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Closed-loop Mechanical Recycling Opportunities in Industrial Cotton Wastes

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ABSTRACT
Reusing industrial wastes in textile production is essential to reduce the total environmental burden of textile products. This study proved that the wastes generated in the ring-spinning process of a lightweight cotton shirting-producing company could be turned into fabrics used in shirts, jackets, and trousers. A total of 21 different yarns in four different counts containing 5–100% waste were produced in OE-rotor and ring spinning lines. These yarns were used to produce 12 different fabrics. Some of the produced yarns and fabrics met the criteria required for the lightweight fabrics. Others, specifically yarns and fabrics produced from short fiber wastes, exhibited suitable properties for the medium and coarse yarn count segment. According to the gate-to-gate LCA analysis, virgin cotton yarn and 100% cotton waste-contained yarn had similar environmental impacts in terms of OE-rotor spinning process.

摘要
纺织生产中工业废物的再利用对于减少纺织产品的总体环境负担至关重要. 本研究证明, 一家轻薄棉衬衫生产公司在环锭纺纱过程中产生的废物可以转化为用于衬衫, 夹克和裤子的织物. OE转杯纺纱线和环锭纺纱线共生产了四种不同支数的21种不同纱线, 含5-100%的废品. 这些纱线被用来生产12种不同的织物. 生产的一些纱线和织物符合轻质织物的标准. 其他产品, 特别是由短纤维废料生产的纱线和织物, 表现出适合中粗纱段的性能. 根据门到门LCA分析, 原棉纱线和100%含废棉纱线在OE转杯纺纱工艺方面具有类似的环境影响.

KEYWORDS
Industrial waste; OE-rotor spinning; ring spinning; closed-loop recycling; LCA

关键词
工业废物; 转杯纺纱; 环锭纺; 闭环回收

Introduction

After the Quota restrictions for textiles and clothing in 2005, lower-cost producers got access to the euro area market, the United States, and other WTO member countries (Nordas 2004). With low-price products, new demands, avid, young consumer profiles, the growing middle-class population across the globe also fueled textile consumption (Ellen MacArthur Foundation 2017; Joy et al. 2012; Niinimäki and Armstrong 2013; Tokatlı 2008). Global fiber production reached 111 million tonnes in 2019 (Textile Exchange 2020) as a result of massive consumption, whereas the production was 52.6 million tonnes in 2000 (Oerlikon Corporation 2010).

As clothing consumption increases with driven factors, the environmental impacts of the industry will also grow (Stone et al. 2020). Water use from the fashion industry was about 79 billion cubic meters, and CO_2 emissions were about 1,715 million tons in 2015. If the fashion industry produces as usual, it is projected that the CO_2 emissions might reach 2,791 million tons in 2030 (GFA & BCG 2017). Besides, heavy chemical use (Swedish Chemicals Agency 2013; UNEP DTIE/Chemicals Branch 2011), ethical problems (Joy et al.

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2012), colossal energy, and material consumption (ETC/WMGE 2019; Palamutcu 2015) and waste problems (Ellen MacArthur Foundation 2017; European Parliamentary Research Service 2017) forced the industry to shift the conventional production to a sustainable way. Although some efforts have been made for a long time (European Commission 2003), since the textile value chain includes lots of different processes from agricultural applications to finishing, individual solutions such as green chemical use have a limited effect. Circular economy offers a holistic approach and a new vision to the textile industry to tackle related problems. This new vision also aims to utilize materials as long as possible. Recycling is one of the most efficient ways to achieve this target (Ellen MacArthur Foundation 2017; Ten Wolde and Korneeva 2019).

Cotton is the second most produced fiber with a 23% share in global fiber production in 2019 (Textile Exchange 2020). Intensive pesticide, fertilizer, and water use and social problems in the cultivation and harvesting of cotton contribute significantly to textiles environmental problems (Bevilacqua et al. 2014; Chapagain et al. 2006; Hoekstra and Chapagain 2006; International Cotton Advisory Committee 2015). Therefore, recycling cotton wastes at all stages from harvest to use phase can remarkably reduce the environmental burden of cotton by eliminating (or diminishing) agricultural impacts (CottonIncorporated 2012). Besides, the ginning process and, if proper color blends can be achieved, the dyeing process can be eliminated. Thus, chemical, water, and energy use in production stages are also reduced.

In cotton yarn production, between 10% and 50% of waste is generated depending on used processes (Altun 2012). Depending on the yarn spinning system and waste type, some can be reused in the same process; the remains can be sold or disposed (Altun 2012). The producers avoid using waste as raw material because of the concern that their product quality will be getting worst (Watson et al. 2017). Therefore, high-value industrial wastes are generally sold and used as downcycling applications instead of closed-loop applications. This study aims to contribute to this perception's change by obtaining high-quality recycled yarn, which is comparable with virgin yarn.

Various researchers have conducted various studies on the use of cotton production waste in OE-rotor yarn production. In these studies, generally different blending ratios and machine parameters in the range of Ne 6/1-20/1 were studied (Demiröz Gün and Öner 2019; Halimi et al. 2007; Halimi, Hassen, and Sakli 2008; Hasani, Semnani, and Tabatabaei 2010; Khan and Rahman 2015; Khan, Rossain, and Sarker 2015; Telli and Babaarslan 2017; Wanassi, Azzouz, and Hassen 2016). In the study, finer yarn counts and higher waste rates were tried in different yarn counts and fiber blends. The study also focused on producing the finest yarn using the highest amount of waste that can be used. A gate-to-gate LCA study was also conducted to compare the environmental impacts of virgin and recycled yarn production for OE-rotor yarn spinning.

Materials and methods

Work plan

The present study was carried out in a company that produced finer and super finer cotton ring spun yarns and cotton woven fabrics for shirt manufacturing. The study was designed as closed-loop, and Ne 60/1 count yarn production line was chosen to be examined. The blend of Aegean and Egypt Gizza cotton fibers were used to produce ring-spun yarns. The production wastes, which were generated in the ring-spinning process, were aimed to be reused in the company's ring-spinning and weaving processes.

