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Effect of Reprocess on the Sustainability of T-Shirt Production

İşlem Tekrarının T-Shirt Üretiminde Sürdürülebilirliğe Etkisi

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Araştırma Makalesi / Research Article

EFFECT OF REPROCESS ON THE SUSTAINABILITY OF T-SHIRT PRODUCTION

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ABSTRACT: Additional processing steps in textile manufacturing such as reprocess in finishing department have severe unforeseen effects on sustainability. Here, we present a Life Cycle Assessment cradle-to-gate analysis of 100% cotton and 50% cotton/50% polyester T-shirts with and without reprocess. In the assessment, the functional unit is Medium (M) size short-sleeve polo necked T-shirt. Results showed that water footprint of fibre production, the global warming and abiotic depletion potential of the manufacturing step are the major factors that increase the environmental impacts. In 100% cotton T-shirt manufacturing, removing reprocess decreased the acidification, eutrophication potential, and water scarcity footprint. In the raw material (chemicals) step of cotton/polyester T-shirt production, the reprocess significantly increased the ozone layer depletion and abiotic depletion potential. Results suggest that reducing/eliminating reprocess in finishing department could decrease the environmental impact of apparel production by minimizing the use of chemicals, water, and energy.

Keywords*:* cotton t-shirt, cotton/polyester t-shirt, life cycle assessment, finishing, sustainability

İŞLEM TEKRARININ T-SHİRT ÜRETİMİNDE SÜRDÜRÜLEBİLİRLİĞE ETKİSİ

ÖZ: Tekstil imalatında ek işlemler, örneğin terbiye işletmesindeki işlem tekrarları, sürdürülebilirlik üzerinde öngörülemeyen ciddi etkilere sahiptir. Bu çalışmada işlem tekrarı yapılan ve yapılmayan %100 pamuk ve %50 pamuk/%50 polyester T-shirtlerin, beşikten kapıya (cradle-to-gate) Yaşam Döngüsü Değerlendirme analizi yapılmıştır. Değerlendirmede fonksiyonel birim orta (M) beden kısa kollu polo yaka T-shirt olarak seçilmiştir. Çalışma sonuçları, lif üretiminin su ayak izi, konfeksiyon üretiminin küresel ısınma ve abiyotik tükenme potansiyelinin çevresel etkileri artıran başlıca faktörler olduğunu göstermiştir. %100 pamuklu T-shirt üretiminde, işlem tekrarı gerçekleşmediğinde, asidifikasyon, ötrofikasyon potansiyeli ve su kıtlığı ayak izinde azalma sağlanmıştır. Pamuk/polyester T-shirt üretiminin hammadde (kimyasallar) aşaması değerlendirildiğinde, işlem tekrarının, ozon tabakasının incelmesi ve abiyotik tükenme potansiyelini önemli ölçüde arttırdığı görülmüştür. Sonuçlar, yaş işlem tekrarının azaltılmasının/elimine edilmesinin, giysi üretiminin çevresel etkisini, kimyasal, su ve enerji kullanımını en aza indirerek, azaltabileceğini göstermektedir.

Anahtar kelimeler: pamuk T-shirt, pamuk/poliester T-shirt, yaşam döngüsü analizi, terbiye, sürdürülebilirlik

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1. INTRODUCTION

Textiles and clothing play an important role in the manufacturing industry. Over the last years, global fibre production has almost doubled from 58 million tonnes in 2000 to 109 million tonnes in 2020 [1]. Nonetheless, textile industry is a major contributor to environmental pollution and scarcity. It releases a variety of pollutants, including pesticides/solvents during fibre production, industrial chemicals during finishing and also textile fibres (microplastics) itself into oceans during the use phase [2-4]. Regardless of raw material type, natural or synthetic, textiles pose risk to freshwater environments such as rivers and lakes [5]. As the demand for clothing increases alongside 'fast fashion', so do the environmental effects arise from raw material/garment manufacture, use phase and disposal of textiles [6]. Thus, it is essential to control the whole process considering the present hazardous practices and the consumer concern which is the key driver of the industry. Life Cycle Assessment (LCA) is a technique that evaluates the environmental impact of a product over its lifecycle, including all steps from raw material extraction to end-use. The analysis involves different stages such as a full assessment of the product (cradle-to-grave) or a partial life cycle from manufacture to factory gate (cradle-to-gate)[7, 8]. The LCA studies on textile industry mainly focused on analysing the impact of fundamental processing parameters such as raw material production [9, 10]. In these studies, finishing is considered as a single repeat step unlike the real processing conditions [11-13].

The number of textile production steps mainly varies depending on the fibre source, fabric type/quality and as well as complexity of the end product. For instance, from the cradle-to-gate perspective of cotton knitted T-shirt production, ginning, spinning, knitting, finishing, garment production and sales are the main manufacturing steps [14]. LCA studies on textiles produced from cotton fibre alone or in blends with other fibres are important to understand the environmental impacts of production steps in fibre production, garment manufacturing and also use of products so that new alternative routes can be developed to enhance the sustainability of textiles [15, 16]. However, in textile manufacturing, there are severe effects of additional process steps on sustainability, such as reprocess in finishing department (dyeing & finishing) that are unforeseen but meantime can be improved.

