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Effect of fiber length and blending method on the tensile properties of ring spun chitosan–cotton blend yarns

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Abstract

Chitosan has been widely studied for use in many areas, such as for its applications in the biomedical, engineering and pharmaceutical fields, as well as in industry, because of its unique properties, including biodegradability, antimicrobial activity, polycationic nature and biocompatibility. Thanks to the rapid development of materials science, chitosan applications are now possible in textiles. However, there are still many limitations of chitosan fibers in terms of their high electrostaticity, poor mechanical properties and high cost, which are obstacles that inhibit potential applications of chitosan fiber in the industry. Generally, in order to achieve the best performance with chitosan and enhance its commercial value, chitosan fibers are usually blended with long cotton fibers in the textile industry. Therefore, based on preliminary experiments and feedback from the industry, this study was carried out to further investigate the relationship between fiber length, fiber interaction and yarn performance. The results of this study would therefore help to reduce the production cost of yarns with the blending parameters used and also expand the utilization and applications beyond medical applications to fashion-based functional wear. The sliver-blending method offers better tensile properties of yarn samples, while the fiber-blending method offers higher uniformity of fiber distribution. This study would help to reduce the production cost of yarns by blending and also to expand the utilization and application not limited to fashion-based functional wear.

Keywords
chitosan fiber, fiber blending, fiber migration, ring spinning, tensile properties

Chitosan has become one of the most popular biomedical textile materials in recent years. Due to its unique properties, such as biodegradability, antimicrobial activity, polycationic nature and biocompatibility,[1–6] it has been widely studied for use in many applications, such as tissue engineering, drug delivery, wound dressings, and so on.[7–10] Thanks to the rapid development of material science, chitosan applications are now possible in textiles. Products based on chitosan fiber have been commercialized for hygienic and medical applications.[11–16]

The preparation of chitosan fibers is primarily achieved by using a chitosan solution and through wet spinning. Spinning is carried out after the dissolution, deaeration and filtration of the chitosan. The chitosan fibers will also be refined and dried, and receive post-treatment. Chitosan fibers are significantly more expensive than other fibers. The price ranges from US$50,000 to US$100,000 per ton depending on the degree of deacetylation of the chitosan. Yet there are still currently key limitations of chitosan fibers, including high electrostaticity and poor mechanical properties, which inhibit the applications of chitosan.[14,17] To offer a relative solution for the above problems and expand on the utilization and applications of chitosan in the textile industry, non-woven technologies have been considered, which would mean lower production costs and facilitation of prototype production. However, these technologies have many disadvantages, such as unsustainability and poor hand feel due to the formation of the fiber structure.[18] Nowadays, there is an emerging technique in the textile industry in which chitosan fibers are blended with long cotton fibers for woven and knitted fabrics in order to achieve the best performance with chitosan and enhance its commercial value.

However, there are still many limitations of chitosan fibers. According to chitosan spinning factories in the industry, many short white broken fibers are found when producing chitosan yarn blended with long cotton fibers in spinning mills. In the 50:50 chitosan/cotton yarn samples spun in the experiment here, many fibers were broken into shorter ones during yarn spinning. Most of the chitosan fibers, which are 38 and 46 mm long, are broken into a length that ranges from 21 to 30 mm (shown in Figure 1(a)). Chitosan/cotton fabric with different blend ratios (0:100, 30:70, 50:50 and 70:30) was tested on a YG402 fabrics friction-type electrostatic measuring instrument for studying the electrostatic properties of the materials. In addition, there is a phenomenon found in which the electrostatic properties change when the blend ratio of the chitosan fibers is different (see Figure 1(b)). Apart from that, the voltage induced onto chitosan and polyester is close (Figure 1(c)) when 100% silk, cotton, polyester and chitosan fibers are tested with the YG402 instrument. However, only chitosan experienced the following issues. When chitosan fibers are spun on normal rollers (without foil paper), the phenomenon of fibers that stuck together occurs, but this changes when foil is adhered onto the rollers (used as a conductive roller; see Figure 2(a)). Fibers that stick on rollers of polyester are a rare phenomenon, and this explains that the electrostatic property of chitosan fibers is not the main reason for the difficulties in yarn spinning. The adhesion of foil onto the rollers offers a temporary solution for the sticking of the chitosan fibers (Figure 2(b)). According to the theory of static properties in textiles, when broken fibers come into contact with each other, or any other objects, there is friction that causes electrification, and the charges will be transferred onto the fiber surface. The strong surface resistivity provides the fibers with greater ability to impede the rapid escape of the charges more so than its own electric resistance, which finally causes the fibers to generate electrostaticity. During spinning, broken fibers come into contact with each other and they generate electrostaticity on the spinning roller, which distorts the ideal twist triangle compared to fibers without electrostaticity (Figure 2(c)).This problem might create difficulties in spinning, and has also become an obstacle for the development of yarn-to-textile with higher ratios of composite strength. Moreover, in terms of blending technology in yarn spinning, several key aspects of fibers could affect yarn formation and the resultant quality, such as the length of each fiber component, strength and the electrostaticity. Yet, there is a paucity of publications in the literature that focus on the performance of chitosan fibers and their yarn formation in the yarn spinning of chitosan blends.

