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Research article

Sustainable and cleaner production of elastic core-spun yarns for stretch denim with maximal utilization of recycled cotton extracted from pre-consumer fabric waste

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ABSTRACT

Stretch denim is an exclusive and stylish textile made with elastic core-spun yarns. It has gained substantial traction for offering essential elasticity and resilience to the garments while retaining a snug fit and comfort when worn. Denim is produced from coarser cotton yarns necessitating a significant quantity of cotton fiber. Owing to the escalating costs of cotton and the harmful environmental impacts associated with its cultivation, it is imperative to explore alternative fibers for denim. Herein, for the very first time, an expedient technique of manufacturing elastic core-spun denim yarns utilizing recycled cotton is investigated. Recycled cotton fibers, in the range of 10–60 %, extracted from pre-consumer fabric waste were blended with virgin cotton and spun into 16 Ne (36.9 Tex) elastic core-spun yarns. To address the challenges posed by the lower spinnability of recycled fibers, attributed to lower fiber length, uniformity index, and higher short fiber content, a compact spinning system featuring a novel pin spacer was used. This combination effectively improved the fiber control within the drafting zone, enabling maximum incorporation of recycled cotton, up to 60 %, into the yarn. The produced yarns exhibited significantly lower unevenness, imperfections, and hairiness along with higher strength and elongation that fell within the top 5 %–50 % ranking of Uster Statistics 2023. The elastic core yarn, even containing 60 % recycled fiber, demonstrated its suitability for use as a weft yarn in a commercial high-speed air-jet loom operating at 950 rpm (equivalent to weft speed 94 km/h or 1577 m/min). The production of denim yarn incorporating 60 % recycled cotton represents an innovative concept to advance sustainable development goal (SDG) 12. This initiative aims to reduce the proportional demand for cotton cultivation and its subsequent processing, thereby making significant contributions to environmental preservation on various fronts. Moreover, this approach offers potential cost savings in the production of denim clothing.

1. Introduction

Elastic core-spun yarns have revolutionized the textile industry due to their versatile applications. They are manufactured by wrapping an elastomeric core filament with a sheath of staple fibers, mostly cotton, combining the stretch and recovery properties of the core material with the desired aesthetics of the outer sheath [1,2]. These yarns exact the consumer expectation of garments that

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offer pleasant body movement while retaining their form-fitting ability even after repeated use [3]. In the fashion industry, they are particularly chosen to produce stretch denim garments like figure-hugging jeans. Beyond fashion, elastic core-spun yarns have been utilized in creating biaxial and triaxial auxetic woven fabrics where expansion in two or more directions is required [4]. Moreover, these yarns have been employed in the development of elastic textile carriers designed for healthcare purposes. Cotton is a non-allergenic fiber and does not cause skin irritation. Hence, cotton-wrapped elastic core-spun yarns have been used to produce stretchable and adaptable garments for patients, compression garments and bandages, medical braces, and other therapeutic textiles [5].

Led by reputed clothing retail giants like Zara, UNIQLO, Forever 21, and H&M, the global fashion industry started a new business model around the 1990s with the name ‘Fast Fashion’ or so-called ready-to-wear to meet the quick-changing habits of young consumers [6,7]. This concept involves a business strategy centered on providing consumers with regularly novel, affordable (low-cost), and trend-focused items [8,9]. The current rapid expansion in apparel manufacturing, propelled by increased wealth and consumption in developing countries, is a result of the deliberate embrace of the "fast fashion" concept. Low-cost garments deteriorate quickly and are discarded more rapidly, raising the issue of waste disposal. Consequently, fast fashion has gained greater attention in discussions related to sustainability and environmental awareness [10,11]. This industry depletes limited resources like raw materials, freshwater, land, and energy, while also using harmful chemicals and microplastics that contaminate the water resources [12]. For example, the ever-growing throwaway culture results in approximately 92 million tons of textile waste produced worldwide annually, and this figure is projected to increase significantly to around 134 million tons per year by 2030 [6]. Furthermore, the fast-paced manufacturing methods of the industry contribute to nearly 20 % of the global wastewater output and nearly 10 % of the total global carbon emissions which is ultimately a greater amount of global greenhouse gases compared to the combined emissions from international flights and maritime shipping [13,14].

The overall textile industry is one of the primary sectors worldwide when it comes to emitting pollutants and generating waste [15]. The primary contributors to the worldwide environmental effects of the textile industry are dyeing and finishing processes (36 %), yarn preparation (28 %), and fiber production (15 %). Cotton is the second most produced fiber in the world after polyester and its annual production is about 24.7 million tons which accounts for approximately 22 % of the world fiber production in 2021. Approximately 75 % of the world’s clothing items incorporate some form of cotton [16]. Cotton is known to be a thirsty crop as its cultivation has the largest impact on freshwater withdrawal (from a surface water or groundwater source). More than 250 billion tons of water are needed for global cotton cultivation annually and approximately 10,000–20,000 L of water is required to produce one Kg of cotton fiber [17,18]. Conventional cotton farming often involves the use of various synthetic chemicals, including pesticides and fertilizers, to control pests and boost production. There are several environmental and health concerns associated with the heavy use of these chemicals. Excess fertilizers, not absorbed by plants, reach groundwater by leaching through soil, and rainfall or irrigation can lead to runoff, carrying them into nearby water bodies. The aerial spraying of pesticides, usually practiced in cotton fields, disperses them extensively throughout the environment [17]. To address these concerns, there has been a growing movement toward a more sustainable and environmentally friendly approach to reducing the production of cotton fiber [19]. In this context, the utilization of recycled cotton fibers extracted from waste fabric can be a viable alternative for alleviating the strain on cotton cultivation.

In 2022, Bangladesh exported garments worth US$ 47 billion, preserving its previous status as the second-largest contributor of garments exports globally after China. While making apparel, 12–15 % of the fabrics go to waste as cut-clips (leftovers in garment cutting tables) which is called pre-consumer waste [20,21]. Bangladeshi textile factories produce around 570,000 tonnes of recyclable pre-consumer waste every year. Through a shredding operation, currently, 1–5 % of such waste is converted into fibers to reproduce yarn and various domestic goods like pillows, quilts, and mattresses. Around 35 % of waste fabrics are either disposed of in landfills or incinerated in boilers by mixing with husk as a substitute for gas or oil. The rest 40 % of the textile wastes are exported to neighboring countries at cheaper prices where they are recycled and sold back to the local garment industry at a higher price [22]. Recently, many international buyers and renowned brands have imposed a mandatory condition on the use of recycled fibers, instead of 100 % ’virgin cotton’ in the product. The EU is going to make use of 30 % recycled fiber mandatory on its imported apparel products from 2025 as a prerequisite to enjoying concessionary duty benefits. As a result, 23 companies in Bangladesh have established textile recycling plants, and together, these companies can produce approximately 220,000 tons of recycled fibers. There is a projection that the utilization of

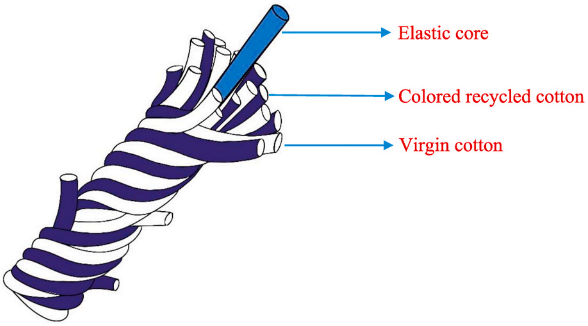

Fig. 1. An architectural model of elastic core-spun mélange yarns showing an elastane filament in core and blends of recycled cotton/virgin cotton as sheath.

30 % recycled cotton in textile production could potentially replace the need for importing virgin cotton valued at USD 1.0 billion per year [23].

Taking the aforementioned facts into consideration, the current researchers were motivated to adopt a sustainable and efficient approach, for the first time, to valorize recycled cotton fibers sourced from pre-consumer fabric waste to produce elastic core-spun yarn for denim. Recycled fibers generated from fabric waste through a vigorous mechanical shredding operation contain plenty of short fibers and neps-like fiber lumps that become uncontrolled in drafting zones of draw frame, speed frame, and ring frame. Due to this reason, recycled fibers cannot be exclusively converted into yarn through the traditional spinning process. Consequently, virgin cotton fibers need to be added with recycled fibers, which serve as carriers throughout the entire spinning line. In the end, the current work was turned to manufacture a core-spun yarn with an elastane core, surrounded by a mixture of recycled cotton and virgin cotton, as illustrated in Fig. 1. However, a huge number of short fibers contained in recycled fibers appear as protruding fibers in the yarn surface [21]. To maximize the integration of those fibers with the yarn body with precise fiber control in the spinning frame, a compact spinning system combined with a newly designed pin spacer was used. Compact spinning is the redesigning of the conventional ring spinning where the spinning triangle was eliminated. This results in the optimum translation of fiber properties into the yarn with significant enhancements in different yarn qualities like lower hairiness and imperfection, higher evenness and strength, better resistance to abrasion, and a lower tendency of pilling [20,24–27].

2. Materials and methods

2.1. Materials

To manufacture elastic core-spun yarns with consistent yarn quality suitable for commercial denim production, the current investigators employed industrial-scale sophisticated machines with continuous operation. Three kinds of fibers used to produce elastic core-spun yarns are shown in Fig. 2 (a – c). Black recycled cotton fiber shredded from pre-consumer knit garment clips was collected from 'Recover Bangladesh' (a newly-established Spanish project in Bangladesh that processes consumer fabric waste). The purpose of choosing recycled black fiber was to create a range of shades, similar to the popular mélange yarns available in the market, by blending it with virgin cotton in different proportions. Virgin cotton fibers (origin: Brazil) and elastane filament (Creora H350, Hyosung, Vietnam) were procured through local suppliers. HVI (High-volume instrument) fiber properties of virgin cotton and recycled cotton along with the specification of elastane filament are given in Table 1.

2.2. Fiber mixing

This study aimed to produce elastic core-spun yarns incorporating maximal recycled cotton while ensuring the required strength of resulting denim yarn for use as weft in commercial air-jet weaving. The experiment was started by blending a small percentage of recycled cotton, such as 10 %, with virgin cotton, and core-spun yarn was produced accordingly. Then the yarn strength was evaluated in terms of the stress required for weaving. Subsequently, the amount of recycled cotton was increased up to 70 % in blends. Finally mixing with recycled cotton: virgin cotton blend ratios of 10:90, 20:80, 30:70, 40:60, 50:50, 60:40, and 70:30 were prepared. In the case of the 70:30 blend, breakage of roving in between the drafting zone and flyer eye of the speed frame (Simplex) machine was observed which ultimately disrupted the roving production. This problem arose because the excessive presence of short fibers could not withstand the stress imposed on the drafted fiber strand before twisting in the commercial Simplex machine. As a result, it was not possible to prepare yarn using the 70:30 recycled and virgin cotton blend.