According to preliminary findings, all waste types were not proper for reuse in the company's ring spinning line. The improper waste was turned into OE-rotor yarn in a recycling company. All kind of recycled yarns (ring and OE-rotor spun) produced in the study were woven to be used in shirt and garment manufacturing.

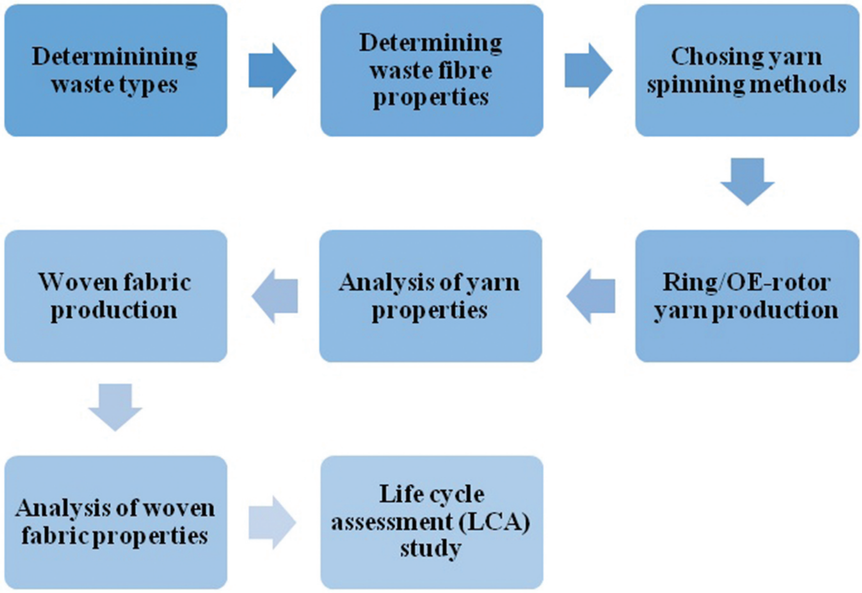

Figure 1. Working plan of the study.

Various physical and mechanical properties of the produced yarns and fabrics have been evaluated. An LCA study was also conducted. The working plan is given in Figure 1, and the studied ring-spinning process is shown in Figure 2.

Determining the waste types

The generated wastes were analyzed according to the source, form, fiber properties, and quantity (Table 1). Combing process produced the highest amount of waste (53.3%). The waste generated in carding machine (22.8%), the sliver wastes (10.78%), and the waste collected as a result of air suction in the ring-spinning machine (5.96%) are other wastes generated in high quantities. Waste sources of the studied process are presented in Figure 2.

Determining the waste's fiber properties

Fiber properties of wastes were determined by Uster HVI (High Volume Instrument) and AFIS (Advanced Fiber Information System). Some wastes contained high amounts of impurities and high variation values. These wastes were opened and cleaned in Microdust and Trash Analyzer with Rotor Attachment (SDL MDTA 3). Then, the fiber properties of the wastes were tested. Virgin cotton fibers used in the study were also tested in HVI and AFIS test devices to compare with waste fibers. Aegean and Egyptian Gizza cotton fibers are graded as high-quality Turkish and Egyptian cotton fiber, respectively. The test results are given in Table 2.

This study focused on high-volume wastes. However, some wastes in this category have been eliminated due to the following reasons: The wastes generated from carding machine (drum-taker-in) had high impurity, neps, and seed coat nep (SCN) values as shown in Table 2. Sliver waste from the first and second passage draw frame contained different raw materials. These wastes were ignored since it was aimed to produce finer yarns. Carding waste (drum-card flat-W1), waste from first and second passage draw frame containing long fiber (W2), combing waste (W3), and air suction waste generated in ring -machine (W4) were chosen.