Textile manufacturing requires consistency on product properties to satisfy the ever-growing demands in terms of quality, variety and other technical requirements. Therefore, in the context of quality assurance, fibres, yarns, fabrics, garments and accessories are assessed for quality during production and also with a final inspection after packaging [17]. In terms of fabric quality control, reprocess occurs following the finishing due to fabric dyeing faults such as colour, shade variation (batch to batch), stains and dye spots [18, 19]. Pre-treatment (bleaching), colouring (dyeing and printing) and finishing are the main steps of fabric wet processing. In the LCA studies of the textile industry, dyeing & finishing processes were reported as the highest contributor to environmental impacts [20]. It is also reported that polyester–cotton fabric printing & dyeing has high environmental impacts on marine aquatic ecotoxicity potential, global warming potential and abiotic depletion elements and system-oriented improved production designs can help to reduce the environmental impacts of the current production [21]. Each step of textile finishing involves a high amount of chemicals (dyes, pigments, surfactants, etc.) and water usage [22, 23]. Therefore, reprocess contributes to an increase in water, chemical and energy consumption resulting in higher/additional environmental load of textile garments.

The present study aimed to investigate the environmental implications of reducing the reprocess in finishing department during manufacturing. In the study, the reprocess of fabrics only due to the colour faults that don't meet the customer demand was considered. Since the goal of the study is to provide textile manufacturers, retailers and consumers the environmental impact of reprocess, the output of the calculations is presented only in the form of percentage.

2. METHODOLOGY-LIFE CYCLE ASSESSMENT (LCA)

The goal of the study was the environmental evaluation of processing steps for T-shirt production using cotton and polyester (polyethylene terephthalate (PET)) fibres, through a comprehensive analysis including all relevant processes needed from a cradle-to-gate perspective. This study uses the LCA methodology based on 14040/14044 standards created by the International Organization for Standardization (ISO).

2.1. System boundary and functional unit

Life cycle processes included in the analysis and system boundaries are illustrated in Figure 1. Upstream Processes (A1: Raw Material Supply), Core Processes (A2: Transportation and A3: Manufacturing), Downstream Processes (A4: Distribution). Within the system boundaries, the production steps prior to garment manufacturing are also discussed to show the particular impact of T-shirt manufacturing (cut-make-trim) in the textile company. In this context; P1 covers the raw materials (fibres and yarns), raw material transportation, knitting and finishing of fabrics, P2 covers the cut-make-trim (CMT) and garment transportation.

Transportation of raw materials (fibres and fabrics) and garments (T-shirts) for the production step with and without reprocess in finishing department was also considered and discussed. Transport of chemicals and other materials and all the aspects related to the selling, usage and final disposal were not taken into account. Four different life cycle analyses were carried out: 100% cotton and 50% cotton/ 50% PET knitted (circular knitting) and dyed short-sleeve polo necked T-shirts are chosen as the declared unit, as shown in Table 1. In the assessment, the functional unit is Ne 30/1 Medium (M) size short sleeve polo necked T-shirt (323 gr). Following the fabric knitting, bleaching, dyeing (dark colour) and enzyme washing & softening were applied. In the assessment, the reprocess in finishing department, only due to the fabric colour faults that do not meet the customer demand, was considered. It should be noted that, reprocess in scenario II and IV covers only the dyeing and softening (Table 1).

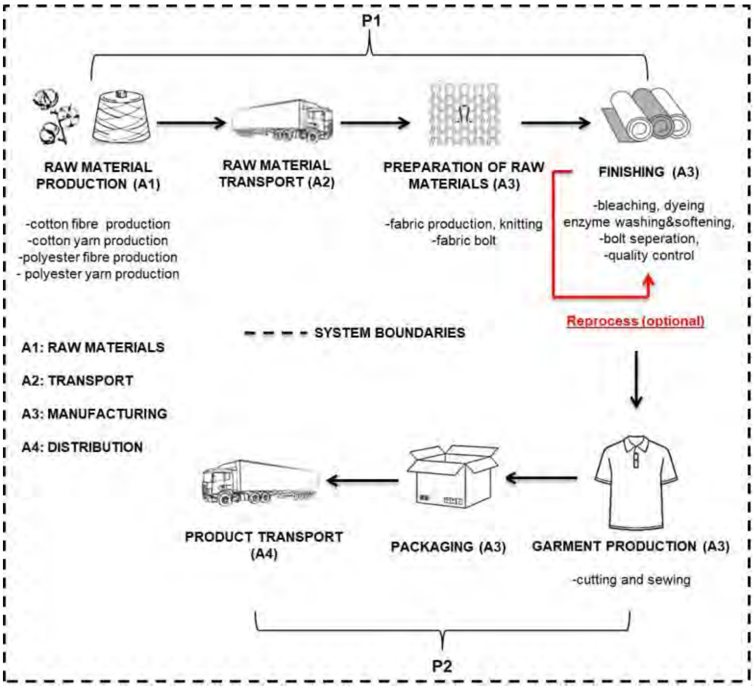

Figure 1. Life cycle system boundaries of the selected 100% cotton and 50% cotton/ 50% PET T-shirts

Table 1. Life cycle scenarios for short sleeve 100% cotton and 50% cotton/ 50% PET T-shirts.

Scenario	I	II	III	IV
Product	Polo neck T-shirt	Polo neck T-shirt	Polo neck T-shirt	Polo neck T-shirt
Raw material	100% cotton	100% cotton	50% cotton/50% PET	50% cotton/50% PET
Fabric quality control	approved	reprocess	approved	reprocess

Developed scenarios were grouped into two key themes representing main changes in T-shirt manufacturing; changes in raw material selection and reprocess of fabrics following the quality control (Table 1). The implications of these differences are discovered and measured for each scenario in accordance with the life cycle assessment perspective.