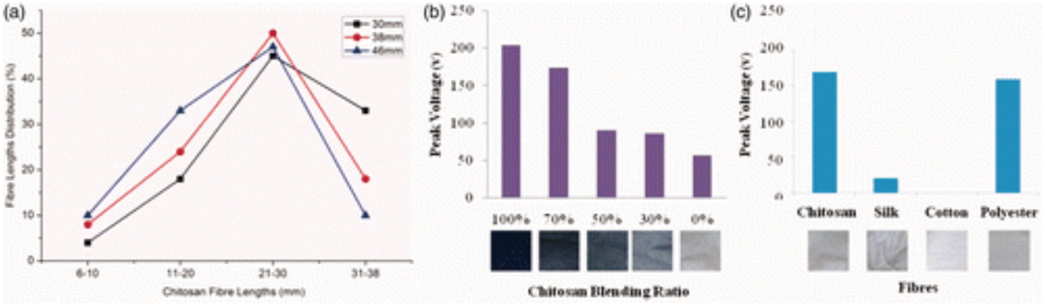


Figure 1. (a) Fiber length distribution in 50:50 chitosan/cotton yarn samples (yarns with chitosan fibers that are 30, 38 and 46 mm in length) determined by manual untwisting of yarn and counting of fibers. (b) Peak voltage of the technical front side of knitted fabrics with different blend ratios of chitosan/cotton (0:100, 30:70, 50:50, 70:30 and 100:0) rubbed on 100% nylon fabric for 30 seconds. (c) Peak and half-life voltages of four knitted fabrics (chitosan, silk, cotton and polyester): technical front side of knitted fabrics rubbed on 100% nylon for 30 seconds.

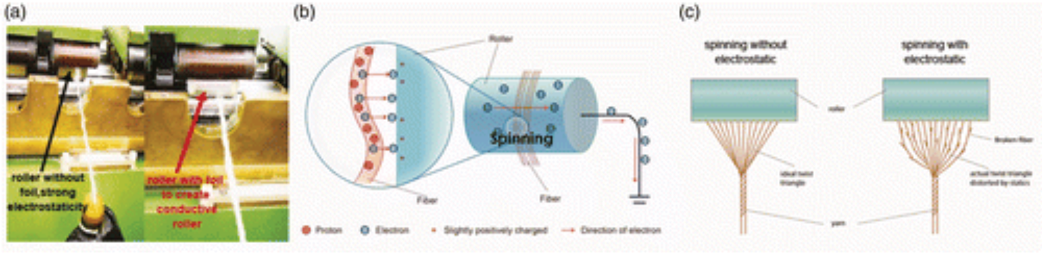


Figure 2. (a) Chitosan fibers stuck onto the roller without foil and the conductive roller during the yarn spinning process. (b) Temporary solution (roller with adhered foil). (c) Broken fibers come into contact and generate electrostaticity on the spinning roller, which distorts the ideal twist triangle compared to spun fibers without electrostaticity.

Therefore, this study addresses the lack of research through the implementation of preliminary experiments and based on feedback from the industry, to understand how the strength of yarn and the electrostaticity of fibers create spinning difficulties, and to further examine the relationship between fiber length, fiber interaction and yarn performance by using a blend of chitosan/cotton fibers with the fiber-blending and sliver-blending methods.

Theoretical details

For practical purposes, fiber-blending and sliver-blending are the two general blending methods used in yarn spinning. The former provides the most intimate mixing of fibers in terms of fiber distribution, while the latter provides an alternative way to manipulate the fiber distribution, thus affecting the quality of the final products.[19–22] The fiber distribution obtained by both methods depends on the fiber alignment during yarn spinning. Furthermore, the fiber-blending method will also affect the desired characteristics and performance of the yarn. The composition of each fiber component and interactions between them influence the outcome of the final yarn. For example, insufficient fiber strength would affect the yarn fabrication process and the fiber length is one of the critical key elements that could affect the quality of the yarn during production, such as load sharing between broken fibers during yarn breakage.[23–25] In a staple yarn structure, fiber slippage and breakage are the two main interactions that induce tensile deformation.[26,27]When fibers have the tendency to slip, friction force is generated between them, which would induce tensile forces along the axial direction of the fibers. Due to the equilibrium of the forces, the tensile forces on different segments of fibers continuously vary, and the segment that is the farthest from the fiber ends would experience the largest tensile force. The tensile force would then increase along with the friction force between the fibers (Figure 3).

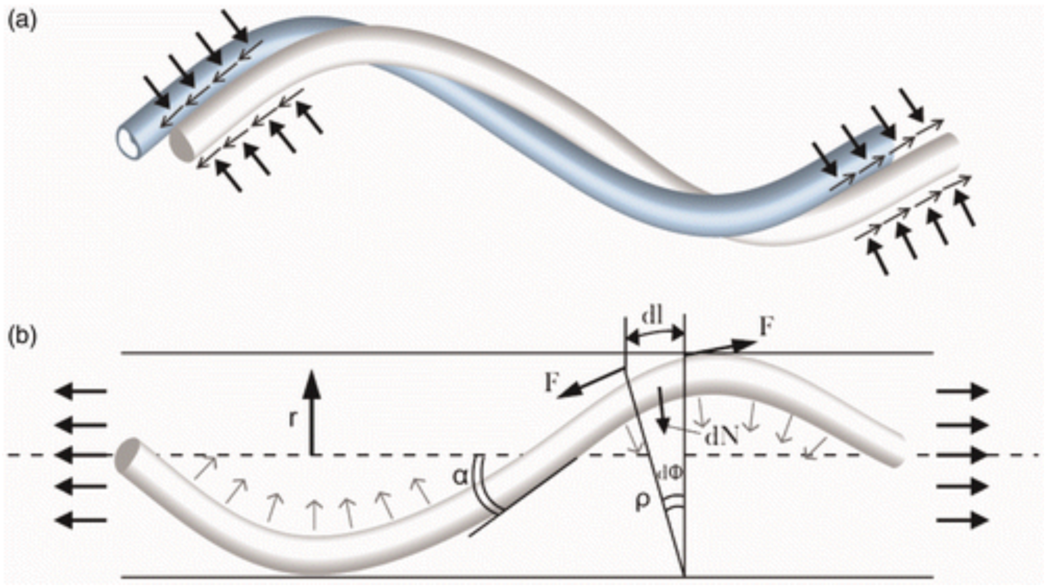


Figure 3. Schematic of (a) friction and tensile forces in fiber in the yarn matrix and (b) centripetal force.