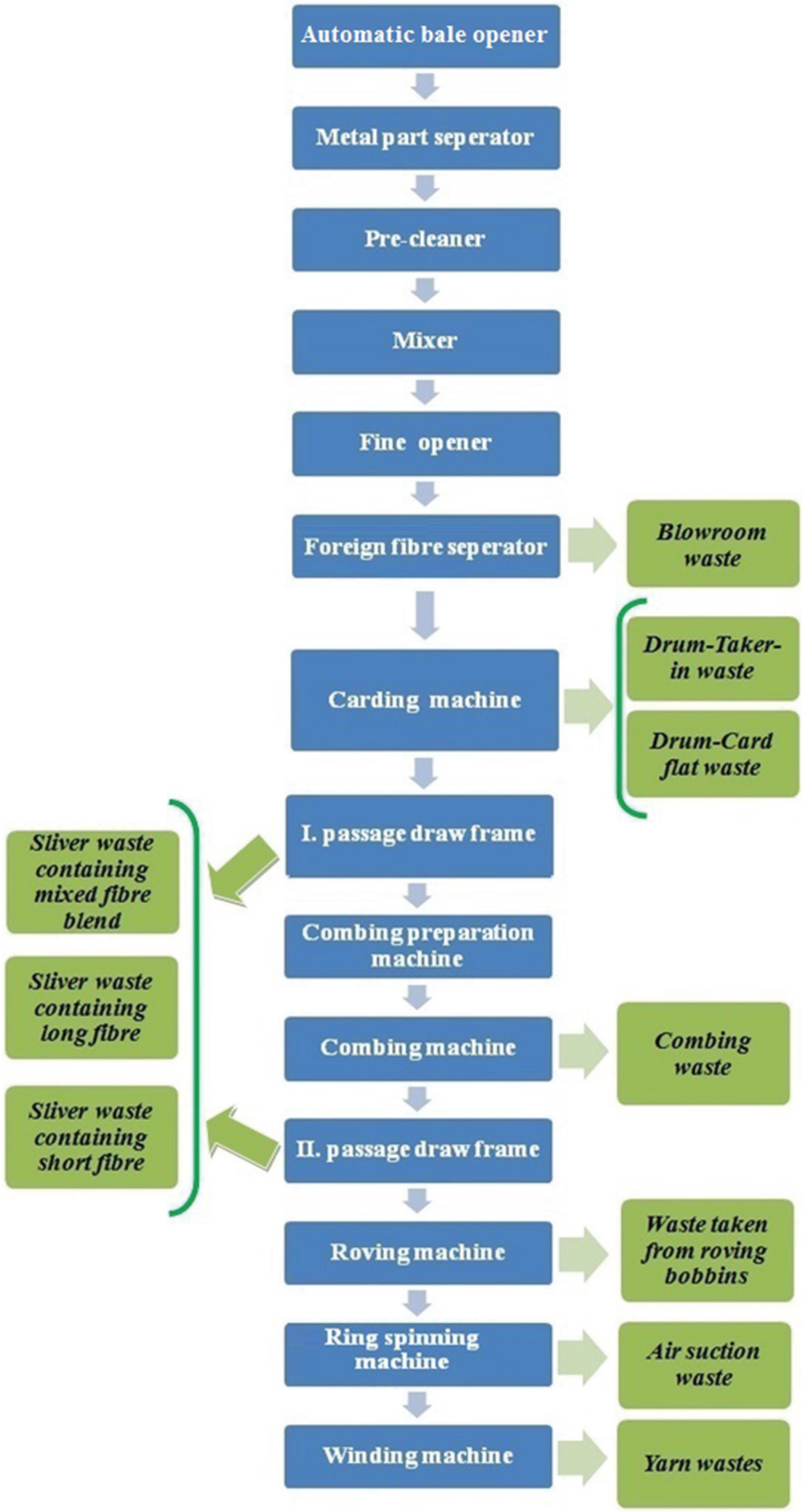

Figure 2. Ring spinning yarn production line of the company and waste collection processes.

Table 1. Generated wastes.

Waste Name	Source	(%)	Form
	Blowroom line waste	1.50	Fiber
	Carding waste (Drum-Taker-in)	10.08	Fiber
W1	Carding waste (Drum-Card flat)	12.72	Fiber
	I. and II. passage draw frame sliver waste containing mixed fiber blend	4.62	Sliver
W2	I. and II. passage draw frame sliver waste containing long fiber	4.36	Sliver
	I. and II. passage draw frame sliver waste containing short fiber	1.8	Sliver
W3	Combing waste	53.30	Fiber
	Waste taken from roving bobbins	3.28	Roving (Twisted)
W4	Air suction waste from ring spinning machine	5.96	Fiber
	Yarn wastes taken from ring cops	1.39	Yarn (twisted)
	Wastes swept from the floor	0.97	Mixed

Table 2. Properties of virgin and waste cotton fibers.

Samples	UHML (mm)	UI (%)	Fineness (Mic.)	Strength. (g/tex)	Elongation (%)	SFI (%)	Impurity (%)	SCN (Cnt/g)
Virgin cotton	34.02	85	4.163	34	6.2	5.8	-	1
Blowroom line waste	35.82	84.3	3.95	46.8	5.1	2.5	3.37	7
Carding waste (Drum-Taker-in)	27.34	75.5	6.46	30.1	6.2	20.6	57.9	65
Carding waste (Drum-Card flat) (W1)	28.38	78.0	4.5	36.3	6.1	14.4	3.7	62
Sliver waste containing mixed fiber blend	32.96	81.2	4.4	40.30	5.0	6.30	6.2	2
Sliver waste containing long fiber (W2)	29.09	83.8	4.7	35.4	4.4	5.2	1.3	1
Combing waste (W3)	19.46	66	3.8	27.9	3.4	46.1	–	6
Air suction waste (W4)	30.17	83.7	4.4	50.5	4.2	5	2.3	6

Choosing proper yarn spinning methods

Fiber length values (UHML) should be minimum 21–25 mm for OE-rotor spinning system while 28 mm for ring-spinning system (Klein 1998; Lawrence 2003). Wastes other than combing waste (W3) provided the required fiber length values for OE-rotor and ring yarn spinning.

The uniformity index (UI) values express that the fibers' length distribution should be a minimum of 80%, mainly for ring-spinning system (Klein 1998; Lawrence 2003). Waste from first and second passage draw frame containing long fiber (W2), and air suction waste (W4) provided the minimum value.

Fiber fineness affects the number of fibers in the yarn cross-section and hence yarn count. Micronaire value expresses that the fineness of cotton fibers is recommended to be 4.0 and above for ring spinning and 3.0–3.7 for OE-rotor spinning (Klein 1998; Lawrence 2003). All wastes provided the required fiber fineness and number of fiber values in the yarn cross-section.

It should be at least 28 g/tex in the OE-rotor spinning system and 25 g/tex in the ring-spinning system in terms of fiber strength (Klein 1998; Lawrence 2003). It was seen that the strength values of all wastes are 28 g/tex and above. On the other hand, fiber breaking elongation values should be between 5% and 8% for both yarn spinning systems (Klein 1998; Lawrence 2003). All wastes except W1 was below 5%.

Short fiber index (SFI) values should be lower than 10% for ring spinning to produce less hairy ring-spun yarns (Klein 1998; Lawrence 2003). Combing waste (W3) and carding machine waste (W1) had high short fiber content, as expected, while sliver (W2) and air suction wastes (W4) provided the required value.

Impurity values were obtained from MicroDust Waste Analysis Unite (SDL MDTA 3), and according to Shirley's principle, all waste fibers' impurity ratios were less than 10%.

When the seed coat nep (SCN) values obtained from the AFIS device were examined, it was observed that the waste fibers except the carding waste (W1) had slightly higher values than the virgin cotton. The presence of seed coat fragments (SCF) and other contaminants increases yarn unevenness

Table 3. Chosen yarn spinning systems according to fiber properties.

Sample type	UHML (mm)	UI (%)	Fineness (Mic.)	Strength (g/tex)	Result
W1	OE/R	OE	OE/R	OE/R	OE
W2	OE/R	OE/R	OE/R	OE/R	OE/R
W3	OE	OE	OE	OE/R	OE
W4	OE/R	OE/R	OE/R	OE/R	OE/R

OE: OE-rotor yarn spinning system
R: Ring yarn spinning system

and faults, i.e. thick places and neps; on the other hand, it reduces strength and elongation. (Gupta and Vijyashankar 1995; Farber 1996; Jones and Baldwin 1996; Krifa, Gourlot, and Drean 2001; Matusiak, Frydrych, and Hecquet 2001; Frydrych and Matusiak 2002).