Based on the blend ratio, the necessary quantities of recycled cotton and virgin cotton fibers were weighed using an electric balance. Afterward, the fibers were manually mixed and left for conditioning at ambient temperature for a minimum of 8 h. Total of 7 mixing (100 % cotton, and recycled cotton blends with 10, 20, 30, 40, 50, and 60 %) were prepared manually. To generate sufficient yarns for testing and the production of fabric samples, 40 kg fiber was taken for each mixing, as shown in Fig. 4, to obtain 20 roving

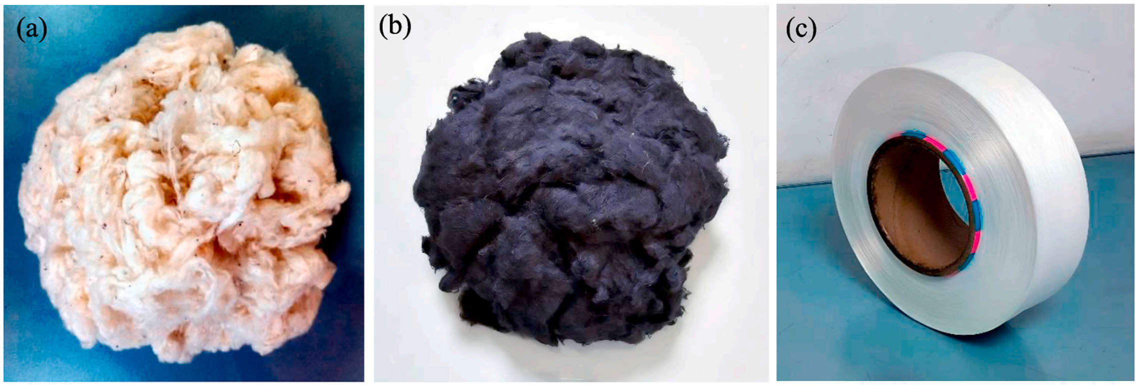

Fig. 2. Fibers used in the study. (a) Virgin cotton, (b) Recycled cotton, and (c) Creora spandex filament.

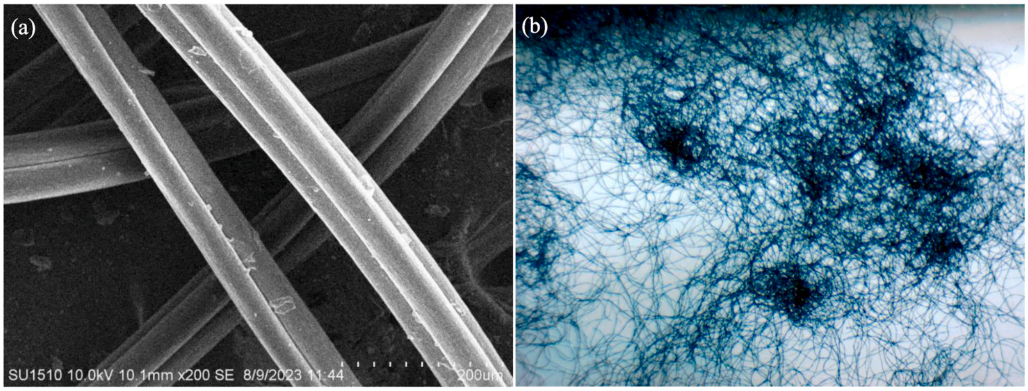

Fig. 3. (a) Scanning electron microscope (SEM) of Creora 40D/3F filament showing 3 spandex monofilaments are coalesced together, and (b) Optical microscopic image (100 ×) of black recycled cotton containing neps-like fiber clusters.

Table 1
HVI *fiber properties* of virgin cotton and recycled cotton. Parameters of elastane filament are also included.

Fiber type	SCI	Fineness	Upper-half mean length (UHML) (mm)	Uniformity Index (UI) (%)	Short fiber index (SFI) (%)	*Strength (g/tex)*	Elongation (%)
Virgin cotton (Brazil)	***134***	***4.01 Mic***	***30.89***	***82.2***	***5.6***	***30.3***	***7.9***
Pre-consumer waste cotton	***3***	***4.21 Mic***	***22.23***	***67.9***	***43.3***	***12.5***	***5.3***
Elastane (Creora H 350)	***-***	***40D/3F***[a]	***-***	***-***	***-***	***8.1***	***450***

[a] Creora H350 40D/3F is a product of 3 spandex monofilaments coalesced together that act as a single filament as shown in Fig. 3a.

Fig. 4. A representative mixing of recycled cotton: virgin cotton 40:60.

bobbins each weighing between 1.2 and 1.3 kg.

2.3. Fiber processing in spinning line

Following the conditioning process, the blended fibers were fed into the blow room line through Mixing Bale Opener (MBO) and then passed to carding and two passages of draw frame, namely breaker draw frame and finisher draw frame. The details of the machinery and technical specifications are given in Table 2. Notably, both recycled cotton and virgin cotton fibers got an opportunity for intimate blending during manual mixing, blow room, carding and two draw frames. Finally, their homogeneous blends were achieved in finisher draw frame, as sliver images are illustrated in Fig. 5 (a – g).

Finisher-drawn slivers were characterized by the Advanced Fiber Information system (AFIS Pro-2) following ASTM D5866-05 method. Parameters of all slivers obtained from AFIS are tabulated in Table 3. For the convenience of comparison, AFIS parameters of 100 % virgin cotton and 100 % recycled cotton fibers are also included in Table 3. When compared with virgin cotton, it is seen that recycled cotton fiber contains more fiber neps (shown in Fig. 3b) and short fibers that were generated during the aggressive shredding operation of consumer waste fabric [21]. Though a good amount of waste was removed in blow room and carding depending upon the recycle fiber% in mixing (as shown in Table 4), the number of neps and shorts fibers were still higher in corresponding finisher drawn slivers (Table 3). However, the waste derived from blow room and carding are reused in mixing for the production of mélange yarn in rotor spinning frame.

2.4. Manufacturing of recycled cotton/virgin cotton yarn with elastane core

Core-spun yarns are exclusively produced in ring spinning machines [1,28–32]. Here, 16 Ne (36.9 Tex) elastic core-spun yarn, frequently used in industry as weft yarn in stretch denim fabric, was produced in a ring spinning machine equipped with a Suessen Elite® compact system. Suessen Elite® compact spinning stands as a pioneer in the field of compact spinning technology and has achieved remarkable success as a provider of compact spinning systems. The system utilizes an aerodynamic process to condense the fiber strand through a profile tube that is surrounded by a perforated lattice apron as shown in Fig. 6c. A supplementary top roller drives this perforated lattice apron, facilitating the condensation of the fiber strand [33].

To compare the improvement of yarn properties in compact spinning, the same count of yarns was also produced in a conventional ring spinning machine. Before spinning elastic core-spun yarns, an additional feeding attachment (Wuxi Longtex International Corporation, China) was experimentally installed for twelve units (6 spindles per unit × 2) in both conventional ring and compact spinning frame to feed elastane as core filament. Elastane is delivered using a positive feed roller that allows the controlling of the elastane draft. The drafted elastane is fed into the front roller nip, utilizing a V-grooved roller where the sheath fibers envelop it. The desired level of elastane draft is achieved by controlling the speed difference between the positive feed rollers and the front roller of the drafting unit of the ring frame. The elastane is integrated with the drafted fiber strand at the back of the additional top roller [1]. Fig. 6a and b demonstrates the process of manufacturing elastic recycled/virgin cotton core-spun yarn in both conventional ring spinning and compact ring spinning, respectively.

2.5. Characterization of yarns

The coefficient of variation of mass (CVm%), imperfections (thin places, thick places, and neps) [34], and hairiness of yarns were

Table 2
Production details for the preparation of recycled cotton contained elastic core-spun yarn.

Process	Machine & Model	Country of Origin	Delivery Materials	Speed
Blow Room	Rieter (MBO B34, UniClean B12, Unimix B76, Unistore A79, Uster Jossi Magic Eye, Condenser A21)	Switzerland	Card mat: 650 Ktex	1000 kg/h: Chute feed to card
Carding	Rieter C60	Switzerland	Card Sliver: 6.6 Ktex	130 m/min
Breaker Draw Frame	Rieter SB-D 22	Switzerland	Drawn Sliver: 5.2 Ktex	550 m/min (6 doubling)
Finisher Draw Frame	Rieter RSB-D 24 (with autoleveller)	Switzerland	Drawn Sliver: 5.3 Ktex	550 m/min (8 doubling)
Simplex	Electrojet Rovematic AF	Spain	Roving: 0.74 Ktex (TPM 46)	950 rpm (Flyer speed)
	Drafting Zone: Texpart PK 1550	Germany		
Ring Frame	Jingwei F1520 m	China	Yarn Count: 16 Ne (36.9 tex), (TPM 792 for compact, 780 for conventional)	10000 rpm (Average spindle speed)
	Drafting Zone: Texpart-2630SE	Germany		
	Compact attachment: Suessen	Germany		
	Lycra Attachment: Wuxi Longtex International Corporation	China		
Autoconer	Savio Polar M	Italy		1200 m/min

Fig. 5. Finisher draw frame slivers prepared with different blend ratios of recycled cotton:virgin cotton (a) 0:100 (100 % virgin cotton), (b) 10:90, (c) 20:80, (d) 30:70, (e) 40:60, (f) 50:50, and (g) 60:40.

Table 3
AFIS test reports of 100 % virgin cotton, 100 % recycled cotton, and finisher draw frame slivers consisted of recycled cotton and virgin cotton blends.

Material	Recycled cotton: Virgin cotton	Fiber neps (FN)/g	FN size [µm]	Seed-coat neps (SCN)/g	SCN size [µm]	Upper Quartile length (UQL) [mm]	Short fiber content, SFC (w) % [<12.7 mm]	Fineness [mtex]
100 % virgin cotton		249	674	15	1030	31.68	6.4	158
Finisher draw frame slivers	0:100	89	581	2	695	31.79	6.7	158
	10:90	102	592	2	721	31.50	7.8	161
	20:80	117	586	2	750	31.42	8.7	161
	30:70	141	590	3	781	31.17	9	162
	40:60	162	583	3	835	31.01	11.2	162
	50:50	184	602	4	868	30.32	12.3	163
	60:40	252	609	5	965	29.28	14.9	163
100 % recycled cotton		1104	811	156	1393	21.54	32.6	166

Table 4
Blow room and carding waste for different recycled fibre% in mixing.

Recycled fibre%	Blow room waste%	Carding waste%
0	1.8	3.5
10	2.4	4.7
20	3.1	5.9
30	3.9	7.5
40	4.8	9.2
50	6.1	11.8
60	7.6	13.4

measured by Uster® Tester 6 (UT 6, Uster Technologies, Switzerland) following ASTM D1425/1425M-14(2020) standard. Yarn hairiness (H) quantifies the overall length of protruding fibers (in cm) within 1 cm length of yarn. It is assessed by the hairiness sensor provided with the evenness tester, which operates on the optical principle.