The friction force is found to correspond with the breaking tenacity of the fiber. l_c is defined as the length from the ends of the fibers when the friction force equals the breaking tenacity:

$$l_c = \frac{r\sigma_b}{2q\mu} \tag{1}$$

where r is the radius of the fibers, σ_b is the breaking force of the fibers, q is the transverse tension on the fibers and μ is a coefficient of the fiber friction.

The slip coefficient (*SF*) is given by

$$\mathrm{SF} = \frac{\overline{F}}{F_b} = \frac{L - l_c}{L} = 1 - \frac{l_c}{L} \tag{2}$$

where $\overline{F}$ is the average stress of the fibers, F_b is the breaking force of the fibers and L is the length of the fibers. *SF* indicates the efficiency of the fibers in the staple yarns. The tensile properties of blended yarns depend on two main factors: fiber properties (fiber length, line density, surface friction, etc.) and yarn structure (blend ratio, yarn twist, fabrication method, fiber migration, etc.).[28–31] In this paper, the focuses are on the effects of fiber strength, length, distribution in yarn and blending method on the mechanical properties of chitosan/cotton yarns. The fiber blend ratio used is 50:50 chitosan/cotton; long cotton fibers (upper half mean length (UHML) of 38 mm) are adopted in the experiment, while several different fiber lengths of chitosan (22, 30, 38 and 46 mm) are selected as the parameters for this study.

The aim of this research study is to provide a practical guide to yarn manufacturers that outlines the effect of the length of the chitosan fibers on the fiber distribution in the yarn by producing 50:50 chitosan/cotton blend yarns with the use of the fiber-blending and sliver-blending methods in a ring spinning system. In order to study the effect of the relationship between the fiber length and tensile properties of yarn, the tenacity and elongation of the chitosan and cotton fibers are examined. Comparisons of the yarn performance between the two fiber-blending methods are discussed by using a fitted model. Since the outcome of yarn is affected by the fiber distribution, an analysis of the fiber migration behavior after the two fiber-blending methods are carried out on chitosan/cotton yarn will also be part of the study. The proposed study could help to expand the utilization and applications of chitosan beyond those of a medical nature, to include functional wear with biocompatible and biodegradable abilities due to the chitosan/cotton blend. The results could also contribute to the development of innovative materials for yarn through ring spinning with a systematic approach.

Experimental design

Four different fiber lengths were utilized in the experiment to investigate the effect of the length of chitosan fiber on the fiber distribution in the yarn, in accordance with the principles of scaling in fracture mechanics and real life industry situations. The fiber radial distribution of the fiber components in the yarn samples was determined through observations of the cross-sections and based on migration index calculation. Comparisons of the yarn tensile strength, elongation and fiber migration of the yarn samples were analyzed by using a fitted model.

Materials

Fibers

Cotton fibers with a UHML of 38 mm and chitosan fiber lengths of 22, 30, 38 and 46 mm were used in the experiments. In order to clearly observe the fiber distribution in the yarn during the cross-section experiment with the use of optical microscopy, the cotton was pre-dyed with a navy blue color before the fibers were blended.

Production of chitosan/cotton blend yarn

Eight different types of 20 Ne yarn blend samples (4 kg for each sample) were produced with a blend ratio of 50:50 by using a cotton ring spinning system at a traditional spinning mill. Standard spinning procedures were used to produce the yarn samples. The cotton and chitosan fibers were processed and blended on a short staple carding machine (Qingdao Textile Machinery Co., Ltd, #A186G) for the fiber blending. The cotton and chitosan were separately processed on the same carding machine for the sliver blending. Two passages of drawing were used for the eight chitosan or cotton slivers with a linear density of 4 ktex and the draft ratio was 8 (Shenyang Hongda Textile Machinery Co., Ltd, #FA306A) for the fiber blending. The output sliver was 4 ktex. The card slivers of both types of fibers were then blended in a drawing machine with the same sliver thickness and draft ratio for the sliver blending. A roving sliver with a count of 0.68 ktex was then produced at a speed of 900 rpm (Hebei Taihang Machinery Industry Co., Ltd, #THFA4421). Eight kinds of yarn samples were spun on the ring spinning machine (Jingwei Textile Machinery Co., Ltd, #FA506) at a speed of 620 rpm. Yarn samples F1–F4 are the fiber-blended yarn with different lengths of chitosan fibers (F1: 22 mm, F2: 30 mm, F3: 38 mm and F4: 46 mm), while S1–S4 are the sliver-blended yarn with different lengths of chitosan fibers (S1: 22 mm, S2:30 mm, S3: 38 mm and S4:46 mm; see Figure 4 and Table 1).