According to all the results, it would be expected that W1 and W3 wastes might deteriorate produced yarn properties.

Yarn spinning methods were determined according to the evaluations mentioned above (Table 3). W1 and W3 had shorter fiber length, lower uniformity, and higher short fiber content; hence, OE-rotor spinning system was preferred for these wastes. W2 was also chosen to be used in OE-rotor spinning system since the company produce finer and super finer ring spun yarns. W4 was chosen to be reused in the company's ring-spinning process. W4 also was used in OE-rotor spinning process to produce finer and high-quality OE-rotor spun yarns.

Ring spinning yarn production from wastes

The highest quality waste (W4) was chosen in ring-spinning trials since the company produces finer and super-fine ring spun yarns (Ne 40 and finer yarns such as Ne 200). A blend containing 5% air suction waste (W4) and 95% virgin cotton was formed in blowroom line, and Ne 70/1 conventional ring-spun yarns with weaving twist ($\alpha e = 4.0$, 1318 tpm) were produced in ring-spinning line shown in Figure 2. Conventional ring-spun yarn production line had automatic bale opener (Rieter Unifloc A 1/2), metal part separator (Argema 63500), pre-cleaner (Rieter Uniclean B11), mixer (Rieter Unimix B7/3 R), fine opener (ERM B5/5), foreign fiber separator (Jossi), carding machine (Rieter C4), I. passage draw frame (Rieter D 1/2), combing preparation machine (Rieter Unilap E 5/3), combing machine (Rieter E 7/6), II. passage draw frame (Rieter RSB 390SA-2), roving frame (Rieter F1), and conventional ring-spinning machine (Rieter K44). Spindle speed of conventional ring-spinning machine was 16,500 rpm, and production speed was 12.51 m/min. Significant yarn breaks were not observed in the ring-spinning process.

OE-rotor yarn production from wastes

During the OE-rotor yarn production, the following five issues have been taken into consideration:

- Using of high volume wastes,
- Accomplishing yarns using 100% waste,
- Producing 100% biodegradable or recyclable yarns,
- Using recycled fibers such as recycled PET (rPET) instead of virgin fibers when the required quality parameters could not be achieved,
- Producing the yarns having comparable yarn properties with that of the virgin yarn.

Fiber blends of 50 kg were prepared. Fiber blends for OE-rotor yarn production are given in Table 4.

OE-rotor yarn production processes are given in Figure 3, and production parameters are summarized in Table 5. Production was carried out on an industrial scale. OE-rotor yarn production line had automatic bale opener (Balkan), metal part separator, condenser (Balkan B26), pre-cleaner (Balkan Axi Flo), mixer (Balkan B40), fine opener (Balkan B53), condenser (Balkan B26), carding

Table 4. Fiber blends for OE-rotor yarn production.

Name	1. Waste (%)	2. Waste (%)	3. Waste (%)	Yarn count (Ne)	Description
B1	100	–	–	30/1	W2
B2	50	50	–	30/1	W2 + W4
B3	50	50	–	30/1	W2 + W1
B4	75	25	–	30/1	W4 + virgin PET
B5	75	25	–	30/1	W4 + rPET
B6	50	50	–	30/1	W3 + W1
B7	50	35	15	30/1	W3 + W4 + virgin PET
B8	50	50	–	30/1	W3 + W4
B9	75	25	–	20/1	W3 + virgin PET
B10	50	50	–	20/1	W1 + W4
B11	50	35	15	20/1	W3 + W4 + virgin PET
B12	75	25	–	20/1	W4 + virgin PET
B13	75	25	–	20/1	W4 + rPET
B14	50	50	–	20/1	W2 + W1
B15	50	50		20/1	W3 + W4
B16	100	-	–	16/1	W3
B17	75	25	–	16/1	W3 + rPET
B18	75	25	–	16/1	W3 + PET
B19	75	25	–	16/1	W3 + W4
B20	100	-	–	16/1	W1