2.1.1. Life cycle of 100% cotton and 50% cotton/ 50% PET T-shirt production

The production steps of 100% cotton and 50% cotton/ 50% PET T-shirts are similar, as indicated in Figure 2. The differences mainly lay in spinning and finishing since PET is a melt-spun synthetic fibre and cotton is a natural fibre.

In cotton fibre production, following the cotton cultivation, ginning, separating lint fibre from cottonseed, is applied [24]. Thus, PET fibres are produced by melt-spinning technique [25]. In the present study, 50% cotton/50%PET raw yarn blend was prepared through yarn blending following the spinning of fibres. Circular knitting technique was used in fabric formation resulting in a flexible structure.

In textile manufacturing, fabric finishing improves the appearance and durability of fabrics [26]. Dyeing is performed to give a uniform and permanent colour to fabric in line with customer demand. Wet processing recipes presented in the study differ in dyeing processes; single-bath dyeing for 100% cotton circular knitted fabric and double-bath dyeing for 50% cotton/50%PET circular knitted fabric was applied. From fashion point of view, it is essential to have the same type of cut, quality, and colour to maintain the integrity of a brand. For this purpose, in the study, following the visual observation of dyed/finished fabrics, to ensure consistent colour throughout different batches, a precise measuring equipment spectrophotometer was also used. After quality control, fabrics are either sent to cut-make-trim or back to the plant for reprocess of fabrics. The participant apparel company reports show that monthly repair of circular knitted fabrics of the study due to colour inconsistency is between 3-4%. In the final step of the 100% cotton and 50%cotton/50% PET T-shirt production, approved fabrics are sent to the apparel company for cut-make-trim.

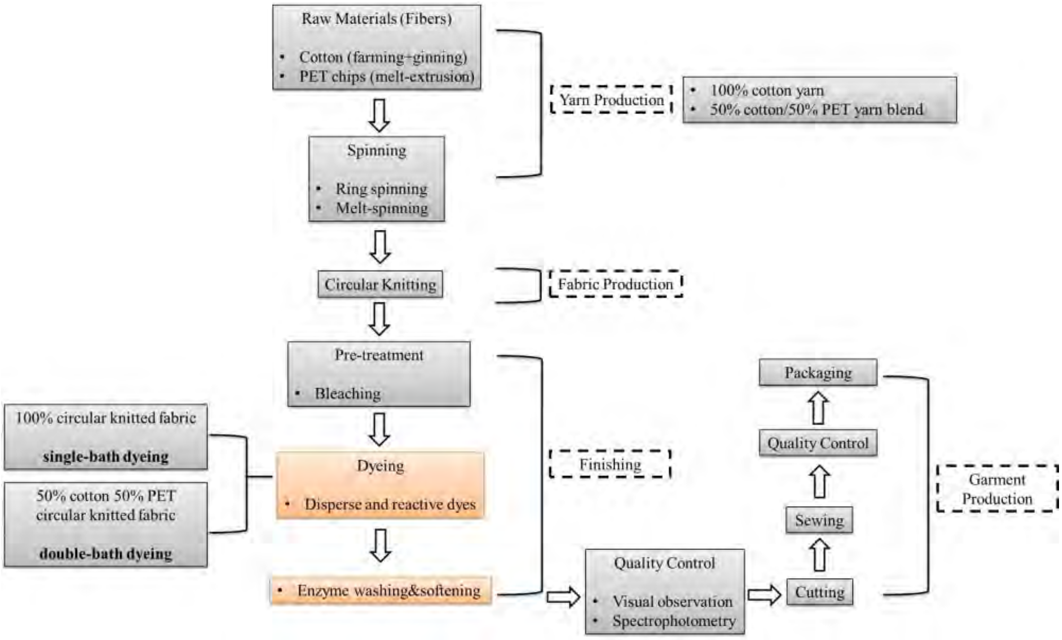

Figure 2. Production steps of 100% cotton and 50% cotton/ 50% PET T-shirts

2.2. Inventory analyses

Life cycle impacts were calculated using the CML-IA baseline and non-baseline, ReCiPe 2008 method, AWARE Method and Water Use Calculator (developed by Metsims) methodology and the system modelling is performed in SimaPro 7.1.8 (LCA software tool). The data used in this study are primary and secondary. Primary data are collected directly from the garment manufacturer including cut-make-trim (A3), packaging (A3) and transportation (A4). For the rest of the steps in the system boundaries, data from the last Ecoinvent database (version: 3.5) available for SimaPro was used as secondary data. Except for the environmental impacts arising from the upper supply chain of raw material production all production data was collected from the company production lines. Raw material production data were taken from the Ecoinvent database. The study addresses the following environmental impact categories: acidification potential (AP) (fate not included, kg SO_2 eq), eutrophication potential (EP) (kg PO_4 eq), global warming potential (GWP) (100a, kg CO_2 eq)), photochemical oxidation (PO) (kg NMVOC), abiotic depletion potential (ADP) (elements, kg Sb eq), abiotic depletion potential (ADP) (fossil fuels, MJ), water scarcity (m^3 eq), ozone layer depletion potential (ODP) (kg CFC-11 eq) and water footprint (USE, m^3). CML-IA baseline and non-baseline were used in ADP (elements), ADP (fossil fuels), GWP, ODP, PO, AP and EP calculation whereas AWARE Method in water scarcity and Water Use Calculator (developed by Metsims) in water footprint calculation. From ReCiPe 2008, formation potential of tropospheric ozone photochemical oxidants with time span of 5 days was taken. Since the goal of the study is to provide textile manufacturers, retailers and consumers the environmental impact of reprocessing, the output of the calculations is presented only in the form of percentage.