The tensile properties of yarns were examined by Titan Universal Testing Machine, James Heal operated with a constant rate of extension principle following ASTM D 2256 standard. A load cell of 100 N, a gauge length of 250 mm, and a crosshead speed of 250 mm/min with 5 cN pretension were used. Before testing, all samples were conditioned according to the ISO 139 standard. The

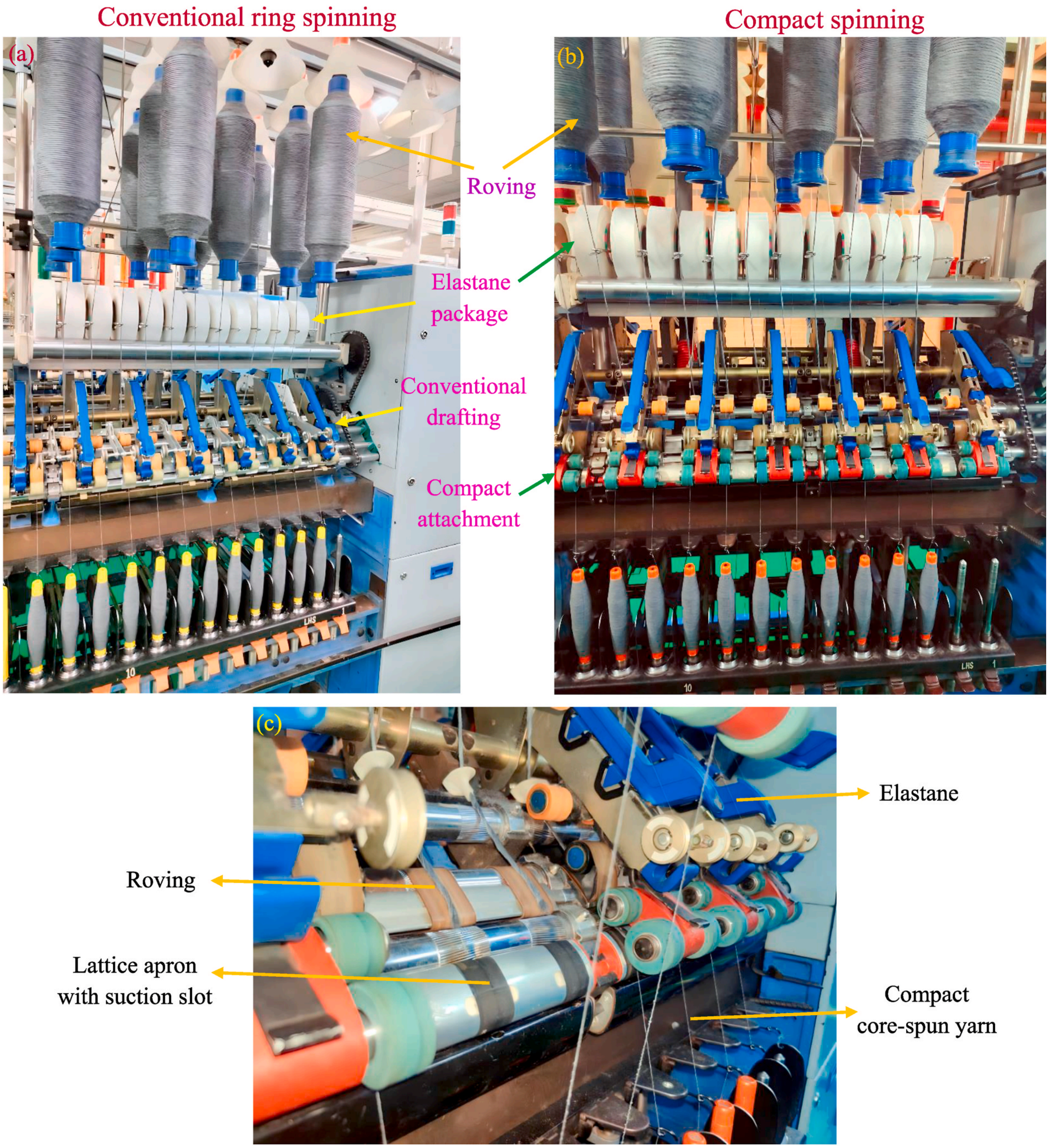

Fig. 6. Manufacturing of elastic recycled-/virgin cotton core-spun yarn in (a) conventional ring spinning and (b) compact spinning. (c) A cradle was lifted to show the Suessen aerodynamic compacting mechanism by lattice apron & suction slot.

laboratory testing environment maintained a standard atmosphere with a relative humidity of 65 ± 2 % and a temperature of 25 ± 2 °C. The test involved conducting 10 readings for each yarn sample, and the mean value was computed.

The surface characteristics of the yarns were observed under an optical microscope, Euromex BV, Model NZ 1703-M, Netherlands, and scanning electron microscope (SEM), JEOL 6460LV, Tokyo, Japan.

3. Results and discussion

3.1. Selection of spacer for manufacturing elastic core-spun yarns

In the main (front) drafting zone of ring frame, the highly attenuated fiber strand is guided up to the front roller nip through the top and bottom aprons. A spacer is used to introduce a gap between the lower edge of the top cradle and the bottom apron nose bar which, in effect, regulates the gap between two aprons. This, in consequence, governs the pressure exerted on the fibers by two aprons, ensuring precise control of drafted fiber strands [35].

In the current investigation, the production of elastic core-spun yarns with different proportions of recycled cotton/virgin cotton was aimed to produce in compact spinning frame using traditional spacers commonly used in ring spinning frame, as shown in Fig. 7 (a – c). When yarns with higher recycled fiber content, such as 40 %, 50 % and 60 % were produced, remarkably high unevenness, imperfections (thin, thick and neps) and hairiness in yarns were observed. It was due to the high amount of short fibers present in recycled cotton (tables 1 and 3), which could not be efficiently controlled between two aprons. Since the structural parameters of yarns determine their mechanical properties, particularly strength and elongation, an attempt was made to improve the yarn structure by better-controlling of fibers within the drafting zone. This improvement involved replacing the traditional spacer with a specially designed PINSpacer.

PINSpacer is the latest concept and was specially designed only for Suessen compact spinning frame. Its merit is yet to be explored by the yarn manufacturers. It was heard from industry insiders that PINSpacer is effective in controlling short fibers within the drafting zone of Suessen compact spinning frame, especially when producing medium to finer counts of carded yarns. Since Suessen's compact spinning technique was employed in this study, Suessen PINSpacer NT underwent testing. PINSpacer NT necessitated the replacement of the conventional cradle with a specially designed cradle, namely active cradle, that is enable to accommodating the PINSpacer [36]. Unlike one-piece PINspacers that are usually used in ring frame, Suessen's active cradle PINSpacer NT consists of three elements: the active cradle, a Spacer NT and a PIN NT (Fig. 8a). The active cradle has a spring-loaded edge. In case the top apron is stretched over time or tolerances are not perfect, this edge prevents the buckling of the top apron which helps in attaining a high yarn evenness. As shown in Fig. 8b, the PIN NT can easily be attached to the Spacer NT. The PIN NT penetrates the path of the drafted fibers just before they reach the nipping line (marked by an arrow in Fig. 8c). PIN is positioned at the center of the triangle between the bottom apron, bottom roller, and front top roller. The PIN NT profile was designed to ensure that the drafted fiber strand is forced to run under the

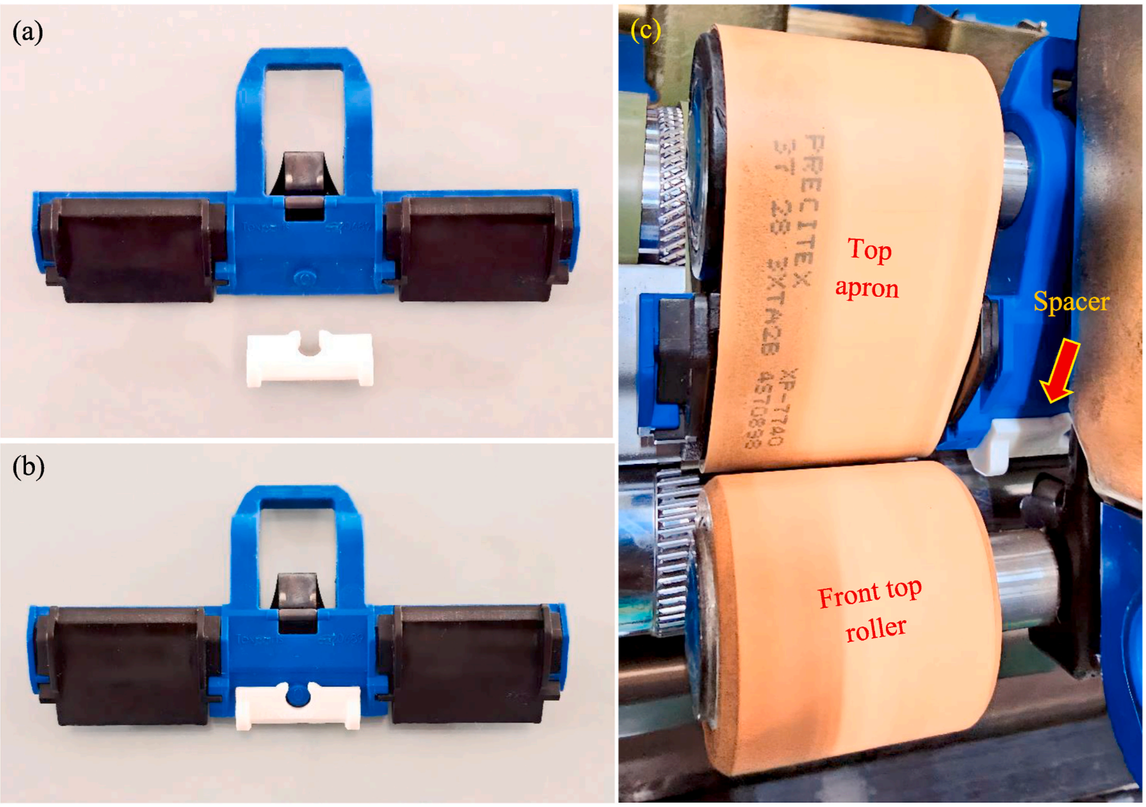

Fig. 7. Traditional spacer used in ring frame: (a) Cradle and spacer, (b) Spacer mounted in cradle, and (c) Spacer (marked by red arrow) drafting zone of ring spinning frame. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