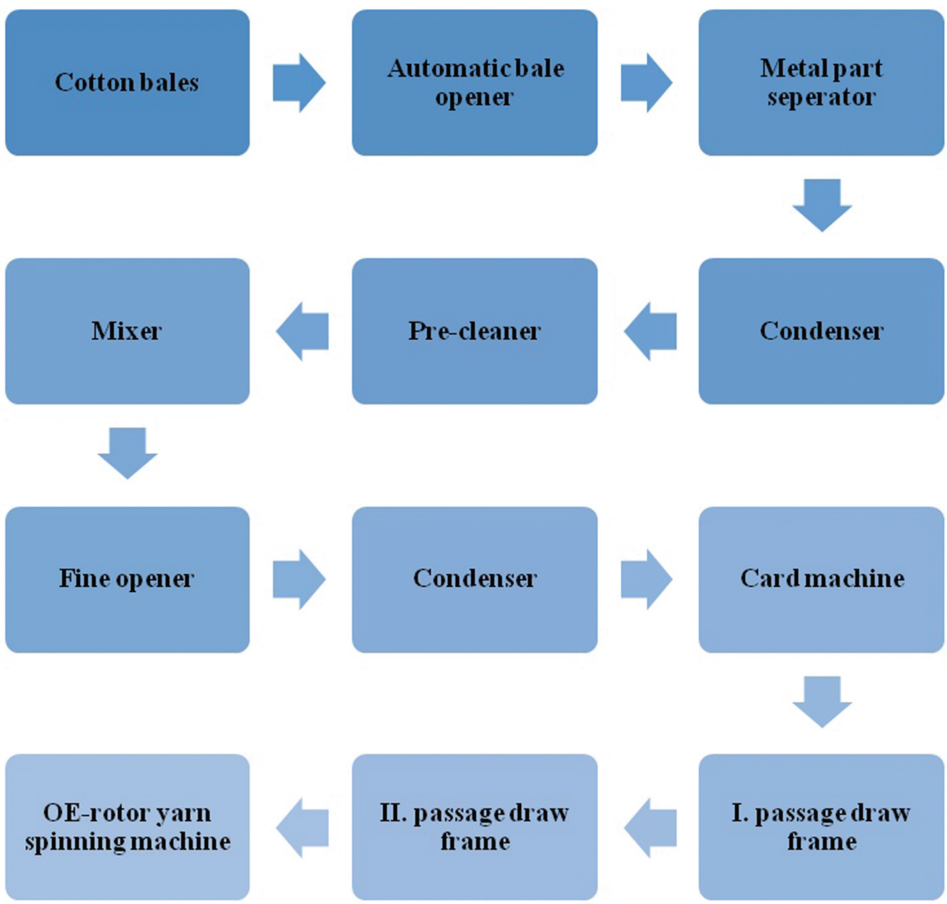

Figure 3. OE-rotor yarn production processes.

Table 5. Production parameters for OE-rotor yarn spinning.

Properties	Value
Card sliver count	6.1 ktex
Sliver count for draw frame	6 ktex
Twist coefficient (αe)	5.0
Opening roller speed of OE-rotor machine	8000–8500 rpm
Rotor diameter	44 mm
Rotor speed	60000 rpm
Nozzle type	Spiral

machine (Lakshmi LC363), I. passage draw frame (Rieter), II. passage draw frame (Rieter), and OE-rotor spinning machine (Rieter R20). OE-rotor spun yarns with weaving twist (αe = 5.0) were produced, and twist values were 787, 880, and 1078 tpm for Ne 16/1, Ne 20/1, and Ne 30/1 rotor yarns. Production speed was 76.2 , 68.2, and 55.7 m/min for Ne 16/1, Ne 20/1, and Ne 30/1 rotor yarns. Significant yarn breaks were not observed in the OE yarn production.

Yarn tests

Unevenness, yarn imperfections such as thin-thick place, neps, and hairiness of the ring and OE-rotor spun yarns were tested on Uster Tester 3 with 400 m/min test speed throughout 2.5 minutes. Yarn tenacity and breaking elongation were determined by Uster Tensorapid test device. Tensile tests were performed for 500 times for each bobbin, and 500 mm was the gauge length. Five samples were tested for each yarn. All tests were carried out on the same device under standard atmospheric conditions.

Fabric production

Fabrics of 2/2 Panama weave type were woven from the produced ring, and OE-rotor spun yarns on the sample loom. Yarns comprising waste fibers were used in both weft and warp direction, and 12 different fabrics were produced. Due to insufficient amount of some yarns, some fabrics could not have been produced enough for all tests. The obtained woven fabrics were named with “F” codes as presented in Table 6.

Fabric tests

Physical and mechanical properties of woven fabrics such as fabric weight (ISO 3801), tearing (ISO 13937–1), tensile (ISO 13934–1) and seam strength (ISO 13936–1, 3 mm), abrasion (ISO 12947–2), and pilling resistance (ASTM D4970, 2000) were determined. Color fastness such as sweat (ISO 105 E04), washing (ISO 105 C06), water (ISO 105 E01), rubbing (dry and wet) (ISO 105 × 12) and shrinkage (ISO 6330–40°C) were also analyzed.

Table 6. Fabric production plan.

Fabrics	Yarn contents
F1	WEFT B1+ WARP B1
F2	WEFT B2+ WARP B2
F3	WEFT B3+ WARP B3
F4	WEFT B5+ WARP B5
F5	WEFT B8+ WARP B8
F6	WEFT B10+ WARP B10
F7	WEFT B11+ WARP B11
F8	WEFT B14+ WARP B14
F9	WEFT B17+ WARP B17
F10	WEFT B18+ WARP B18
F11	WEFT B19+ WARP B19
F12	WEFT B20+ WARP B20

Life cycle assessment study

Life cycle Assessment is one of the techniques to understand and address the potential environmental impacts of products, processes, and services. The LCA process consists of four phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase (ISO (International Organization for Standardization) 2006). ISO 14040 has defined the principles and framework of LCA, and this study was conducted according to ISO 14040.

Goals and scope of the study

This study aimed to compare the environmental impacts of waste and virgin cotton OE-rotor yarn spinning processes. The scope of this gate-to-gate study was limited to the production of OE-rotor yarns; the waste cotton and virgin cotton fibers were the raw materials, and the OE-rotor yarns were the end products. The system boundary of the study is shown in Figure 4. The process where the main study was carried out was followed. 100% virgin cotton yarn, 100% cotton waste contained yarn (B18), and blended yarn (B20) were chosen as end products. One kilogram yarn was determined as a functional unit.

Inventory analysis

The on-site data used in this case study were acquired from an OE-rotor spinning company where the whole study was carried out. The inputs and outputs for chosen yarns are shown in Table 7. The data shown in Table 7 are directly obtained from the measurements carried out during the study. Spin finish did not use through the process.

Impact assessment

The LCIA analysis in this study was performed using Simapro v 8.0.2 and Ecoinvent version 3.1 database. CML-IA baseline was used as LCIA method. The following impact categories were assessed in this study: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), marine aquatic ecotoxicity potential (MAEP), terrestrial ecotoxicity potential (TEP), and human toxicity potential (HTP).