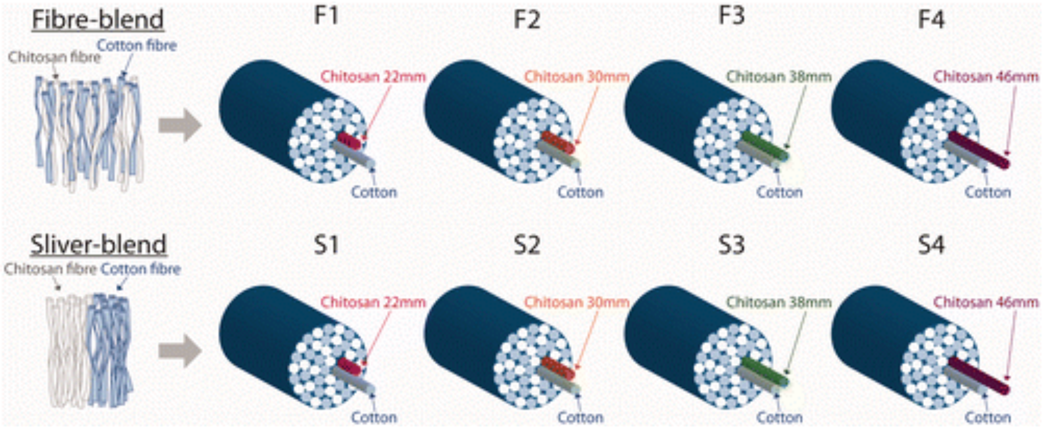
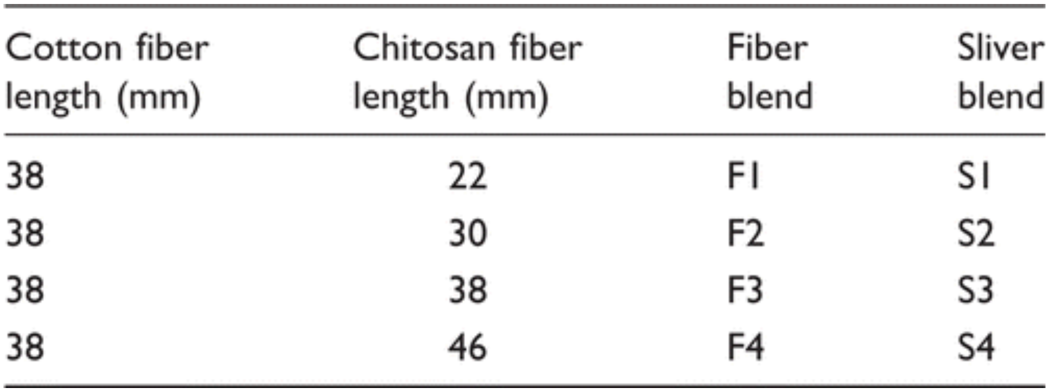


Figure 4. Fiber blending and sliver blending of chitosan/cotton with different fiber lengths (22, 30, 38 and 46 mm).



Cotton fiber length (mm)	Chitosan fiber length (mm)	Fiber blend	Sliver blend
38	22	F1	S1
38	30	F2	S2
38	38	F3	S3
38	46	F4	S4

Table 1. Coding of 50:50 chitosan/cotton blend yarn

Evaluation methods

Evaluation of fibers and yarns

The properties of the cotton fibers were measured on an Uster high volume instrument (HVI). The fiber strength, tensile strain and modulus of chitosan (22, 30, 38 and 46 mm) were measured using an Instron 5566 tensile testing machine in accordance with ASTM standard D3822. Twenty-five samples that consisted of each type of fiber were measured. The testing speed was 50 mm/min, the testing load was 10 N and the testing length was 20 mm.

The yarn strength and elongation, linear density, yarn twist and evenness of all the yarn samples were investigated. The yarn strength and elongation properties of all the yarn samples were tested on an UsterTensorapid III in accordance with ASTM standard D2256. Data on 50 tested samples were acquired. The clamping length was 500 mm, the pretension force was 10 cN/tex and the testing speed was 5000 mm/min. The linear density of the yarn samples was measured by using a Mesdan Lab electronic wrap reel in accordance with ASTM standard D1907 and 30 of each yarn sample (100 m) were examined. The twist in the yarn samples was determined by using the untwist–retwist feature on an electronic yarn twist tester (Mesdan) in accordance with ASTM standard D1422. Twenty-five specimens from each yarn sample were measured with clamps by using a gauge length of 250 mm. The yarn evenness was measured by using an Uster Tester III Evenness Converter in accordance with ASTM standard D1425. The running speed for all of the yarn samples was 400 m/min. In order to analyze the changes in the length of the chitosan fibers after ring spinning, small pieces of the yarn samples with a longer fiber length (46 mm) were manually untwisted for fiber counting.

Use of the migration index to characterize the cross-section of fibers

The fiber radial distribution, which is affected by different blending methods, is determined through observations of the cross-sections and based on the migration index calculation. Fiber migration could influence the tensile properties of blended yarns, which means that the control of migration could be a means to improve yarn properties. In this study, the migration behavior of the chitosan/cotton blend yarns with different fiber lengths and blended through two different methods is characterized by using the Hamilton migration index.[31,32] The calculation method is as follows.

The cross-sections of each yarn sample were observed by using an optical microscope (Nikon Optiphot-POL) and recorded with a charge-coupled device (CCD) camera, and then processed with the Leica Application Suite software on a computer (Figure 5(a)).The cross-sections were divided into five regions with equal radial spacing and labeled as 1, 2, 3, 4 and 5 (Figure 5(b)).