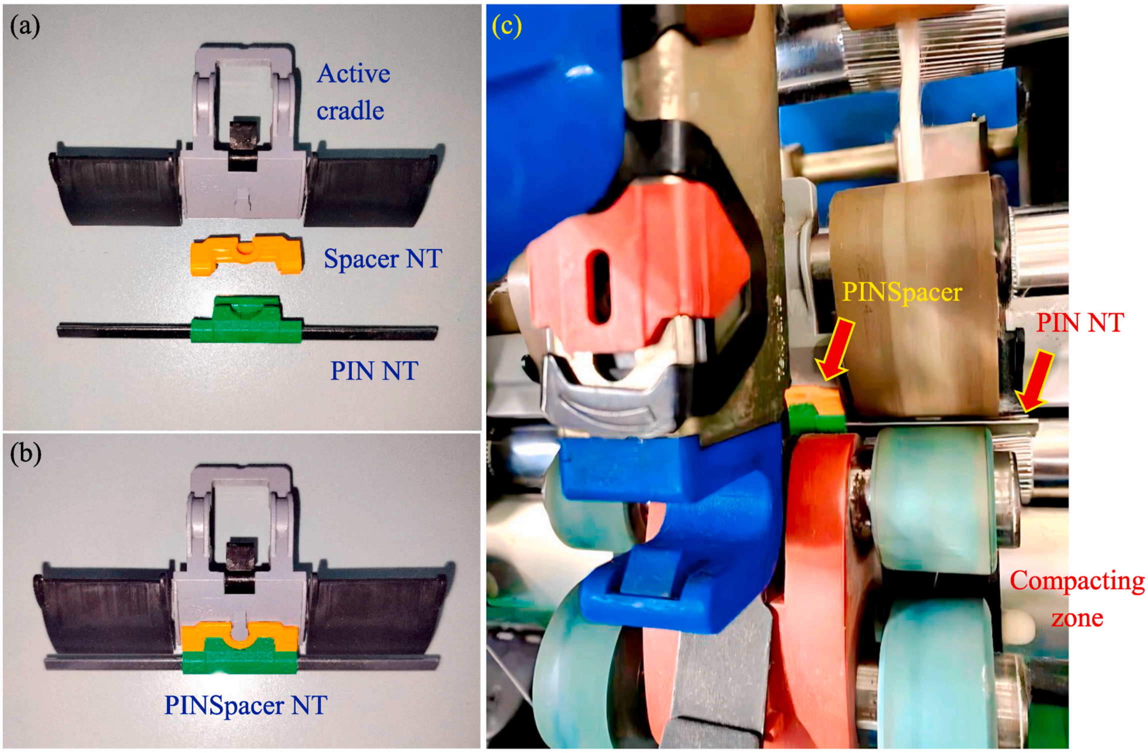

Fig. 8. Image of (a) Active cradle, Spacer NT and PIN NT, (b) PIN NT combined with PINSpacer NT and attached with cradle, and (c) PINSpacer NT installed in spinning frame. Projected PIN of PIN NT (indicated by arrow) acts as guide of drafted fiber strand.

PIN. The effect is similar to the one that is achieved with the well-known pressure bar on draw frames. By restricting the fiber flow to some extent, the PIN NT ensures a more even drafting, which results in up to 40 % reduction of imperfections and an increase in tenacity from 0.5 to 1 cN/tex [37].

There are as many as 50 combinations of PIN NT and Spacer NT (5 different pins and 10 different spacers). After several trials, the lowest unevenness, imperfections and hairiness for recycled cotton/virgin cotton elastic core yarn were obtained for PIN NT green (Immersion depth 0.00 mm and spindle gauge 70/75 mm) and Spacer NT yellow 3.25 mm (shown in Fig. 8).

Fig. 9 displays the SEM images of 16 Ne (36.9 Tex) elastic recycled cotton/virgin cotton (50/50) yarns manufactured in the conventional ring, compact ring with traditional spacer and compact ring with PINSpacer NT. It is obvious that compared to the yarn produced in the conventional ring frame (Fig. 9a), yarns manufactured in compact spinning (Fig. 9b and c) attained a compact structure with lower hairiness. Remarkably, compact yarn produced with PINSpacer (Fig. 9c) shows highest compact structure with lower hairiness than the compact yarn produced with traditional spacer (Fig. 9b). Due to this reason, the whole experiments of this study proceeded using that combination of PINSpacer NT.

It should be mentioned here that, unlike other compact yarns, perfect and homogeneous compacting of the elastic recycled cotton/virgin cotton yarns was difficult to achieve since high short fiber% in recycled yarn were inhibited from binding to the yarn body by the elastic filament in yarn core.

3.2. External view of the elastic core-spun yarns

Fig. 10 displays the 16 Ne (36.9 Tex) elastic core-spun yarns produced with varying percentages of black recycled cotton, specifically 0 %, 10 %, 20 %, 30 %, 40 %, 50 % and 60 %. The yarns exhibit an appearance resemblance mélange yarns with discernible shade differences derived from the different proportions of black recycled fiber within the yarn composition. It can be deduced from the yarn images that by changing the proportion of colored recycled fibers, it is possible to generate diverse types of mélange yarns, such as ecru-, grey-, and anthra mélange, encompassing a wide spectrum of shades.

Melange is a French word denoting the mixture or blend. It refers to the mixing of different colored fibers that give an exclusive shimmering and mottled color effect in yarn or fabric. The diverse spectrum of color shades achieved through fiber blending contributes to its widespread appeal and luxurious aesthetic. With continuous breakthroughs in production technology, mélange yarns have gained popularity in denim, upholstery, and sophisticated fashionable garments. Melange yarn is typically manufactured by blending colored viscose fiber with virgin cotton. Other fibers such as lyocell, bamboo rayon, and seacell can also be used as an alternative to viscose to produce mélange yarns [38]. In the current study, the use of colored recycled fiber alongside virgin cotton presents two distinct advantages: first, it can be manipulated in producing value-added fancy yarns like mélange which offer very

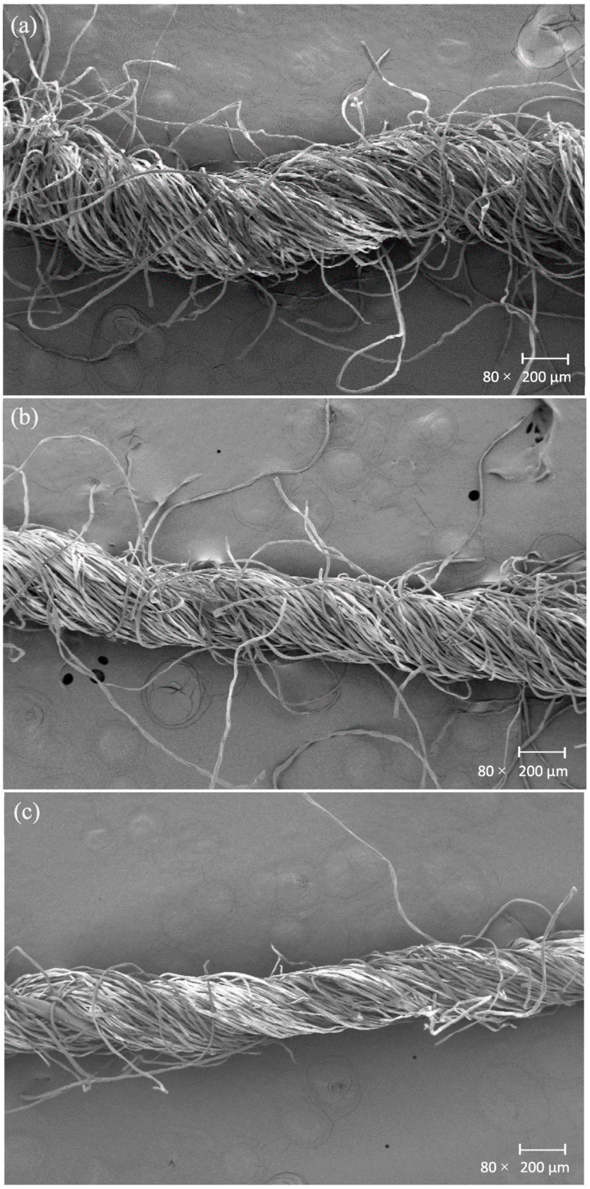

Fig. 9. SEM images of elastic recycled cotton/virgin cotton (50/50) yarns manufactured in (a) conventional ring spinning with traditional spacer, (b) compact spinning with traditional spacer and (c) compact spinning with PINSpacer NT.

attractive prices to the yarn consumers, and second, it can largely reduce the usage of virgin cotton as well as its cultivation.

3.3. Morphology of the elastic core-spun yarns

It is crucial to ensure the perfect centering of elastane in core-spun yarn. This is because the core filament and the outer sheath fibers work together when subjected to tension, leading to higher yarn strength. Off-centered elastic core filament easily ruptures while washing denim garments, especially during stone washing, and that is a common concern of garment manufacturers. As sheath fibers, used in this work, contain shorter-length recycled fibers, hence perfect centering of the core filament, and covering core filament by sheath fibers were carefully controlled during spinning. In this context, the elastane draft has a role in deciding the perfect centering of the core filament [1]. Here, the optimum elastane draft was experimentally determined at 3.33 in terms of perfect centering of filament. This draft was also optimized concerning higher tensile strength, elongation at break, and elastic recovery of yarn.

The morphology of elastic core-spun yarns made with recycled cotton/virgin cotton was studied by an optical microscope. All yarns showed perfect centering of elastic core components. A representative microscopic image of partially ruptured core-spun yarn containing 30 % recycled cotton is shown in Fig. 11a. Before capturing this image, the yarn was slightly untwisted and then pulled on both

Fig. 10. Ring bobbins of 16 Ne (36.9 Tex) elastic melange yarns produced with varying black recycled cotton% in conventional ring, and compact ring spinning. Black recycle cotton% is mentioned in figure.

sides carefully till rupturing only the sheath fibers keeping the elastane core filament unruptured. As seen, the morphology of yarn substantiates the idealized architecture of core-spun yarn, as depicted in Fig. 1, where it was expected that a perfectly centered core filament would be encircled with sheath fibers.

Fig. 11b and (c) exhibit the representative microscopic images of elastic recycled cotton/virgin cotton (30/70) yarns produced in conventional ring and compact ring spinning, respectively. As expected, a distinctive compact structure with lower hairiness can be observed for yarns produced in compact ring spinning. A comprehensive analysis of this matter will be provided in the upcoming sections.

3.4. *Structure and properties of yarns*

3.4.1. *Mass variation of yarns*

The coefficient of mass variation (CVm%) is conveniently used to express the irregularity or unevenness of yarn. Fig. 12 shows the CVm% of 16 Ne elastic yarns made with different proportions of recycled cotton/virgin cotton through both conventional ring and compact ring spinning frames. Additionally, the CVm values of elastic yarns made with 100 % virgin cotton (designated by 0/100 %) are also included for comparison purposes.

It is visible in Fig. 12 that CVm% of all elastic yarns containing recycled fibers is higher than those of yarns composed of 100 % virgin cotton. In addition, CVm% of yarns exhibits gradually higher values with the increase of recycled fiber%. Looking at HVI and AFIS results shown in tables 1 and 3, the reason can be attributed to the comparatively lower fiber length (UHML and UQL) and the presence of a significant amount of short fibers in recycled fibers which were generated due to the intense tearing action of consumer fabric waste during shredding operation. In various stages of the drafting process in spinning lines such as draw frames, Simplex, and ring frames, the short fibers become uncontrolled between the rollers. This causes the formation of irregular waves in the drafting process, ultimately leading to higher unevenness in the yarns.