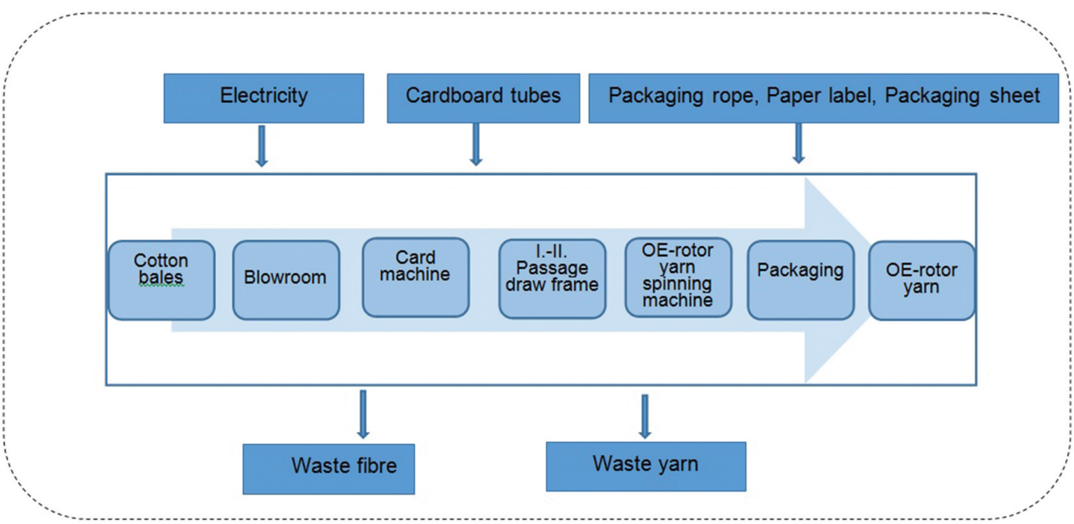

Figure 4. System boundary of the study.

Table 7. Inventory for the spinning process.

Inputs						Outputs		
	Electricity (kwh)	Cardboard tubes (g)	Packaging rope (g)	Paper label (g)	Packaging sheet (g)	Waste fiber (g)	Waste fabric-for packaging-(g)	Waste ring (g)
100% virgin cotton	2.275	16.3	1	3	2.9	139	24	16.4
B18	2.33	16.3	1	3	2.9	170	24	16.4
B20	2.278	16.3	1	3	2.9	136	24	16.4

Results and discussion

Ring spun yarns

Yarn properties

Properties of Ne 70/1 ring-spun yarns were compared with Uster World Statistics, and the results are given in Table 8, in which 5%, 50%, and 95% symbolize the respective Uster quality levels (Uster Technologies Ltd 2013). Ring-spun yarns containing 5% air suction waste (W4) were within the 5% quality segment in all quality parameters taken into account. In other words, Ne 70/1 ring-spun yarns with 5% air suction waste had better quality values in terms of CVm, thin places, thick places, neps, and hairiness than approximately 95% of the yarns produced from cotton in the world.

Woven fabric properties

Produced Ne 70/1 ring-spun yarns were used to weave 2/2 Panama fabric. Various physical properties of the fabrics were tested. The fabrics containing 5% air suction waste satisfied the required limit values for the company. The results are given in Tables 9–10.

Table 8. Comparison of produced Ne 70/1 ring-spun yarns with Uster World Statistics.

	CVm (%)	Thin places (−50%)	Thick places (+50%)	Neps (+200%)	H	Tenacity (cN/tex)	Breaking elongation (%)
Recycled	13.34	7	24	56	3.10	22.42	5
%5 (Uster)	13.70	8	30	66	3.19	22.22	4.66
%50 (Uster)	15.20	19	75	162	3.70	20.60	4.43
%95 (Uster)	17	60	171	370	4.60	16.70	4.30

Table 9. Physical and mechanical properties of the woven fabrics produced from W4 waste.

Property	Expected minimum value	5/95% W4/virgin cotton
Tearing strength (warp) (g)	700	1370
Tearing strength (weft) (g)	700	1337
Tensile strength (warp) (kg)	20	28.47
Tensile strength (weft) (kg)	18	22.64
Seam strength (warp) (kg)	3	8.76
Seam strength (weft) (kg)	3	7.62
Abrasion resistance (cycle)	10000	10000
Shrinkage (warp/length) (%)	Between −3/+3	−1.5
Shrinkage (weft/width) (%)		−1.5

Table 10. Color fastness properties of woven fabrics.

Property	Expected minimum value	95/5% virgin/W4 cotton
Sweat fastness (Acidic)	3/4C, 3/4S	4/5C 4S
Sweat fastness (Alkaline)	3/4C, 3/4S	4/5C 4S
Washing fastness	3/4C, 3/4S	4/5C 4S
Water fastness	3/4C, 3/4S	4/5C 4S
Dry friction fastness	3/4S	4S
Wet friction fastness	3S	3/4S

Table 11. Comparison of produced OE-rotor yarn properties with Uster World Statistics.

Yarn count	CVm (%)		Thin places (−50%)		Thick places (+50%)		Neps (+280%)		H	
Ne 30/1	**5%**	13.4	**5%**	5	**5%**	30	**B4**	7	**5%**	3.1
	B4	14.44	**B4**	8	**B2**	36	**B8**	7	**50%**	4.1
	B2	14.65	**B2**	13	**B7**	37	**B2**	16	**B1**	4.46
	B1	14.71	**B1**	16	**B4**	45	**5%**	16	**B2**	4.93
	50%	14.9	**B8**	16	**B8**	52	**B1**	19	**B4**	5.1
	B8	15.17	**B7**	17	**B1**	54	**B5**	24	**B5**	5.19
	B5	15.42	**50%**	19	**B5**	56	**B7**	31	**B6**	5.25
	B7	15.42	**B5**	28	**B3**	67	**B3**	64	**B8**	5.26
	B3	15.43	**B3**	30	**B6**	69	**B6**	65	**B3**	5.32
	B6	16.12	**B6**	34	**50%**	72	**50%**	57	**95%**	5.5
	95%	16.6	**95%**	71	**95%**	176	**95%**	196	**B7**	5.65
Ne 20/1	**B9**	12.08	**B9**	0	**B9**	3	**B12**	0	**5%**	3.7
	B12	12.5	**B11**	0	**B11**	7	**B9**	2	**50%**	4.9
	B11	12.59	**B12**	0	**B12**	9	**B11**	4	**B12**	5.22
	B10	12.63	**B10**	1	**B15**	12	**B15**	4	**B10**	5.38
	5%	12.7	**B14**	1	**B13**	16	**B13**	5	**B15**	5.39
	B14	12.75	**B15**	1	**B10**	17	**5%**	7	**B14**	5.5
	B15	13.09	**5%**	2	**B14**	18	**B10**	18	**B13**	5.73
	B13	13.15	**B13**	5	**5%**	18	**B14**	18	**B11**	5.91
	50%	14.2	**50%**	8	**50%**	46	**50%**	26	**B9**	6.37
	95%	15.9	**95%**	32	**95%**	124	**95%**	94	**95%**	6.4
Ne 16/1	**B17**	12.19	**B16**	0	**B17**	4	**B17**	2	**5%**	4.1
	5%	12.4	**B17**	0	**B18**	7	**B18**	2	**50%**	5.3
	B18	12.66	**B18**	3	**B19**	7	**B19**	2	**B20**	6.02
	B16	13.09	**B19**	0	**B20**	8	**B16**	4	**B19**	6.57
	B19	13.14	**B20**	1	**B16**	12	**5%**	4	**B17**	6.7
	B20	13.24	**5%**	1	**5%**	13	**B20**	16	**95%**	6.9
	50%	13.9	**50%**	5	**50%**	36	**50%**	17	**B18**	6.86
	95%	15.5	**95%**	20	**95%**	103	**95%**	62	**B16**	7.18