<u>*Transport*</u>

Transport is included in the study based on rough estimates of average transport distances and mode of transportation. Transport data were taken from Ecoinvent (version: 3.5) providing the respective quantities in ton. The cotton yarn is produced in Gaziantep/Turkey and cotton/PET yarn is in Vietnam. The raw materials were transported to Çerkezköy, Tekirdağ/Turkey for knitted fabric production and finishing. Following the finishing, fabrics were sent to Lüleburgaz/Turkey for cutting and then to Alpullu, İstanbul/Turkey for final garment production. After production T-shirts were exported to Germany.

3. RESULTS AND DISCUSSION

This section presents the cradle-to-gate results of knitted polo neck T-shirts made of different raw materials (100% cotton and 50% cotton/50% PET blend). A comparison is made through manufacturing steps with and without reprocess of the knitted fabrics following the quality control of finishing. The raw material impact is also discussed. LCA analysis results of four different scenarios were reported for the environmental impact categories namely, AP, EP, GWP, PO, ADP (elements), ADP (fossil fuels), ODP, water scarcity and water footprint (USE).

From a cradle-to-gate perspective, the life cycle stages of a textile garment can vary depending on the raw material type, fabric production and also garment manufacturing which covers the modelling, cutting, sewing, ironing and packaging of the goods [27]. Apart from fibre production, the differences mainly lay in the finishing of the fabrics to meet performance standards and customer expectations. The wet-processing of fabrics are water and energy-intensive and also requires a variety of chemicals [12, 28]. In the wet-processing of knitted fabrics, pre-treatment (scouring, bleaching etc.), coloration and finishing are the main steps and differ depending on the fibre type [29, 30].

Additionally, in textile manufacturing, there are iterative process steps such as reprocess of dyeing and/or finishing of fabrics. Namely, reprocess following the quality control before garment production includes stain removal, colour/abrage correction, fastness and fabric hand improvement. These additional processes are driven directly by the client and/or client representatives in the companies.

Cotton, a natural plant fibre, has a variety of applications in apparel textiles and is widely used to produce men's and women's outerwear, innerwear, socks and baby/newborn clothes due to its biocompatibility, thermal and tactile comfort [31-33]. Figure 3 presents the relative contributions of system boundary steps to each impact category for 100% cotton T-shirts with and without reprocess of the knitted fabric. The water footprint, water scarcity and ODP were higher for cotton fibre production (A1). For both scenarios I and II, the contribution of transportation and distribution was below 4% in all environmental impact categories. The highest contribution of AP was 48.42% and 43.75% for A1 (raw materials fibre) and A3 manufacturing, respectively.

In cotton T-shirt production, ammonia emission resulting from fertilizers of conventional cotton production, steam for heating and electricity consumption for manufacturing steps are the main sources of the AP impact [34, 35]. Accordingly, the highest ADP mainly forms in fabric manufacturing, yarn production and manufacturing due to high electric consumption [36]. In terms of GWP, PO and ADP (fossil fuels), the added contributions to environmental impacts in 100% cotton T-shirt production (scenario I and II) are significantly caused by the manufacturing step. Similarly, it is reported that, in %100 cotton T-shirt production, making-up of T-shirt is one of the dominant contributors to the ADP (fossil fuels) and GWP and this burden is related to electricity and steam use [37] The ADP refers to the depletion of non-renewable abiotic (non-living) resources (fossil fuels, minerals, etc.) and is caused by the consumption of non-renewable resources such as natural gas, crude oil, and minerals. In terms of fossil fuel depletion, the highest input for the depletion of natural resources is electric consumption [38, 39].

The results show that, in scenario II, the reprocess increased the impact share of the manufacturing process (A3) in AP, EP and water footprint by 4.2%, 10% and 61%, respectively. This significant increase in the EP –the negative impacts on terrestrial and aquatic environments due to excess supply of nutrients- is occurred by the polluting potential of wet processing that can be improved with the elimination of additional chemical usage. In line with reduced reprocessing, green dyeing of fabrics has also a positive impact to decrease energy, water and chemical consumption [34]. Additionally, the environmental impact of the dyeing and finishing process is closely associated with the dyeing method, equipment and chemical quantity [12]. It is also reported that the re-design of dyeing/finishing of knitted fabrics saves energy and water by reducing process temperatures and avoiding some of the baths [40]. The contributions (%) to each impact category for 100% cotton T-shirt, scenario I and II are given in Table 2. The reprocessing of fabrics also caused a notable increase in the ADP (both elements and fuels) resulting from raw materials (chemicals) due to the additional consumption of chemicals during finishing and energy consumption of repeated processes. Thus, the major impacts of raw materials (chemicals) (A1) in scenario II are ADP (elements) (49.81%), ODP (26.81%) and ADP (fossil fuels) (15.78%).