Another observation can be found in Fig. 12 that the CVm% decreases for all compact yarns compared to conventional ring core-spun yarns. The reason can be interpreted in the following manner.

In conventional ring spinning, the spinning triangle is formed right after the drafted fiber ribbon exits the front roller nip. Within this spinning triangle, the fibers experience varying levels of tension based on their positions. The outermost fibers in the spinning triangle are highly deflected and cannot be uniformly integrated into the yarn structure, as evidenced by the SEM image in Fig. 13a. On the contrary, compact spinning operates differently by eliminating the spinning triangle. This approach facilitates a higher degree of parallel alignment and compression of fibers within the condensing zone through the aerodynamic principle after the main drafting process. This ensures the incorporation of a greater proportion of fibers into the yarn structure, as illustrated in Fig. 13b. Furthermore, the utilization of PINSpacer enhances the smooth and uniform advancement of the drafted fiber strand into the compacting zone, as illustrated in Fig. 8. This, in turn, improved the effectiveness of the aerodynamic compacting mechanism and consequently results in the decrease in yarn unevenness [39].

It is noteworthy that the CVm values of the core-spun yarns produced up to 50 % recycled cotton was in the range of 5 %–50 % level of Uster Statistics 2023. CVm of 60 % recycled cotton sample lies in between 50 % and 95 % of Uster Statistics (marked in Fig. 12). This suggests the skilled engineering and precise process control of the yarn manufacturing from the fibers that included a high amount of short fibers i.e. recycled cotton.

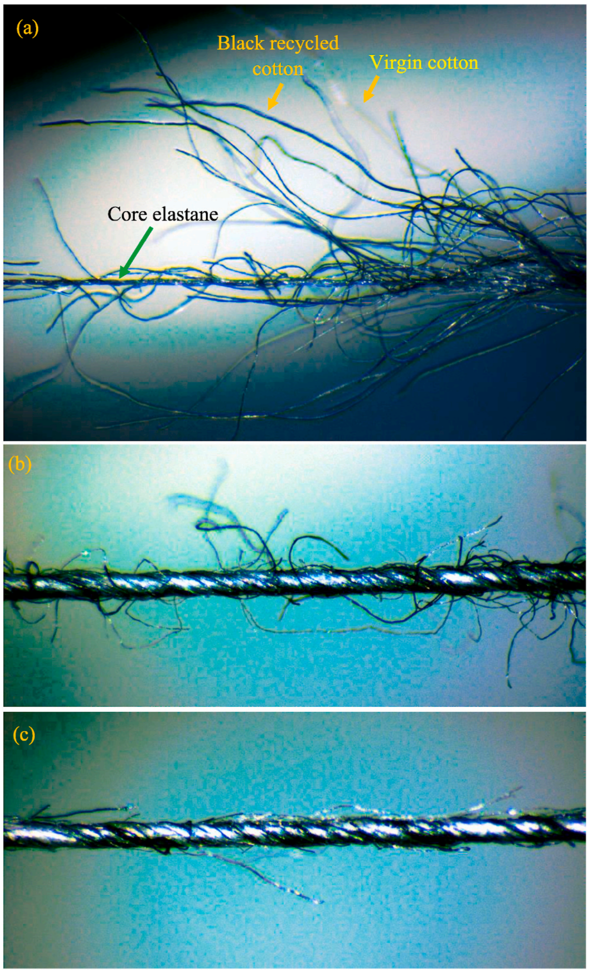

Fig. 11. Optical microscopic images (30 ×) of recycled cotton/virgin cotton (30/70) elastic core-spun yarns: (a) internal morphology of yarns showing perfect centering of core filament surrounded by recycled cotton and virgin cotton fibers. Surface morphology of yarn produced in (b) conventional ring and (c) compact spinning.

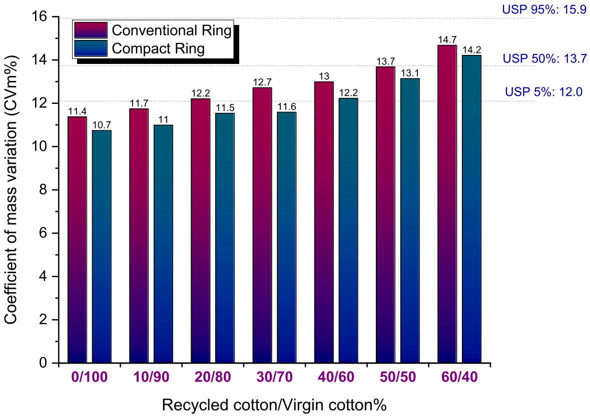

Fig. 12. Unevenness (CVm%) of 16 Ne (36.9 Tex) elastic core-spun yarns made with different% of recycled cotton/virgin cotton manufactured in conventional ring and compact spinning. Values of CVm in Uster Statistics Percentage (USP) 2023 is shown at right side.

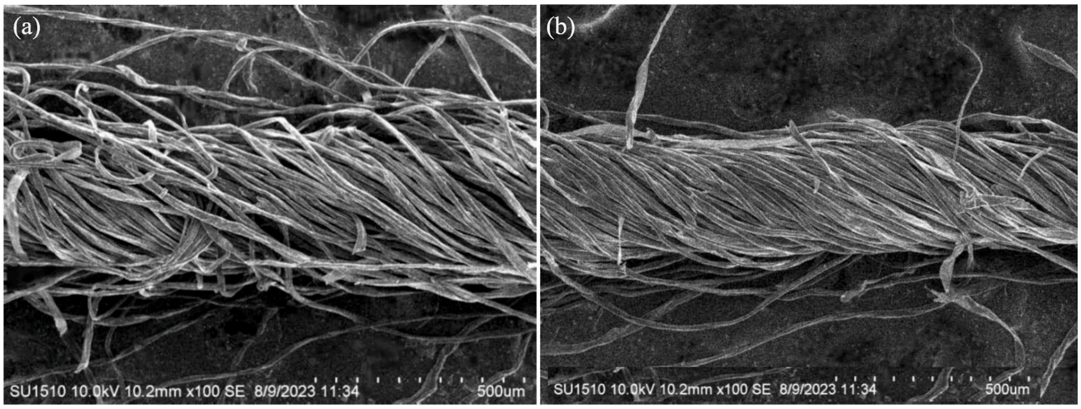

Fig. 13. SEM images of elastic recycled cotton/virgin cotton (30/70) yarns manufactured in (a) conventional ring and (b) compact ring spinning.

3.4.2. Imperfections of yarns

Like CVm%, imperfections are also taken into consideration when evaluating the unevenness of yarns. The imperfections of yarns have a significant impact on the subsequent processing (warping, sizing, and weaving) and the visual appearance of fabrics as well.

The imperfections such as thick place (+50 %), thin place (−40 %), and neps (+200 %) of elastic core yarns spun in conventional ring and compact spinning are exhibited in Fig. 14a and (b) and 14(c), respectively. Imperfection index (IPI) [40], the sum of thin, thick, and neps, is also shown in Fig. 14d. For the calculation of the IPI of ring yarns, thick (+50 %), thin (−50 %), and neps (+200 %) are usually taken. But for all the yarns produced here, thin places in (−50 %) threshold were almost nil, so thin (−40 %) was considered for the convenience of data analysis.

Imperfections increased with the increase of recycled fiber% in yarn that is because of the presence of higher short fiber% and neps-

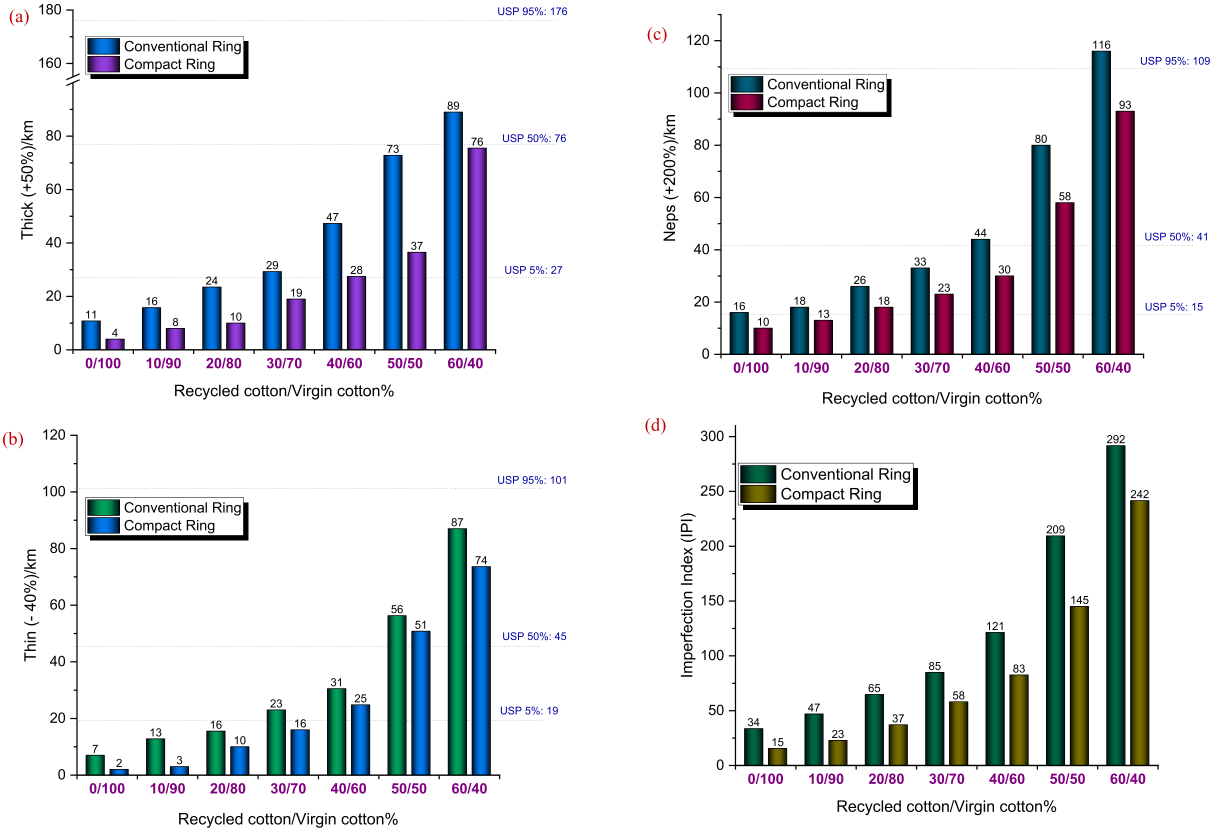

Fig. 14. Imperfections of elastic core-spun yarns containing different recycled cotton/virgin cotton% produced in conventional ring and compact spinning systems: (a) thick places, (b) thin places, (c) neps and (d) Imperfection Index (IPI) [thick + thin + neps].

like fiber agglomerations in recycled fiber shown in Fig. 3. Compared to the core-spun yarn produced in the conventional ring, a notable reduction in thick, thin and neps is evident for the compact yarn. In the compact spinning process, fibers are effectively guided by the projecting pin of the PINSpacer NT, as illustrated in Fig. 8. Subsequently, these fibers are neatly controlled within the condensing zone through the assistance of pneumatic suction, resulting in a firmer yarn structure. The suction system also aids in incorporating protruding fibers into the overall yarn body. The precise control of fiber strands, coupled with the integration of additional fibers, enhances the overall consolidation of the yarn structure.