OE-rotor spun yarns

Yarn properties

Twenty different yarns having different blend ratios and three different counts were produced according to the principles mentioned in earlier sections. Yarn properties of Ne 30/1, Ne 20/1, and Ne 16/1 OE-rotor yarns produced with four different waste types (W1, W2, W3, and W4) were compared with the appropriate Uster 5%, 50%, and 95% quality levels, and the results are presented in Tables 11 and 12.

When the results of Ne 30/1 OE-rotor spun yarns (B1-B8) were evaluated, it was observed that quality levels of the yarns varied depending on the waste type and blend ratio. Regarding yarn unevenness and yarn strength, the B1, B2, and B4 blends that had long fiber wastes were placed between 5% and 50% quality levels. According to thin place values, B1, B2, B4, B7, and B8 samples were between 5% and 50% while B3, B5, and B6 were between 50% and 95% quality levels. All samples were between 5% and 50% for thick places. B2, B4, and B8 were above 5%, and the rest of the yarns were between 5% and 50% for neps. All of the produced yarns were between 50% and 95% for hairiness (except B7) and breaking elongation. B1, B2, B4, and B6 were between 5% and 50%, and the rest of the yarns were between 50% and 95% for tenacity. In congruence with the properties of waste fibers, B3 (W2 + W1) and B6 (W3 + W1) had the worst values in all quality parameters and B2 (W2 + W4) and B12 (W4 + virgin PET) the best.

When the results of Ne 20/1 OE-rotor yarns (B9-B15) were analyzed, it was seen that most of the yarns qualified above 5% quality level except H values. The H values were between 50% and 95% quality level for yarn hairiness. Most of the samples have tensile properties between 5% and 50% quality level except the samples with codes B9, B11, and B14 in yarn tenacity and B12, B13, and B15 in breaking elongation. These blends had the tenacity and breaking elongation values between 50% to 95% level. B9 (W3 + virgin PET), B11 (W3 + W4 + virgin

Table 12. Comparison of tensile properties of produced OE-rotor yarns with Uster World Statistics.

Yarn count	Yarn tenacity (cN/tex)		Breaking elongation (%)	
Ne 30/1	**5%**	14.4	**5%**	7.3
	B1	13.82	**50%**	5.9
	B4	13.33	**B4**	5.77
	B2	12.49	**B7**	5.75
	B6	12.26	**B3**	5.57
	50%	12	**B6**	5.55
	B3	11.87	**B5**	5.23
	B8	11.84	**B2**	5.22
	B5	11.44	**B8**	5.06
	B7	11.19	**B1**	4.92
	95%	10.1	**95%**	4.8
Ne 20/1	**5%**	14.8	**5%**	7.8
	B10	13.62	**B9**	7.46
	B12	13.59	**B11**	6.77
	B15	13.58	**B14**	6.77
	B13	12.57	**B10**	6.36
	50%	12.3	**50%**	6.3
	B11	12.03	**B13**	5.6
	B14	12.03	**B12**	5.44
	B9	11.84	**B15**	5.31
	95%	10.5	**95%**	5.2
Ne 16/1	**5%**	15	**B17**	9.38
	B19	12.94	**B18**	8.1
	B20	12.9	**5%**	8
	B17	12.82	**B20**	7.6
	B16	12.6	**B16**	7.13
	50%	12.5	**B19**	6.97
	B18	12.14	**50%**	6.5
	95%	10.6	**95%**	5.4

PET), and B12 (W4 + virgin PET) gave the highest quality values. According to the experience of employees, PET fiber can facilitate yarn formation. Blending performance can also affect yarn quality.

Similar results to Ne 20/1 were observed for Ne 16/1 OE rotor yarns in terms of yarn irregularity, imperfections, and hairiness. All yarns were between 5% and 50% quality level regarding yarn unevenness and imperfections. Some samples gave better values than 5%, for example, B17 for CVm (%) and B16, B17, B18, and B19 for yarn faults. In yarn hairiness, H values of many samples were between 50% and 95% quality except for the samples B16 and B18. The tenacity and breaking elongation values of almost all yarns fell in between 5% and 50% quality level. Some samples had better values than 5% quality level. Yarns produced from 75% combing waste/25% rPET and 75% combing waste/25% PET waste proved to have best properties.

Woven fabric properties

Fabrics were woven from the produced yarns used in weft and warp directions. Various physical and mechanical properties of the fabrics were tested, and the results are given in Table 13 and Table 14.

Woven fabrics in all counts provided the limit values in tearing, tensile, and seam strengths, as well as abrasion resistance. All fabrics, except F4, F6, F7, F9, and F10, provided limit values for pilling resistance.

Color fastness and shrinkage results of woven fabrics

Sweat, washing, water, and rubbing fastness and shrinkage values of woven fabrics provided the limit values (Table 14).

Table 13. Physical and mechanical properties of woven fabrics.