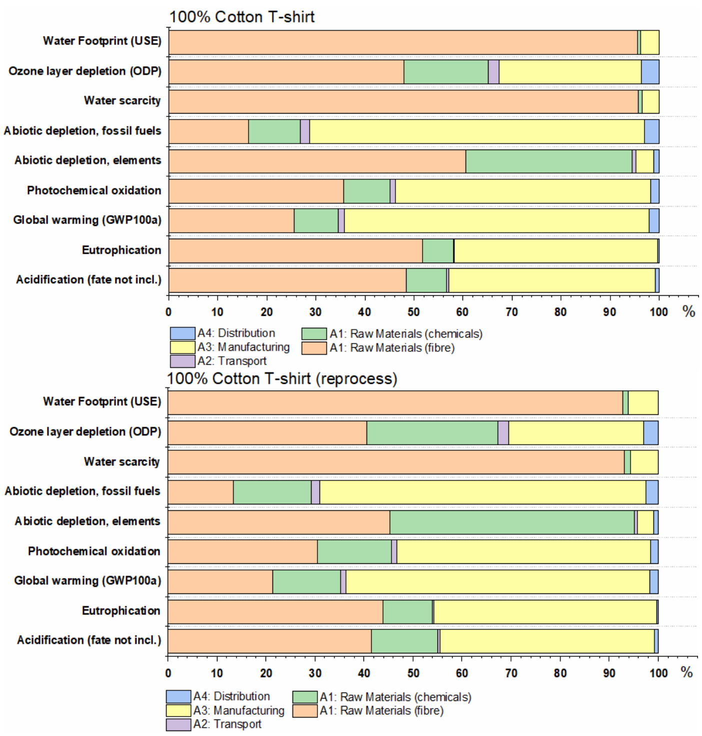

Figure 3. Relative contributions to each impact category for 100% cotton T-shirts with and without reprocess, scenario I and II

Table 2. The contributions (%) to each impact category for 100% cotton T-shirt, scenario I and II

Impact category	**A1*		***A1*		*A2*		*A3*		*A4*	
	I	**II**	**I**	**II**	**I**	**II**	**I**	**II**	**I**	**II**
Acidification (fate not incl.)	48.42	41.59	8.21	13.44	0.53	0.50	42.00	43.75	0.85	0.73
Eutrophication	51.67	43.85	6.33	10.09	0.25	0.23	41.35	45.49	0.40	0.34
Global warming (GWP100a)	25.63	21.42	8.85	13.80	1.27	1.17	62.23	61.91	2.02	1.69
Photochemical oxidation	35.65	30.50	9.46	15.17	1.12	1.06	51.98	51.74	1.79	1.53
Abiotic depletion, elements	60.57	45.28	33.94	49.81	0.72	0.59	3.62	3.45	1.15	0.86
Abiotic depletion, fossil fuels	16.31	13.44	10.49	15.78	1.93	1.76	68.19	66.49	3.08	2.54
Water scarcity	95.73	93.05	0.75	1.35	0.01	0.01	3.49	5.57	0.02	0.02
Ozone layer depletion	47.98	40.54	17.11	26.81	2.23	2.08	29.13	27.56	3.56	3.00
Water Footprint (USE)	95.57	92.75	0.62	1.16	0.02	0.02	3.75	6.04	0.03	0.03

In the textile industry, raw material selection significantly affects the water footprint and GWP and each fibre has its own sustainability challenges in the production process. The large concern attributed to large quantities of water and pesticides required for growing cotton has lead the cotton producer countries to adopt alternative cropping methods such as organic cotton (reduction in fertilizer use and water) which provides a lower yield but also a lower environmental load [2, 41]. Besides, consumers increasingly prefer sustainable brands and raw materials [42, 43]. Alternatively, fibre blends may also serve as an eco-friendly raw material.

Polyester is the world's major man-made fibre for textiles and industrial applications. It is manufactured from non-renewable resources and its production is one of the most energy-intensive, requiring more energy than cotton [44]. On the other hand, depending on its structural properties it has a longer service life than natural fibres and uses comparatively less water [31]. According to Velden et.al, processes starting from raw material extraction to manufactured textile from polyester comparatively has the least impact on the environment in comparison with cotton, nylon and acrylic Besides, the yarn number plays an important role in the environmental burden of yarn production [45].

According to the LCA results of scenario III, in all impact categories, the main contributor is fibre production. Considering the A1 raw material (fibre) impact, water scarcity decreased from 95.73% to 90.62% and water footprint from 95.57% to 93.03% compared to 100 cotton T-shirt production (Table 2 and Table 3). Nevertheless, GWP showed an incline from 25.63% to 45.06% and ADP (fossil fuels) from 16.31% to 47.00%, due to the high energy consumption of polyester fibre production. Comparably, it is revealed that, in % 100 PES T-shirt production, polyester fibre production is the first and yarn production is the second largest contributor of GWP [46]. GWP is the measure of the atmospheric concentration of greenhouse gases in units of kilograms of carbon dioxide equivalent. In scenarios III and IV, the manufacturing step (A3) covers almost half of the contributions for AP, EP, GWP, PO and ADP (fossil fuels) in which the raw material production (A1) shares the rest over 40%. In both scenarios, water scarcity and water footprint were profound (over 85%) for the raw material (fibre) due to the high water demand of fibre production. The relative contributions to each impact category for 50% cotton/50% PET T-shirts with and without reprocess were given in Figure 4.