The role of PINSpacer NT on neps was then investigated in a separate experiment. Ten recycled cotton/virgin cotton (50/50 %) rovings were mounted in a ring frame and passed through the drafting zone of compact spinning while equipped with PINSpacer NT. To check the neps count in fibers through AFIS, the drafted fiber strands were collected through the pneumafil waste collector without making yarn. The same experiment was carried out using the traditional spacer separately. Information regarding neps obtained from the AFIS is tabulated in Table 5.

In Tables 5 and it is seen that in the case of using PINSpacer, neps present in roving decreased whereas they increased when the traditional spacer was used. When the drafted fiber strand comes out from the two aprons and proceeds towards the front roller nip under the pressure imposed by the projecting pin of PINSpacer (shown in Fig. 8), a good number of neps-like fiber lumps (shown in Fig. 3b) get an opportunity to be opened up by the pin. Conversely, in the case of the traditional spacer (shown in Fig. 7), there is no pin to control the movement of the fiber strand. Resultantly, some fibers may have buckled when the drafted fiber strand moves from the apron nip to the front roller nip at high speed, leading to the formation of fiber tangles resembling neps.

The incorporation of PINSpacer in the compacting mechanism contributed to the outstanding reduction of unevenness and imperfections (thick, thin, and neps). Our findings largely surpassed the imperfections levels reported in the previous article which discussed the properties of a similar count of compact yarns made with recycled cotton/virgin cotton blends [20]. It is mentionable that the imperfections of our yarns could have been further decreased if a combing process had been employed. However, opting combing process would have incurred additional cost, making the yarn less economically viable for denim yarn production.

3.4.3. Hairiness and hairiness variation of yarns

In principle, the spun yarns are composed of twisting staple fibers where projecting fibers cause a fuzzy or hairy texture on the yarn surface. Although many short fibers protruding out from the yarn body can enhance the texture significantly, excessive hairiness may negatively affect both the visual and functional characteristics of textile products [41]. The level of hairiness in the yarn is determined by the quantity of hairy fiber ends that extend from the yarn surface [42]. Among various characteristics, hairiness and its variation are also regarded as noteworthy quality parameters of yarns. A certain length of hairiness in yarn is desirable as it provides feel and comfort to the fabric. However, an excessive amount of hairiness can negatively impact yarn performance during weaving and knitting. Variations in hairiness can diminish the quality of final products by affecting visual appeal and texture. Hairiness variation may also cause weft bars and warp-way streaks in the fabric [43].

Fig. 15a and (b) express the dependence of the hairiness index (H) and its variation (standard deviation of hairiness, sH) with the recycled fiber% in yarns for conventional ring and compact ring yarns. Similar trends like CVm% and imperfections are noticeable in the case of the hairiness of the yarn. This outcome can be explained by considering the presence of higher proportion of short fibers in the recycled fibers obtained from shredded consumer fabric waste (tables 1 and 3). Moreover, the dyed fibers sourced from consumer waste tend to be coarser [44] as indicated by the fiber fineness values in tables 1 and 3. In ring spinning, shorter and coarser fibers tend to migrate toward the outer layer of the yarn balloon, whereas longer and finer fibers gravitate toward the yarn core [44,45]. These phenomena likely contribute to the higher yarn hairiness observed when the colored recycled fiber in the yarn is increased.

However, there was a notable reduction in hairiness values across all compact core yarns. In general, the hairiness of core-spun yarns is higher compared to non-core yarn. This is because, in the presence of core filament, the sheath fibers cannot integrate tightly within the yarn structure due to their uncontrolled movement during the ballooning operation in the spinning process, leading to higher hairiness [46]. The results illustrated in Fig. 15a and b indicate that implementing a compact spinning system together with PINSpacer can effectively reduce both the hairiness and its variation. The values of H and sH reduced to the level of the Uster Statistics nearly 5 % threshold, indicating the perfect controlling of the short fibers that existed in recycled cotton.

The fascinating lower hairiness of elastic core yarn containing recycled fibers was observed by examining the yarn surface with a scanning electron microscope (SEM). Representative SEM images of yarns containing 30 % recycled fibers are exhibited in Fig. 16 (a, b). In good agreement with the optical microscope images shown in Fig. 11, SEM image of elastic compact core yarn manifests a very compact structure with highly aligned fibers and much less hairiness even with the presence of shorter length of recycled fibers. As previously elucidated, the compacting process involves the insertion of a twist to a straightened and condensed fiber strand, resulting in fewer protruding hairs. Conversely, the elastic core-spun yarn manufactured through the conventional ring spinning system showcases a considerably less impeccable structure in comparison to the compact yarn. Many fibers adhere to the yarn in a disorderly manner. The fibers at the outer edges of the spinning triangle cannot be fully integrated, protruding from the twisted yarn body and

Table 5

AFIS neps data while using normal spacer and PINSpacer NT of compact ring frame for recycled cotton/virgin cotton (50/50 %) rovings.

Materials	Fiber Neps/g	Fiber neps size (μm)	Seed-coat neps (SCN)/g	SCN size (μm)
Roving	159	598	5	860
Pneumafil (traditional spacer)	197	609	3	869
Pneumafil (PINSpacer NT)	138	607	2	730

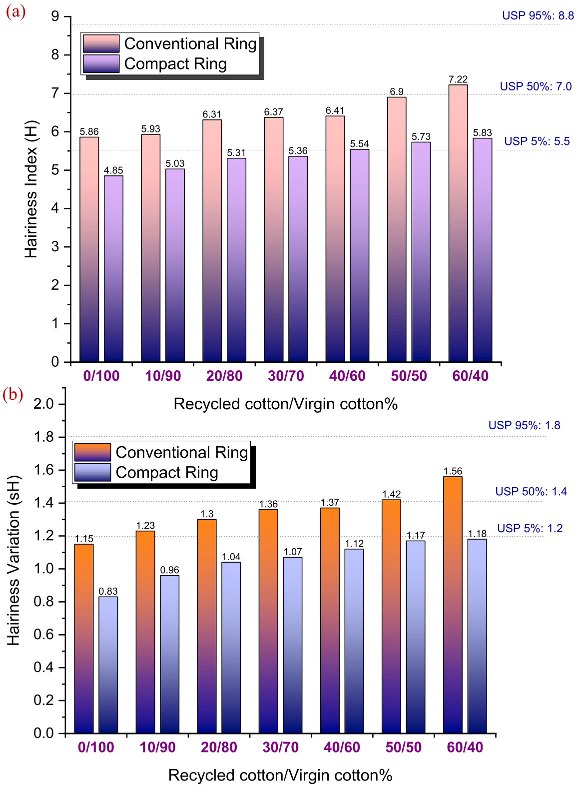

Fig. 15. (a) Hairiness index (H) and (b) hairiness variation (sH) of elastic core-spun yarns containing different recycled cotton/virgin cotton% produced in conventional ring and compact ring spinning. Values of H and sH in Uster Statistics Percentage (USP) 2023 are shown at right side.

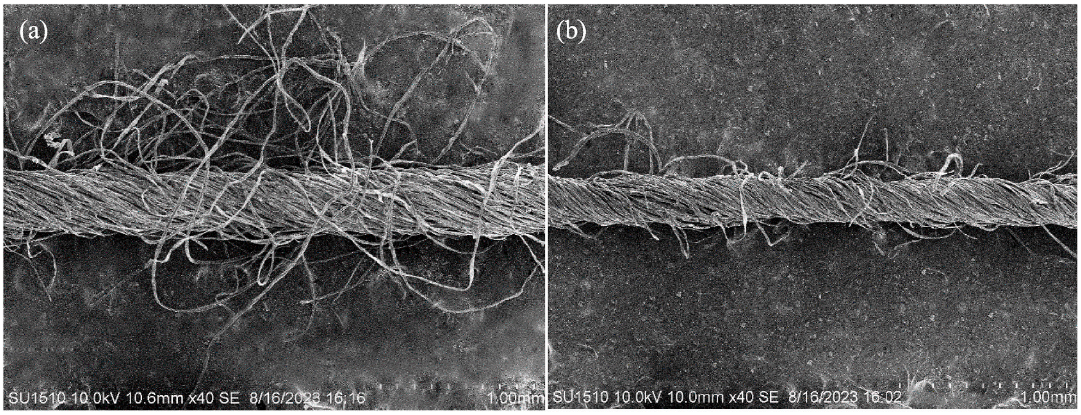

Fig. 16. Scanning electron microscope (SEM) images of elastic core-spun yarns containing 30 % recycled cotton produced in (a) conventional ring and (b) compact spinning.

leading to pronounced hairiness across the yarn surface.

3.4.4. Correlation between yarn structure and mechanical properties

The dependence of the proportion of recycled cotton on the tensile properties of the conventional ring and compact ring yarns was studied. Fig. 17a and b illustrate the representative stress-strain curves of the elastic core-spun yarns produced in conventional ring and compact spinning frames. Compared to the yarn manufactured with 100 % virgin cotton, yarns containing recycled cotton show a gradual decrease in strength and elongation with the increase of recycled cotton%. In addition, compact yarns exhibit higher strength and elongation than the yarns prepared in conventional ring spinning.

To evaluate the performance of the yarns in subsequent processing, two kinds of yarn strength are considered in the industry: (i)

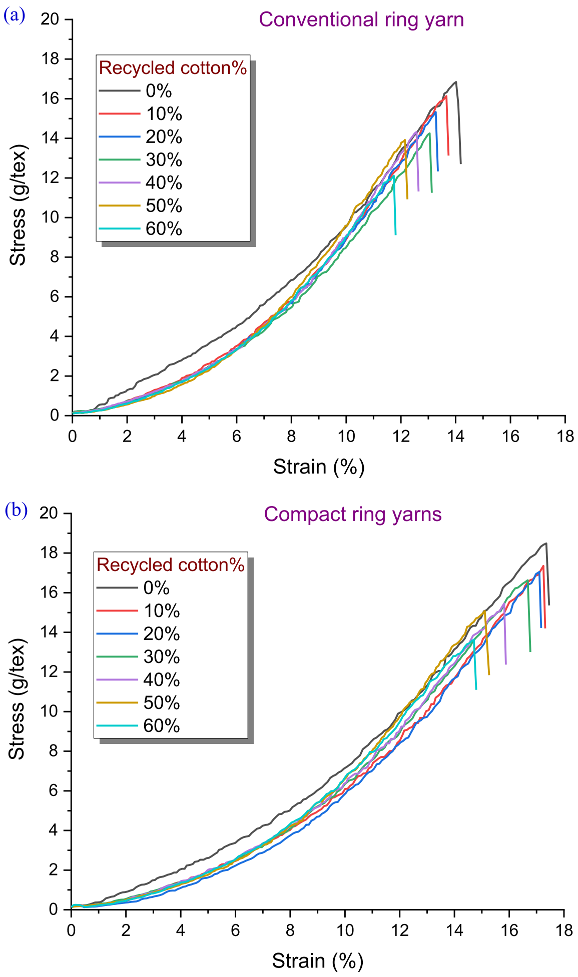

Fig. 17. Stress-strain curves of 16 Ne (36.9 Tex) elastic core-spun yarns containing different% of recycled cotton/virgin cotton produced in (a) conventional ring and (b) compact spinning frame.

