permeability of reference fabric and recycled cotton fabrics

LCA Evaluation Results:

Simapro software is used when performing LCA to determine, report and control the environmental impacts of a product or service at each stage of its life cycle, from raw materials to the disposal of waste generated as a result of production. All production inventories were collected in order to enter data in the life cycle analysis. As a result of inventory analysis, a list was categorized based on environment (air, water, soil) or process emerges. Accordingly, the environmental impacts calculated in the life cycle assessment were determined and interpreted for the reference suprem fabric and recycled cottonadded suprem fabric. Life cycle analysis (LCA) of the suprem fabrics obtained was made with SimaPro software (2018, vers. 8.5.2.2.), and as a result of the LCA evaluation, the effect of the use of cotton with a high percentage of recycling additives instead of the original cotton, as in the reference fabric, on resource depletion (fossil fuels), global warming, depletion of the ozone layer, the toxic effect on human, freshwater, and terrestrial life, total water use and other categories was revealed (Table 3).

Table 3. Comparison of LCA Results for single jersey fabrics [20]

Impact category	**Improvement (%) of LCA results**		
	80% cotton +20% recycled cotton	%85 cotton +%15 recycled cotton	%90 cotton +%10 recycled cotton
Abiotic depletion (kg Sb eq)	14,92	11,19	7,46
Abiotic depletion (fossil fuels) (MJ)	1,10	0,83	0,55
Global warming (GWP100a) (kg CO2 eq)	2,56	1,92	1,28
Ozone layer depletion (ODP) (kg CFC-11 eq)	6,93	5,19	3,46
Human toxicity (kg 1,4-DB eq)	4,18	3,13	2,09
Freshwater toxicity (kg 1,4-DB eq)	17,6	13,2	8,8
Terrestrial ecotoxicity (kg 1,4-DB eq)	19,8	14,85	9,90
Total Water Use	13,85	10,39	6,92

According to the Life Cycle Analysis (LCA) results, the use of recycled cotton with contributions ranging from 10% to 20% instead of 100% original cotton demonstrated significant improvements in resource depletion (fossil fuels), global warming, ozone layer depletion, toxic impact on human life, toxic impact on freshwater life, toxic impact on terrestrial life, and total water usage, as shown in Table 3. In the life cycle analysis, it was observed that the use of pre-consumer recycled yarn in fabrics produced with 20% recycled fiber resulted in a 14.92% improvement in resource depletion, 2.56% in global warming, 6.93% in ozone layer depletion, 17.6% in toxic impact on freshwater life, 19.8% in toxic impact on terrestrial life, and 13.85% in total water usage.

5. CONCLUSION

As is known, the recycling process of cotton begins with appropriate classification. At this stage, pre-consumption wastes within the enterprise and post-consumption wastes outside the enterprise can be used. Pre-consumption wastes are formed during yarn production, weaving, knitting, finishing, sewing or quality control stages. A classification is made according to the quality and color of the incoming wastes. In this classification, different criteria such as the structure of the waste (yarn count, production method, fabric weight, etc.), raw material, size and color are used. The quality of the fibers obtained as a result of the recycling process is closely related to the properties of the waste material [21]. There are different results in the literature on how the type and ratio of raw material for recycled cotton fiber is reflected in the recycled fiber-added fabric.

In this study, it was planned to evaluate the usability of single jersey knitted fabrics produced from mechanically recycled raw materials in apparel production in terms of fabric performance properties. In the study, the knit structure widely preferred in apparel fabrics was selected. These fabrics were produced under controlled operating conditions and subjected to certain tests according to standards and the results (fabric shrinkage, spirallity, fabric stiffness and air permeability) were evaluated. When the obtained test results were compared with the reference fabrics, it was seen that increasing the recycling rate did not significantly reduce the fabric quality in terms of performance properties. In addition, LCA evaluation was made and the obtained results showed that the use of recycled cotton containing additives provided significant improvements compared to the use of 100% original cotton in terms of resource depletion (fossil fuels), global warming, ozone layer depletion, toxic effects on human life, toxic effects on freshwater life, toxic effects on terrestrial life and total water use.

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