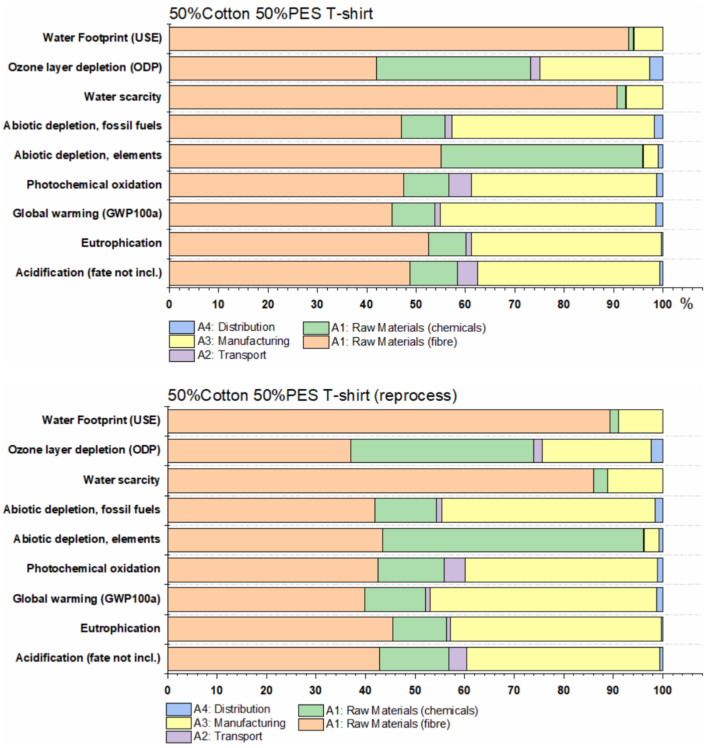

Figure 4. Relative contributions to each impact category for 50% cotton/50% polyester T-shirts with and without reprocess, scenario III and IV

In the 50% cotton/50% PET T-shirt production, the reprocess increased the ODP from 31.18% to 37.01% and the ADP (elements) from 40.90% to 52.62% in step A1 raw materials (chemicals). This increase originated from chemicals is due to the additional consumption of dye stuffs/finishing agents during reprocess (Table 3). Textile finishing has a severe environmental burden due to the high consumption of water, energy and chemicals. This impact on the environment inevitably increases with the reprocess. In the manufacturing step (A3), the reprocess increased the GWP from 43.77% to 45.70% and EP from 38.51% to 42.54%.

Table 3. The contributions (%) to each impact category for 50% cotton/50% PET T-shirt, scenario III and IV

Impact category	**A1*		***A1*		*A2*		*A3*		*A4*	
	III	**IV**	**III**	**IV**	**III**	**IV**	**III**	**IV**	**III**	**IV**
Acidification (fate not incl.)	48.74	42.88	9.62	13.90	4.12	3.67	36.82	38.93	0.70	0.62
Eutrophication	52.56	45.54	7.58	10.73	1.00	0.89	38.51	42.54	0.34	0.30
Global warming (GWP100a)	45.06	39.82	8.66	12.19	1.14	1.09	43.77	45.70	1.36	1.20
Photochemical oxidation	47.41	42.46	9.16	13.32	4.71	4.29	37.48	38.82	1.24	1.11
Abiotic depletion, elements	54.99	43.46	40.90	52.62	0.17	0.18	3.04	3.03	0.90	0.71
Abiotic depletion, fossil fuels	47.00	41.86	8.90	12.36	1.28	1.25	41.04	42.96	1.77	1.58
Water scarcity	90.62	85.99	1.86	2.91	0.02	0.02	7.46	11.04	0.04	0.03
Ozone layer depletion	41.99	36.94	31.18	37.01	1.84	1.77	22.35	21.95	2.65	2.33
Water Footprint (USE)	93.03	89.32	1.05	1.76	0.02	0.02	5.86	8.86	0.04	0.04

Water scarcity is related to the lack of insufficient water to support both human and ecosystem water needs whereas the water footprint (USE) is an indicator of volumetric water use and pollution considering the consumption of a unit process or activity [47, 48]. In the first half of the last year, the National Aeronautics and Space Administration (NASA) reported that one-third of the United States is experiencing a moderate level of drought [49]. Besides, recently it is informed that the dry conditions come after several seasons of low rainfall may trigger drought and leave uncertainty for future crop production in Turkey [50]. This alone indicates the necessity of improvements regarding water use in the textile industry as well as in all other industries. The LCA results show that cotton fibre production alone has 95.57% and 91.79% of water footprint share for 100% cotton and 50% cotton/50% polyester T-shirts, respectively (Figure 5). Water footprint of cotton fibre showed a decrease of 3.78% following the incorporation of 50% polyester fibre in the production.

The definition for carbon footprint was proposed by Wiedmann and Minx [51] as ‘The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product’ [51]. In terms of carbon footprint of T-shirt production, fibre production and energy use (electricity, heat and steam) together have around 85% impact for both cotton and cotton/pes blends Figure 5. A comparative analysis of the carbon footprint for a cotton T-shirt is performed by Wang, et.al, and the results show that energy consumption, mainly electricity, is the main contributor to the carbon footprint of textile garments [52]. In polyester T-shirt production, excluding the consumer use phase, polyester yarn spinning is the highest contributor to carbon footprint due to high electric consumption [53].