CSP (for bundle yarn strength) and (ii) tenacity (for single yarn strength). The CSP (count strength product), refers to the product of the yarn count (English count, Ne) and the lea strength (in lb), which is a useful measure to express the bundle yarn strength of yarns. The CSP value allows for the comparison of yarns with a similar, though not necessarily identical count, much like how tenacity values are employed for this purpose. The single yarn strength is expressed by tenacity which is breaking force per linear density and its unit is g/tex or cN/tex. Tenacity is an essential characteristic of yarn necessary to withstand the various production stages of fabric manufacturing like winding, sizing, weaving, and knitting.

Figs. 18 and 19 show respectively the CSP and tenacity of elastic core-spun yarns containing different recycled cotton% produced in conventional ring and compact ring spinning. It is obvious that the CSP and tenacity show a gradually decreasing trend with the increase of recycled fiber% in yarn reflecting the corresponding increase in unevenness and imperfections (shown before in Figs. 12 and 14). The reason was previously explained as the presence of high short fiber content in the recycled cotton that was produced during the intensive shredding process. Unlike long fibers, short fibers cannot properly bind and migrate into the yarn body. When a yarn is exposed to tensile loading, the shorter fibers within the yarn tend to slip rather than actively contribute to resisting the applied force, resulting in a lower strength. Furthermore, the strength of cotton fibers diminishes during the dyeing process, making the dyed recycled cotton, which is weaker, and more susceptible to rupture when subjected to tensile stress [44].

The elongation at break of the elastic core yarns, evaluated from the respective stress-strain curves, is presented in Fig. 20. With the increase of recycled fiber content, a similar declining pattern like.

strength is seen. When force is applied to a yarn, it gets distributed among its constituent fibers, which underscores the importance of yarn elongation as well. The elongation of the yarn is interconnected to the extension of individual fibers along with the alignment and cohesion among the fibers within the yarn structure [25]. Since the recycled fibers consist of numerous short fibers, they cannot integrate well with the yarn structure which leads to easy detachment of fibers when force is applied, ultimately causing lower yarn elongation.

As depicted in Figs. 18 and 19, the CSP and tenacity of all elastic compact core-spun yarns can be observed to rise, indicating a

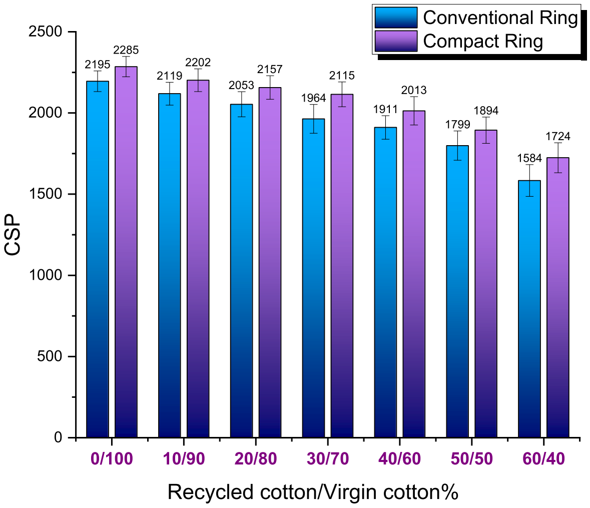

Fig. 18. CSP (Count Strength Product) of elastic core-spun yarns containing different recycled cotton/virgin cotton% produced in conventional ring and compact ring spinning.

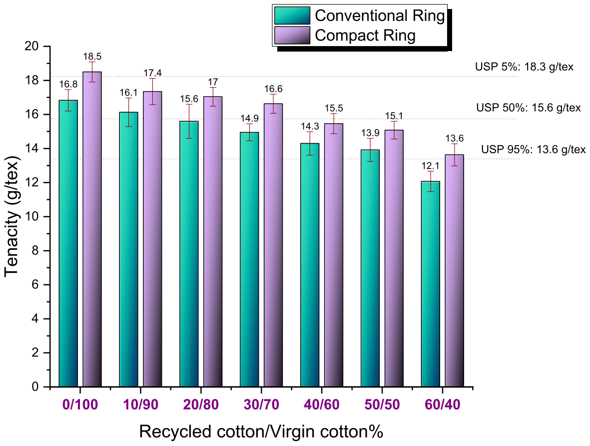

Fig. 19. Tenacity of elastic core-spun yarns containing different recycled cotton/virgin cotton% produced in conventional ring and compact ring spinning.

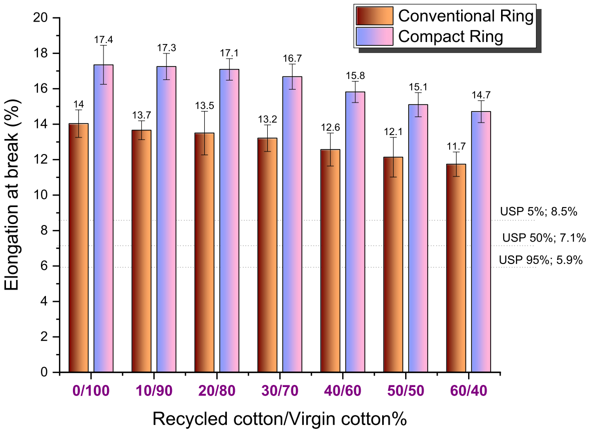

Fig. 20. Elongation at break% of elastic core-spun yarns containing different recycled cotton/virgin cotton% produced in conventional ring and compact ring spinning.

simultaneous reduction in unevenness and imperfections, as demonstrated earlier in Figs. 12 and 14, respectively. Furthermore, Fig. 20 illustrates that these compact core yarns exhibit a greater breaking elongation. The increased CSP, tenacity, and elongation of the compact core-spun yarns can be ascribed to the role played by the compacting zone and PINSpacer in developing the yarn structure, as previously explained.

3.5. Statistical analysis

Paired sample correlations and the significance of different proportions of recycled cotton with various parameters of elastic core-spun yarns are illustrated in Table 6. In the case of elastic core yarns produced in a conventional ring system, a positive correlation is found between recycled fiber% and yarn structural parameters such as yarn unevenness, thin, thick, neps, and hairiness. It implies that with the increase of recycled cotton% in blends, those yarn parameters increase. The fact of positive correlation is in good agreement with the graphical illustrations shown before in Fig. 12 (unevenness), Fig. 14 (imperfections) and Fig. 15 (hairiness). In Table 6, a negative correlation is found for CSP, tenacity, and elongation at break% indicating that with the increase of recycled cotton%, those yarn parameters decrease (referring Figs. 18, Fig. 19, and Fig. 20, respectively). All the correlations are observed to be highly significant ($p = 0.000$).

Similar correlation and significance between recycled cotton and yarn parameters were obtained for elastic core-spun yarns manufactured in compact spinning frame as shown in Table 6.

3.6. Sustainable and cleaner approach

Mélange yarn is manufactured by blending virgin cotton and colored fibers, mostly colored viscose, resulting in a distinctive blend of colors that forms a wavy pattern. Mélange fabrics offer a great advantage in that they do not require additional dyeing even when it is manufactured by blending a small percentage of colored fibers with virgin cotton. It ultimately protects the environment by saving water, dyestuffs, auxiliaries, and energy alongside reducing production costs [47]. However, the production of viscose fiber has notable negative impacts on human beings, the natural environment, and biodiversity. For instance, viscose originates from wood, contributing to the depletion of at-risk woodlands. Its manufacturing process utilizes significant amounts of harmful acids and noxious chemicals, endangering the environment through the contamination of air and water sources [19]. In another process of manufacturing mélange fabric, polyester staple fiber is used instead of viscose. In that case, fabrics are produced from PC (polyester/cotton) or CVC (chief value of cotton) blend yarns and then one part of the fabric is dyed keeping the other part undyed [48]. Melange effect arises in the fabric after dyeing. But the way of introducing the mélange effect in fabric by dyeing necessitates fabric pre-treatment, heat-setting, and dyeing which certainly involves the use of harmful chemicals, huge water, and energy together with discharging the hazardous effluent.

Cotton ranks as the world's second-largest textile fiber in terms of production. Despite its prevalence, it falls into the category with the lowest sustainability rating. The traditional cultivation of cotton involves the application of various chemicals found in fertilizers and pesticides. To put it into perspective, around 5.7 % of the world's pesticides and 16.1 % of insecticides are dedicated to cotton crops, despite utilizing merely 2.4 % of the total agricultural land. This heavy chemical usage not only contaminates the soil and nearby ecosystems but also poses a health risk to the people involved. These harmful chemicals often persist in the fabric even after the manufacturing process, potentially affecting the end-users [49].

The global denim fabric market size was valued at US$18.1 billion in 2020 and is projected to reach US$27.9 billion by 2030 [50]. Since the expense of raw cotton accounts for more than 50 % of the production expenses of ring-spun yarn [51], the addition of recycled cotton in manufacturing yarns with virgin cotton will result in a proportional decrease in the expense of raw materials. Cotton accounted for 24 %, or 26.5 million tonnes, of the global fiber market in 2020, while recycled cotton made up less than 1 percent [52]. So, there is a clear opportunity to build the enablers to scale up the recycling of cotton textiles.

The Sustainable Development Goals (SDGs), a set of 17 global goals, were adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. The 17 SDGs are meant to be integrated and indivisible, recognizing that progress in one goal often depends on progress in others [53]. Global manufacturing sectors are proactively transitioning towards sustainable and cleaner production methods in alignment with SDGs 12

Table 6

Paired sample correlations for recycled cotton% with various properties of elastic core-spun yarns.

Parameters	**Conventional Ring**		**Compact Ring**	
	Correlation coefficient	Significance	Correlation coefficient	Significance
Recycled cotton% & Unevenness	0 .939	0.000	0.917	0.000
Recycled cotton % & Thin	0.764	0.000	0.850	0.000
Recycled cotton % & Thick	0.857	0.000	0.813	0.000
Recycled cotton % & Neps	0.822	0.000	0.781	0.000
Recycled cotton % & Hairiness	0.802	0.000	0.807	0.000
Recycled cotton % & CSP	−0.881	0.000	−0.898	0.000
Recycled cotton % & Tenacity	−0.870	0.000	−0.911	0.000
Recycled cotton % & Elongation	−0.767	0.000	−0.561	0.000

targets which aim to achieve the environmentally sound management of chemicals and substantially reduce waste generation through prevention, reduction, recycling, and reuse, all while avoiding releases into air, water, and soil. This collective effort seeks to mitigate potential negative effects on both human health and the environment [54,55]. The production of denim yarn using as much as 60 % recycled cotton in this study introduces a concept aimed at advancing sustainability, and concurrently, providing the opportunity for cost-efficient denim clothing production. This approach not only reduces the necessity for cultivating new cotton and the accompanying processing but also makes noteworthy strides in environmental conservation across multiple dimensions indirectly meeting the other SDGs goals like goal 3 (good health and well-being), goal 6 (clean water and sanitation), goal 11 (sustainable cities and communities), goal 13 (climate action), goal 14 (life below water) and goal 15 (life on land) [53].