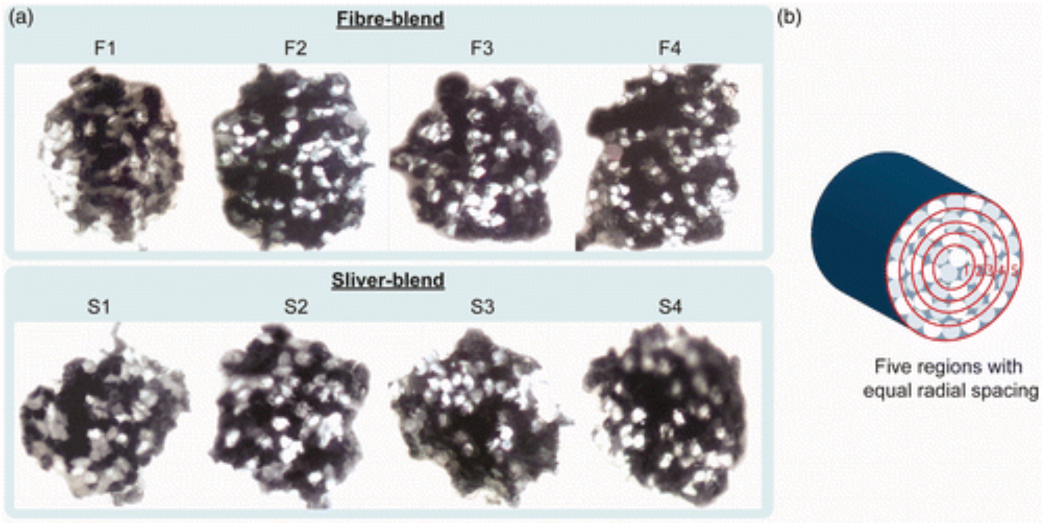


Figure 5. (a) Cross-section of each yarn sample: fiber-blended (F1, F2, F3 and F4) and sliver-blended (S1, S2, S3 and S4). (b) Five regions with equal radial spacing for yarn cross-section observations.

The volume of the chitosan and cotton fibers for all five regions was determined by using ImageJ, an image processing software. The fibers were identified according to the different colors (cotton fibers were navy blue and chitosan fibers were white).

From the counts, the migration index, M, was determined with Equations (3a) and (3b):

$$M = \frac{\mathrm{FM}_a - \mathrm{FM}_u}{\mathrm{FM}_u - \mathrm{FM}_i} \times 100 \qquad \mathrm{FM}_a > \mathrm{FM}_u \tag{3a}$$

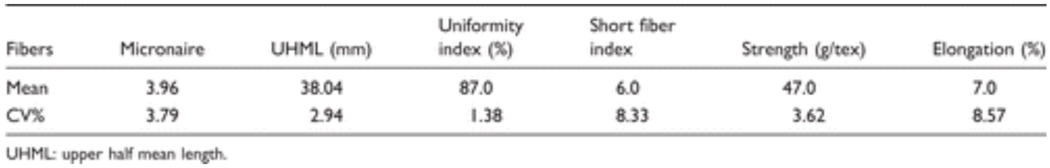
$$M = \frac{\mathrm{FM}_a - \mathrm{FM}_u}{\mathrm{FM}_o - \mathrm{FM}_u} \times 100 \qquad \mathrm{FM}_a < \mathrm{FM}_u \tag{3b}$$

where FM_a is the fiber distribution, FM_u is the ideal uniform distribution, FM_i is the maximum inward migration and FM_o is the maximum outward migration.
If $FM_a < FM_u$, M is negative, and FM_i must be calculated; if $FM_a > FM_u$, M is positive, and then FM_o is calculated. Positive and negative migration indexes denote the preferential migration of the fibers outward to the surface of the yarn and inward to the core of the yarn, respectively. A migration index of zero denotes an even and uniform distribution of the fibers between the core and surface.

Results and discussion

Tenacity of chitosan and cotton fibers

In normal practice, most blended yarns with long fibers are expected to have higher tensile properties. Besides, similar lengths of fibers better facilitate the production of blended yarns in the industry.[22,33,34] In this paper, cotton fibers with long lengths were selected in the blend with chitosan. To reflect real life production, four different lengths of chitosan fibers were selected for the experiment: 22, 30, 38 and 46 mm. The breaking tenacity of the cotton fibers was 47 g/tex (Table 2), while that of the chitosan fibers was 15.85 (22 mm), 14.90 (30 mm), 15.49 (38 mm) and 16.20 (46 mm) cN/tex (Table 3). Compared to the chitosan fibers, cotton fibers have greater strength in the blended yarn structure.

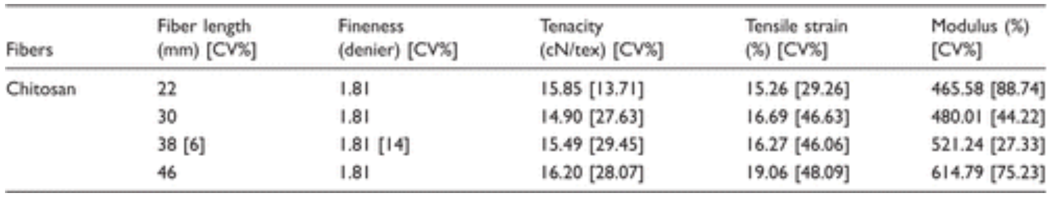


Fibers	Micronaire	UHML (mm)	Uniformity index (%)	Short fiber index	Strength (g/tex)	Elongation (%)
Mean	3.96	38.04	87.0	6.0	47.0	7.0
CV%	3.79	2.94	1.38	8.33	3.62	8.57

UHML: upper half mean length.