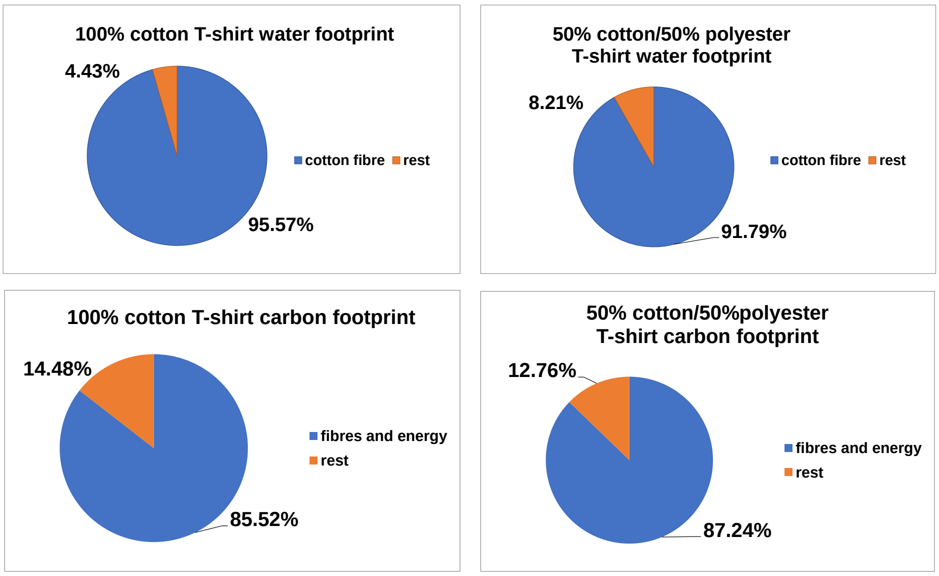

Figure 5. Water footprint and carbon footprint of 100% cotton and 50% cotton/50% polyester T-shirts

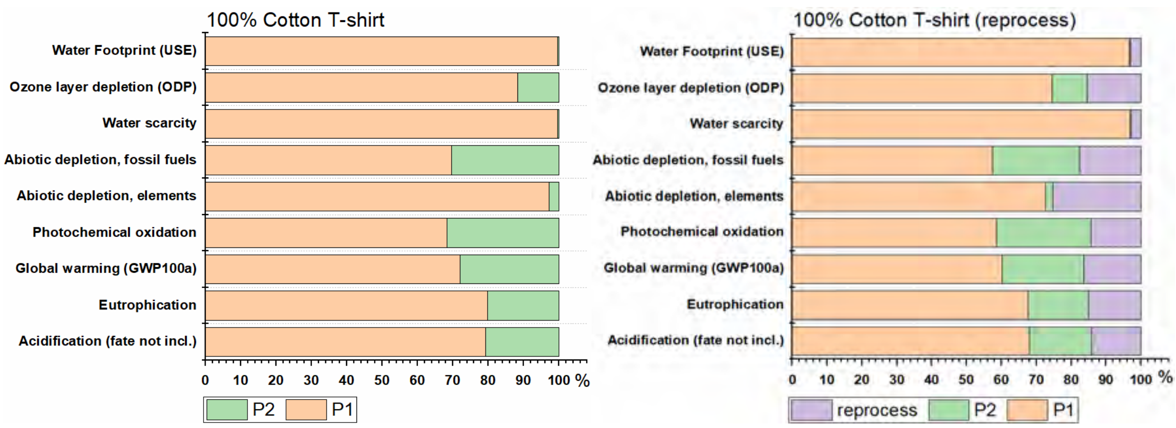

Figure 6. The impact of manufacturing steps for 100% cotton T-shirts; P1 covers the raw material production, raw material transportation, preparation of raw knitted fabrics and dyeing process, P2 covers CMT and garment transportation.

In the study, the environmental impact of production steps before garment manufacturing (the production steps of the participant apparel industry) is also discussed. In Figure 6 and Figure 7; P1 indicates the raw materials (fibres), raw material transportation, preparation of raw materials (fabric) and finishing (fabric), P2 involves the CMT and transportation. The impact of the reprocess of fabrics is presented individually (not included in the P1).

In 100% cotton T-shirt production, the production steps before garment manufacturing (P1) with and without reprocess showed an impact of over 60% in all environmental impact categories. Without reprocess, the highest impact was seen in the water footprint (99.62%), followed by water scarcity (99.54%) and ADP (elements) (97.20%) (Table 4).

100% cotton garment production in the apparel company (P2) has the highest contribution of PO (31.67%) due to the high fossil fuel-based energy consumption in sewing machines and ironing followed by ADP fossil fuels of 30.38%. It should be noted that chemicals in the packaging materials are known to increase the PO impact during textile production [54]. The PO potential, known to be the secondary air pollution, depends largely on carbon monoxide (CO), nitrogen oxide (NO) and NMVOC (non-methane volatile organic compounds) and provides information on emissions by sectors such as energy production and distribution, energy use in industrial processes and road transport [55]. The contribution of reprocess was determined to be over 13% in all environmental impact categories except water scarcity and water footprint. GWP and EP of reprocess were determined as 16.40% and 15.14%, respectively. Moreover, ADP (elements) impact share was notable (25.24%).

Table 4. The percent contributions to each impact category for 100% cotton and 100% cotton (reprocess) T-shirt including different manufacturing steps (P1, P2 and reprocess)

Impact category	*100% cotton T-shirt*		*100% cotton T-shirt (reprocess)*		
	P1	*P2*	*P1*	*P2*	**reprocess**
Acidification (fate not incl.)	79.17	20.83	68.00	17.89	14.11
Eutrophication	79.72	20.28	67.65	17.21	15.14
Global warming (GWP100a)	71.95	28.05	60.15	23.45	16.40
Photochemical oxidation	68.33	31.67	58.48	27.10	14.43
Abiotic depletion, elements	97.20	2.80	72.67	2.09	25.24
Abiotic depletion, fossil fuels	69.62	30.38	57.36	25.03	17.60
Water scarcity	99.54	0.46	96.75	0.45	2.80
Ozone layer depletion (ODP)	88.24	11.76	74.55	9.94	15.52
Water Footprint (USE)	99.62	0.38	96.68	0.37	2.96