3.7. *Cost factors associated with sustainability*

Due to the relentless depletion of natural renewable resources, there is a growing global focus on exploiting recoverable waste in novel ways. Furthermore, because raw material expenses account for a significant portion of production costs, incorporating unavoidable processing waste into the manufacturing process offers substantial cost benefits to manufacturers [56,57].

The manufacturing cost of 16 Ne (36.9 Tex) elastic core-spun yarn covered by different proportions of recycled cotton and virgin cotton was calculated and compared with the same conventional elastic yarn produced with 100 % virgin cotton. The comparison is shown in Table 7.

Consumption of fibers in yarns was calculated using the following formulae that are usually practiced in industries [1]. Since the elastane draft remained constant i.e. 3.33 for all yarns, its consumption in each yarn was the same. The consumption of virgin cotton varied with changing the recycled cotton%.

(i) Elastane consumption% $= \frac{\frac{\textit{Elastane denier}}{\textit{Elastane draft}}}{\textit{Resultant yarn denier}} \times 100\ \% = \frac{\frac{40}{3.33}}{333.12} \times 100\ \% = 3.62\ \%$

(ii) Virgin cotton consumption% = [100 - (Recycled fiber consumption% + Elastane consumption%)].

Here, recycled fiber consumption was 10, 20, 30, 40, 50 and 60 %, and elastane consumption was 3.62 %.

As seen in Table 7, the manufacturing cost of elastic core-spun yarn with 100 % virgin cotton is USD 3.218/kg. With a gradual increase of the recycled cotton, the cost of yarn proportionally decreased and for 60 % recycled cotton containing yarn, the cost turns to USD 2.768/kg. This difference in manufacturing cost arises as the cost of virgin cotton (USD 2.2 USD/kg) is much higher than the cost of recycled cotton (1.36 USD/kg).

3.8. *Application of the yarns in denim production*

The performance of the 16 Ne (36.9 Tex) elastic core-spun mélange yarns produced in compact spinning was investigated by inserting as weft in a modern air-jet weaving machine (Picanol OMNIplus Summom, Belgium). It should be mentioned that elastic core yarn is commonly used in the weft when producing stretch denim fabric. The warp was 10 Ne (59.05 Tex) white ring-spun yarns and the fabric structure was 66 × 50 (EPI × PPI) with 3/1 right-handed twill. Fig. 21a and b show the representative 16 Ne elastic core-spun yarn containing 60 % black recycled cotton and the produced fabric by insertion of the yarn in weft direction. As seen, the weft yarns were prominent in the technical back side of the fabric as shown in Fig. 21c and d. It was found during weaving that elastic core yarn, which included 10–40 % recycled cotton, could operate at a rate of 1000 rpm (picks/min), while yarn with 50–60 % recycled cotton could run at a slightly reduced speed of 950 rpm. The loom speed of 950–1000 picks/min is equivalent to a weft speed of 94–99 km/h (reed width: 65 inches). This can be considered to be a great achievement of the current work that yarn containing 60 % recycled cotton was possible to be inserted as weft in a high-speed weaving machine. Furthermore, as depicted in Fig. 21 (b – d), the resulting denim fabrics look to be remarkably smooth and balanced, boasting a pleasing aesthetic appeal. It was challenging to recognize that the weft yarns in these fabrics contain as high as 60 % recycled cotton.

However, this article does not delve into the characterization of the fabric. To arrive at a solid conclusion regarding its

Table 7
Cost to manufacturing 1 kg of 16 Ne (36.9 Tex) elastic recycled cotton/virgin cotton yarn in compact spinning.

	The ratio of Recycled cotton: Virgin cotton: Elastane in Yarn						
Cost Components	**0: 96.38: 3.62**	**10: 86.38: 3.62**	**20: 76.38: 3.62**	**30: 66.38: 3.62**	**40: 56.38: 3.62**	**50: 46.38: 3.62**	**60: 36.38: 3.62**
Virgin cotton (2.2 USD/kg) (a)	2.12	1.9	1.68	1.46	1.24	1.02	0.8
Recycled cotton (1.36 USD/kg[a]) (b)	0	0.14	0.27	0.41	0.54	0.68	0.82
Elastane (4.38 USD/kg) (c)	0.158	0.158	0.158	0.158	0.158	0.158	0.158
Total Raw materials cost per kg yarn, d (a+b + c)	2.278	2.198	2.108	2.028	1.938	1.86	1.78
Manufacturing Overhead[b] per kg yarn (e)	0.94	0.95	0.955	0.965	0.97	0.98	0.99
Total cost of yarn per kg yarn (d + e)	**3.218**	**3.148**	**3.063**	**2.993**	**2.908**	**2.838**	**2.768**

[a] Current price of recycled cotton in Bangladesh is used. The price of recycled fiber varies time to time with the market demand.

[b] Manufacturing overhead (production cost including electricity & labor cost) slightly increased with the increase of recycled cotton% in yarn as the speed of ring frame had to be reduced accordingly to control the end-breakage.

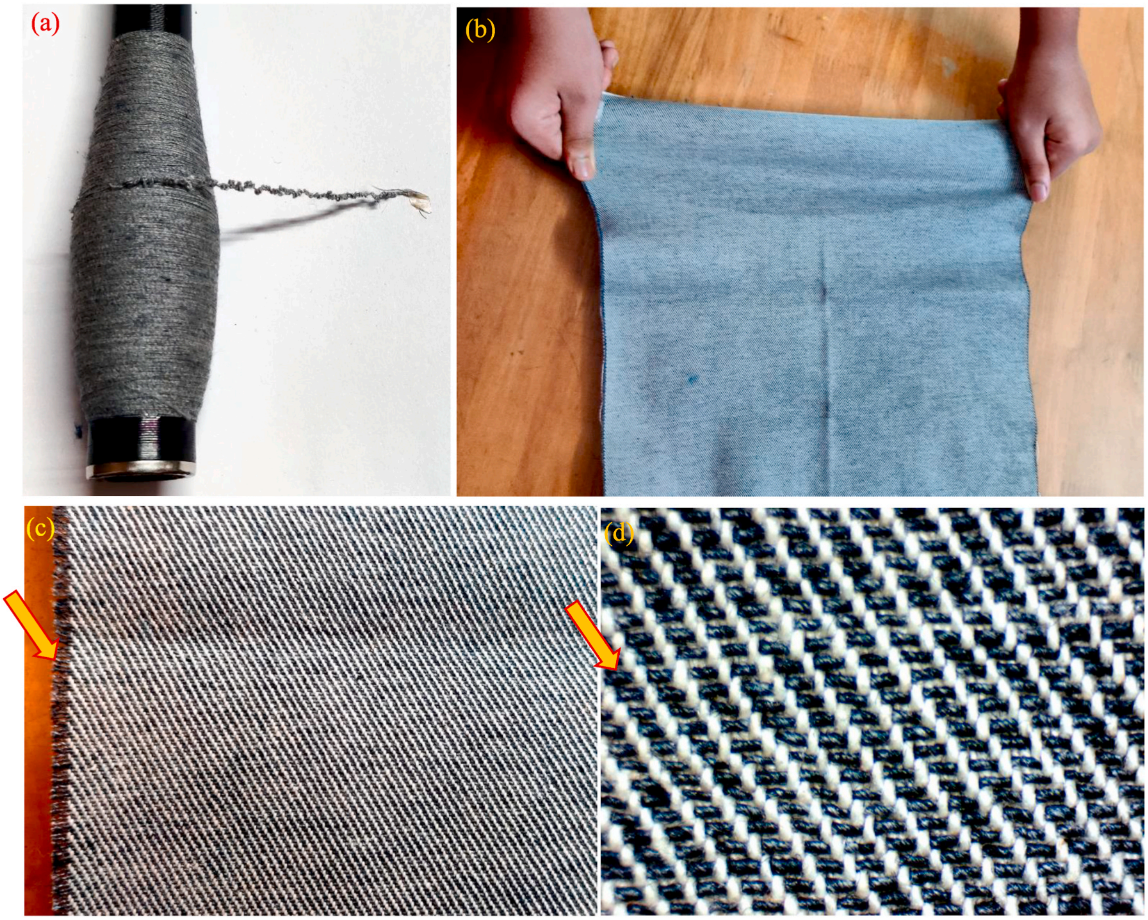

Fig. 21. (a) Elastic core-spun yarn containing 60 % black recycled cotton. (b) Stretch denim fabric produced in air-jet loom by inserting the recycled yarn in weft direction with white warp. (c) 10 × and (d) 100 × magnified images of the fabric that show the weft yarn in fabric (marked by arrow).

serviceability, it is necessary to conduct a comprehensive evaluation of the fabric properties.

4. Conclusion

Different ratios (10–60 %) of recycled cotton derived from mechanical shredding of pre-consumer fabric waste were blended with virgin cotton to manufacture 16 Ne (36.9 Tex) elastic core-spun yarns for denim. To maximize the utilization of recycled cotton in yarn production, a compact spinning system alongside a new pin spacer was employed. This combination significantly improved the fiber control within the drafting zone of the ring frame, and consequently, 60 % recycled cotton was possible to include in yarn. Despite containing a substantial proportion of recycled cotton, the produced elastic core yarns demonstrated remarkably low levels of unevenness, imperfections, hairiness, strength and elongation values that fell between the top 5 % and 50 % thresholds of Uster Statistics 2023. The elastic core yarns, even made with 60 % recycled cotton, proved to be viable as a weft yarn in a commercial high-speed air-jet weaving machine, running smoothly at an operational speed of 950 rpm, which is equivalent to a weft speed of 94 km/h (1577 m/min).

The production of elastic core-spun yarn through the utilization of raw materials, such as recycled cotton, plays a crucial role in fulfilling various objectives outlined in the Sustainable Development Goals (SDGs), with a particular emphasis on SDG 12—focusing on 'Responsible Consumption and Production.' This aspect underscores the sustainable handling and effective utilization of natural resources, as well as the environmentally conscious management of chemicals and waste at every stage of their lifecycle, leading to a significant decrease in their emissions into the air, water, and soil. Furthermore, this approach substantially addresses waste management by actively promoting recycling and reuse practices.

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Data availability

Data will be made available on request.

CRediT authorship contribution statement

Ahmed Jalal Uddin: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Mostafizur Rahman:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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