Table 2. High volume instrument test results for cotton fibers used in 50:50 chitosan/cotton blend yarn

Table 3. Fiber specifications, tenacity, tensile strain and modulus of chitosan fibers used in 50:50



Fibers	Fiber length (mm) [CV%]	Fineness (denier) [CV%]	Tenacity (cN/tex) [CV%]	Tensile strain (%) [CV%]	Modulus (%) [CV%]
Chitosan	22	1.81	15.85 [13.71]	15.26 [29.26]	465.58 [88.74]
	30	1.81	14.90 [27.63]	16.69 [46.63]	480.01 [44.22]
	38 [6]	1.81 [14]	15.49 [29.45]	16.27 [46.06]	521.24 [27.33]
	46	1.81	16.20 [28.07]	19.06 [48.09]	614.79 [75.23]

chitosan/cotton blend yarn

In order to explain the fiber breakage of chitosan, the tenacity and strain of the fibers were plotted. The plotting of the tenacity and strain of the chitosan fibers of four different lengths showed low linear regions. The chitosan fibers had high moduli and strong resistance to tensile force; however, upon further stress, they showed yielding points at around 1.2 cN/dtex before they broke. In comparison to the chitosan fibers, the cotton fibers had lower modulus and elongation but higher strength (Figure

6).When the strain passed the yielding points, plastic deformation would occur until the fibers broke. Thus, this proves that cotton fibers provide better physical strength in a blended yarn structure.

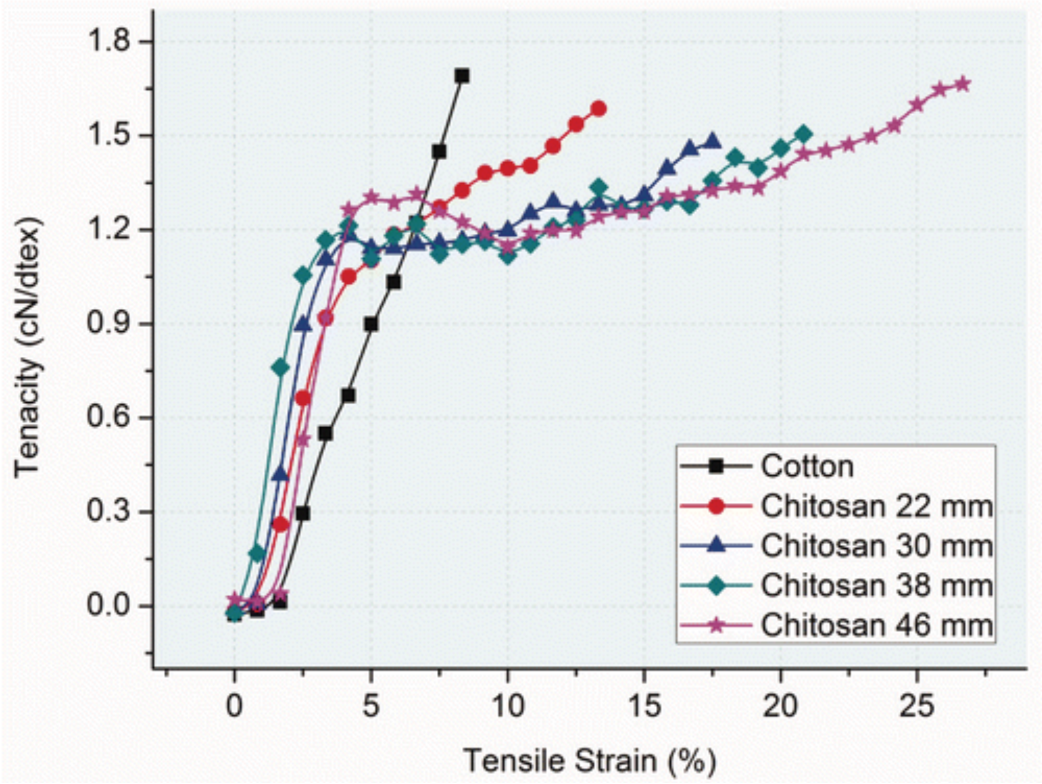
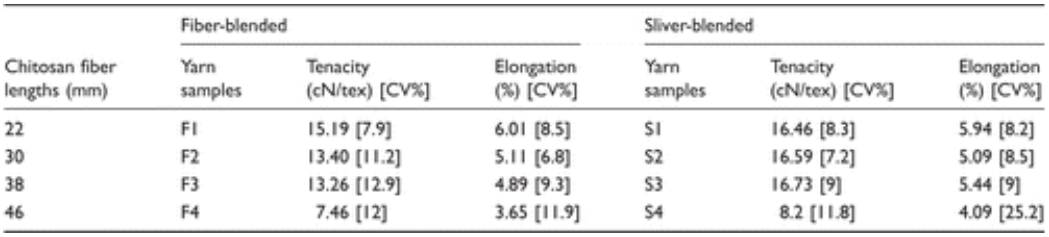


Figure 6. Tenacity versus tensile strain of blue-dyed cotton and chitosan fibers used in the 50:50 chitosan/cotton blend yarn.

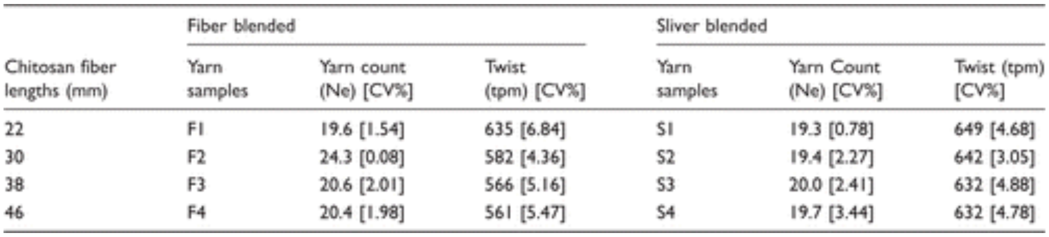
Physical properties of fiber-blended and sliver-blended chitosan/cotton yarn

In consideration of the performance and functionality of chitosan yarn and the possibilities of yarn spinning, a blend ratio of 50:50 was adopted in the experiment. The fiber-blending and sliver-blending methods were used in the blending process of ring spinning. The measured physical properties of the yarn samples, including linear density, twist, evenness, tenacity and elongation, are shown in Tables 4–7.