		Tearing strength (g)		Tensile strength (Kg)		Seam strength (Kg)		Abrasion resistant (cycle)	Pilling resistance
		Warp	Weft	Warp	Weft	Warp	Weft		
Yarn count	Fabric type	Min. 700	Min. 700	Min. 25	Min. 18	Min. 2,5	Min. 2,5	Min. 10000	3
Ne 30/1	F1	4468	4795	32.08	39.94	6.30	3.56	10000	3
	F2	4925	4012	32.20	31.31	5.15	4.56	10000	3
	F3	5317	4501	36.42	37.10	7.14	4.02	10000	3
	F4	4892	4566	32.77	29.96	6.32	4.04	10000	2/3
	F5	5284	4468	30.63	36.26	6.88	3.71	10000	3/4
Ne 20/1	F6	6524	6002	53.50	40.69	3.67	5.84	10000	2/3
	F7	5610	5447	45.81	31.88	4.51	6.50	10000	2/3
	F8	6167	6132	52.20	37.79	4.31	5.34	10000	3
Ne 16/1	F9	6230	5284	67.80	40.92	4.76	9.24	10000	2/3
	F10	6524	5512	65.70	45.71	5.32	8.69	10000	2/3
	F11	6524	5936	71.00	48.87	4.79	7.23	10000	3
	F12	6524	5806	69.80	39.62	5.78	8.52	10000	3/4

Table 14. Color fastness and shrinkage values of woven fabrics.

		Sweat fastness		Washing fastness	Water fastness	Friction fastness		Shrinkage (%)	
		Acidic	Alkaline			Dry	Wet	Warp/length	Weft/width
Yarn count	Fabric type	Min. 3/4C, 3/4S	Min. 3/4C, 3/4S	Min. 3/4C, 3/4S	Min. 3C, 3S	Min. 4S	Min. 3/4S	−2	−2
Ne 30	F1	4C 4S	4C 4S	4C 4S	4C 4S	5 S	4S	0.5	−2
	F2	4/5C 4S	4/5 C 4S	4/5 C 4S	4/5 C 4S	5 S	4S	1	−2
	F3	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	5 S	4/5S	0.5	−1.5
	F4	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	5 S	4/5S	0.5	−2
	F5	4C 4S	4C 4S	4C 4S	4C 4S	5 S	4S	1	−2
Ne 20	F6	4C 4S	4C 4S	4/5C 4S	4C 4S	5 S	4S	−0.5	−2
	F7	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	5 S	4/5S	−0.5	−1.5
	F8	4/5C 4S	4C 4S	4/5C 4S	4C 4S	5 S	4S	−0.5	−1.5
Ne 16	F9	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	5 S	4/5S	−0.5	−0.5
	F10	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	4/5C 4/5S	5 S	4/5S	−0.5	−0
	F11	4/5C 4S	4C 4S	4/5C 4S	4C 4S	5S	4S	−1	−1.5
	F12	4C 4S	4C 4S	4/5C 4S	4C 4S	5S	4S	−1	−1.5

Results of LCA study

The inventory table showed that all the inputs and the outputs were the same, except electricity consumption. The electricity consumption in waste containing blends was slightly higher due to breakages and stops during spinning process; some quality parameters of waste fibers such as shorter fiber length, higher CVm values, and lower tenacity could cause machine performance problems. The most considerable difference (0.0174 kwh/kg) in consumed electricity had been between 100% virgin cotton and 100% combing waste.

The largest contributor to environmental impacts was electricity consumption for all impact categories. Electricity consumption represented at most 99% of the impact (for marine aquatic ecotoxicity) and at least 92.7% (for eutrophication). In line with the electricity consumption values, 100% combing waste had the highest and 100% virgin cotton had the lowest values in all impact categories as depicted in Table 15.

Table 15. Environmental impacts of OE-Rotor Yarn spinning.

	GWP100	OLD	AP	EP	MAEP	TEP
Units	kg CO_2-eq	kg CFC- 11 eq	kg SO_2-eq	kg PO_4^{3-} eq	kg 1,4 DB eq	kg 1,4 DB eq
Virgin cotton	1.67	2.3 E-8	0.0106	0.0064	2.97 E3	0.00235
100% combing waste (B18)	1.74	2.12 E-8	0.0111	0.0067	3.1 E3	0.00246
75% combing waste + 25% virgin PET (B20)	1.68	2.04 E-8	0.0107	0.0064	2.98 E3	0.00236

According to the results, waste use has not been contributed significantly to the environmental impacts of the OE-rotor spinning process.

Conclusions and further studies

The present study aimed to reuse the waste obtained from the ring-spun yarn production line of a shirt fabric company. The wastes turned into yarn with two different spinning systems, ring and OE-rotor. Then fabrics were woven with produced yarns. The yarn and fabrics were evaluated with the company's quality limits and international standards. Ring-spun yarns and fabrics produced from blend containing 5% waste have met the quality requirements of the company.

Recycled OE-rotor yarns had high performance comparable to those yarns obtained from virgin raw materials. Hairiness values of the yarns were between 50% and 95% because of higher quantity short fibers and lower fiber length. Although any attempt was not made to reduce hairiness in this project, a new study is planned related to this issue. In the preliminary trials, encouraging results were obtained with gassing. Other methods to prevent hairiness will also be tried. Yarns with high hairiness can currently be used when hairiness creates a fashionable effect.

Waste use reduces the environmental burden of cotton yarns owing to eliminating field stage and ginning. According to the LCA study, waste use has not increased environmental burden comparing to virgin material in the spinning process, which was a possibility because of production troubles caused by low-quality material.

Cost analysis was not included in this study. However, the raw material cost in OE-rotor yarn production is 64%–77% within the total cost; it takes place between 44%–61% in ring-spun yarn production (Kaplan and Koç 2010; Koç and Kaplan 2007). Therefore, companies' use of yarns produced from their own waste can significantly reduce their raw material costs.

The use of secondary raw materials will become more widespread in the upcoming period. During the project, it was experienced that, it is also an essential requirement for yarn, weaving, and knitting machine manufacturers to adapt quickly to these new raw materials, which will lead to better quality textile products.

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