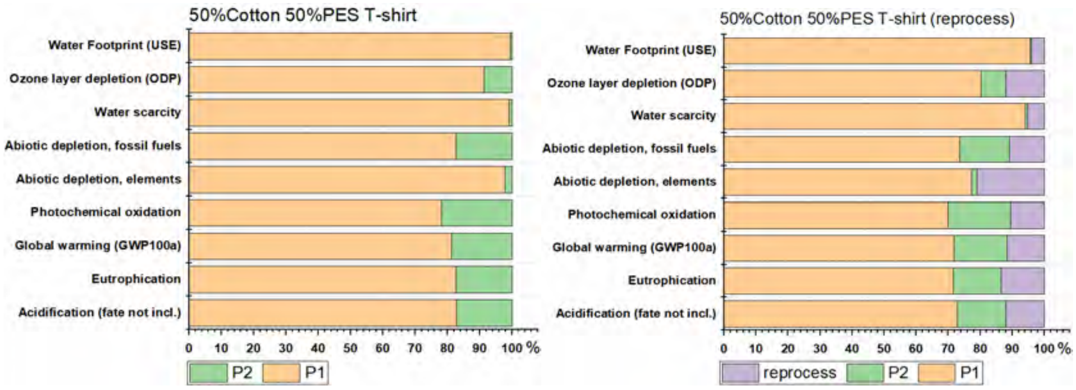

Figure 7. The impact of manufacturing steps for 50%cotton/ 50% polyester T-shirts; P1 covers the raw materials, raw material transportation, preparation of raw materials and dyeing process, P2 covers CMT and garment transportation.

Table 5. The percent contributions to each impact category for 50% cotton/50% polyester and 50% cotton/50% polyester (reprocess) T-shirt including different manufacturing steps (P1, P2 and reprocess)

Impact category	*50% cotton/50% polyester T-shirt*		*50% cotton/50% polyester T-shirt (reprocess)*		
	P1	*P2*	*P1*	*P2*	**reprocess**
Acidification (fate not incl.)	82.81	17.19	72.86	15.13	12.01
Eutrophication	82.63	17.37	71.58	15.05	13.37
Global warming (GWP100a)	81.32	18.68	71.86	16.51	11.63
Photochemical oxidation	78.18	21.82	70.02	19.54	10.45
Abiotic depletion, elements	97.81	2.19	77.30	1.73	20.97
Abiotic depletion, fossil fuels	82.65	17.35	73.62	15.45	10.93
Water scarcity	99.15	0.85	94.08	0.81	5.11
Ozone layer depletion (ODP)	91.29	8.71	80.31	7.66	12.02
Water Footprint (USE)	99.49	0.51	95.53	0.49	3.99

In 50% cotton/50% PET T-shirt production, P2 has the highest PO impact of 21.82% and the least water footprint of 0.51% since the production in the apparel company is energy-intensive. The share of P1 was determined to be over 78% in all impact categories. Considering the impact of apparel company (P2), in the presence of PET fibre, a decrease was observed in all impact categories excluding water scarcity and water footprint. This decrease was significant in GWP and ADP (fossil fuels) (Table 4 and Table 5).

In all environmental impact categories except water scarcity and water footprint, the contribution of reprocess was determined to be above 10% and similar to 100% T-shirt production, ADP (elements) impact share was notable (20.97%). EP and ODP of reprocess were determined as 13.37% and 12.02% respectively (Table 5).

4. CONCLUSION

In this study, life cycle assessment of short sleeve polo necked knitted T-shirts produced from different raw materials were analysed with a cradle-to-gate perspective starting from the fibre production to the distribution of T-shirt garments. Reprocess in finishing department was also considered. The study served the purpose of determining the chemical, water and energy consumption from reprocess and providing data for the LCA comparison of T-shirt products. Among the evaluated scenarios, in 100% cotton T-shirt production (scenario I), raw materials (fibre) (A1) was found to have the highest water scarcity and water footprint impacts of all. In scenario II, the reprocess caused a notable increase in the ADP (both elements and fuels) resulting from raw materials (chemicals) due to the additional consumption of chemicals during finishing and energy consumption of repeated processes. In the presence of 50% polyester fibre (scenario III), water scarcity decreased from 95.73% to 90.62% and water footprint from 95.57% to 93.03% for raw materials (fibre) (A1). Nevertheless, GWP showed an incline from 25.63% to 45.06% and ADP (fossil fuels) from 16.31% to 47.00%, due to the high energy consumption of polyester fibre production. In the 50% cotton/50% polyester T-shirt production, the reprocess (scenario IV) increased the ODP from 31.18% to 37.01% and the ADP (elements) from 40.90% to 52.62% in step A1 raw materials (chemicals). Considering the environmental impact of production steps, CMT and garment transportation (P2) has the highest contribution of PO due to the high fossil fuel-based energy consumption. It can be concluded that, in T-shirt production, reducing the number of reprocessing of fabrics both reduces the production costs and the environmental impact of production in all categories. Based on the results, the participant apparel company invested in solar energy-a renewable/green energy system considering the high electricity consumption during the production of polo neck cotton and cotton/polyester blend T-shirts. On the other hand, the approval of the fabric quality in apparel production is managed by the clients. Thus, the client plays an important role in increasing the colour tolerance of fabrics (reduces reprocess), choosing environmental-friendly raw materials, informing/guiding consumers, choosing conscious/ethical fashion to fast fashion. Also, bio-based/biodegradable raw materials, recycling concepts are considered to be more important for the future in terms of the sustainability policies of companies, beyond the use of natural resources. The results of the analysis underline the importance of enhancing the quality of finishing of textiles to reduce reprocess of fabrics. It is therefore highly mandatory to carry out further case studies (dyeing recipes, parameters etc.) with industry to provide feasible solutions by putting the results of the LCA studies into practice resulting in an enhancement for the sustainability of various textiles.

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