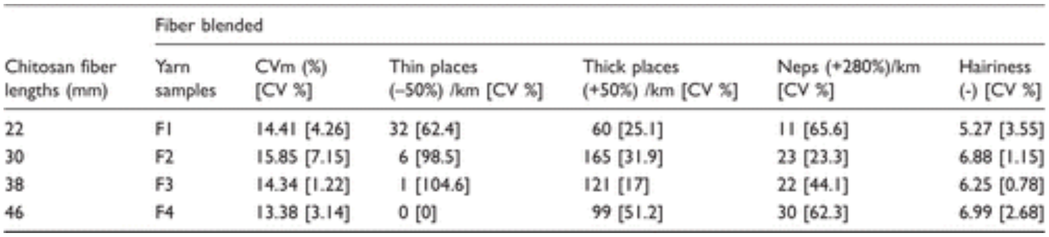
Chitosan fiber lengths (mm)	Fiber-blended Yarn samples	Tenacity (cN/tex) [CV%]	Elongation (%) [CV%]	Sliver-blended Yarn samples	Tenacity (cN/tex) [CV%]	Elongation (%) [CV%]
22	F1	15.19 [7.9]	6.01 [8.5]	S1	16.46 [8.3]	5.94 [8.2]
30	F2	13.40 [11.2]	5.11 [6.8]	S2	16.59 [7.2]	5.09 [8.5]
38	F3	13.26 [12.9]	4.89 [9.3]	S3	16.73 [9]	5.44 [9]
46	F4	7.46 [12]	3.65 [11.9]	S4	8.2 [11.8]	4.09 [25.2]

Table 4. Yarn tenacity and elongation of 50:50 chitosan/cotton blend yarn



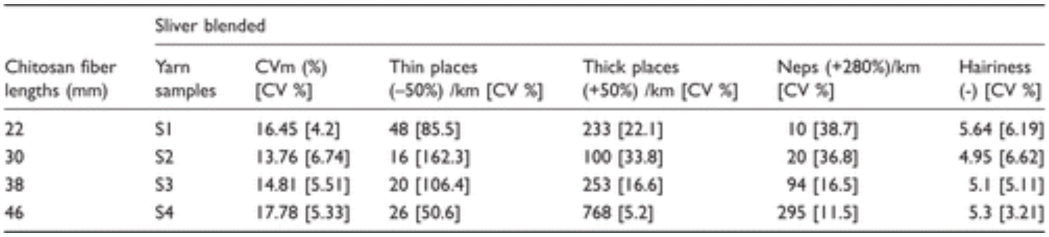
Chitosan fiber lengths (mm)	Fiber blended Yarn samples	Yarn count (Ne) [CV%]	Twist (tpm) [CV%]	Sliver blended Yarn samples	Yarn Count (Ne) [CV%]	Twist (tpm) [CV%]
22	F1	19.6 [1.54]	635 [6.84]	S1	19.3 [0.78]	649 [4.68]
30	F2	24.3 [0.08]	582 [4.36]	S2	19.4 [2.27]	642 [3.05]
38	F3	20.6 [2.01]	566 [5.16]	S3	20.0 [2.41]	632 [4.88]
46	F4	20.4 [1.98]	561 [5.47]	S4	19.7 [3.44]	632 [4.78]

Table 5. Yarn linear density and twist of 50:50 chitosan/cotton blend yarn



Chitosan fiber lengths (mm)	Fiber blended Yarn samples	CVm (%) [CV %]	Thin places (−50%) /km [CV %]	Thick places (+50%) /km [CV %]	Neps (+280%)/km [CV %]	Hairiness (-) [CV %]
22	F1	14.41 [4.26]	32 [62.4]	60 [25.1]	11 [65.6]	5.27 [3.55]
30	F2	15.85 [7.15]	6 [98.5]	165 [31.9]	23 [23.3]	6.88 [1.15]
38	F3	14.34 [1.22]	1 [104.6]	121 [17]	22 [44.1]	6.25 [0.78]
46	F4	13.38 [3.14]	0 [0]	99 [51.2]	30 [62.3]	6.99 [2.68]

Table 6. Yarn evenness of 50:50 chitosan/cotton fiber-blended yarn



Chitosan fiber lengths (mm)	Sliver blended Yarn samples	CVm (%) [CV %]	Thin places (−50%) /km [CV %]	Thick places (+50%) /km [CV %]	Neps (+280%)/km [CV %]	Hairiness (-) [CV %]
22	S1	16.45 [4.2]	48 [85.5]	233 [22.1]	10 [38.7]	5.64 [6.19]
30	S2	13.76 [6.74]	16 [162.3]	100 [33.8]	20 [36.8]	4.95 [6.62]
38	S3	14.81 [5.51]	20 [106.4]	253 [16.6]	94 [16.5]	5.1 [5.11]
46	S4	17.78 [5.33]	26 [50.6]	768 [5.2]	295 [11.5]	5.3 [3.21]

Table 7. Yarn evenness of 50:50 chitosan/cotton sliver-blended yarn

Tensile properties and length of chitosan fibers

Yarn fabricated by using both types of blending methods exhibited similar tensile properties in terms of the length of the chitosan fibers (Figure 7(a)). For both types of blending methods, the tenacity of the yarn was relatively stable and the variant was less than 13% with increased length of the chitosan fibers from 22 to 38 mm. However, when the length of the chitosan fiber was 46 mm, the tenacity rapidly decreased by about 51%. In terms of the sliver blending, when the length of the chitosan fiber was 46 mm, the tenacity decreased by 50.2% in comparison to that of the chitosan fiber of 22 mm.

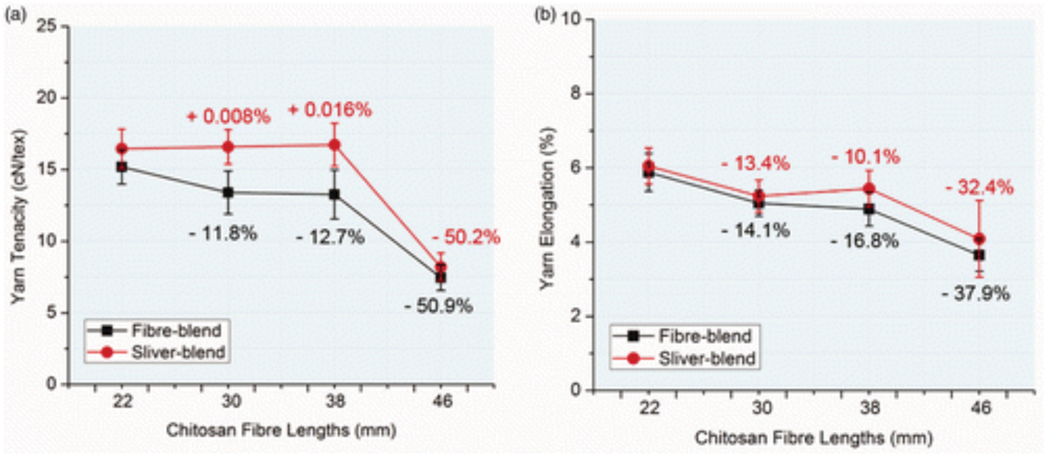


Figure 7. Yarn sample properties: (a) yarn tenacity; (b) yarn elongation.

The elongation of the yarn samples was also reduced with increased lengths of the chitosan fibers (Figure 7(b)).With a fiber length less than 38 mm, the breaking elongation did not increase or decrease. However, when the fiber length is longer than 38 mm, the breaking elongation rapidly decreased, which is similar to the case of the yarn tenacity, and reflected the deterioration of the yarn quality due to the change in the fiber length. The elongation at break of the F4 and S4 samples, which are 44 mm in length, decreased by 37.8% and 32.4%, respectively, in comparison to the F1 and S1 samples, which are 22 mm in length.

The deterioration of the yarn quality with a longer length of 46 mm might be induced by the production process.[14] The results from the manual fiber counting for obtaining the fiber length distribution for the F4 sample verified this hypothesis (Figure 8). In yarn, most of the fibers break into shorter ones during the spinning process and these short fibers lead to insufficient strength of the yarn.

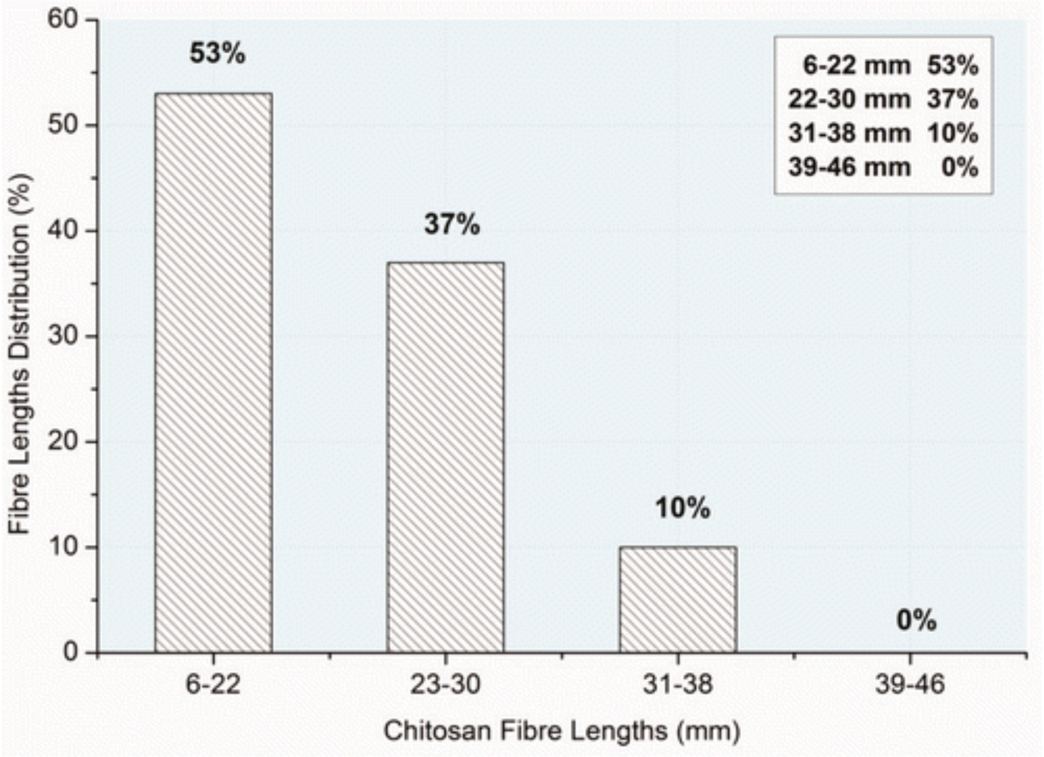
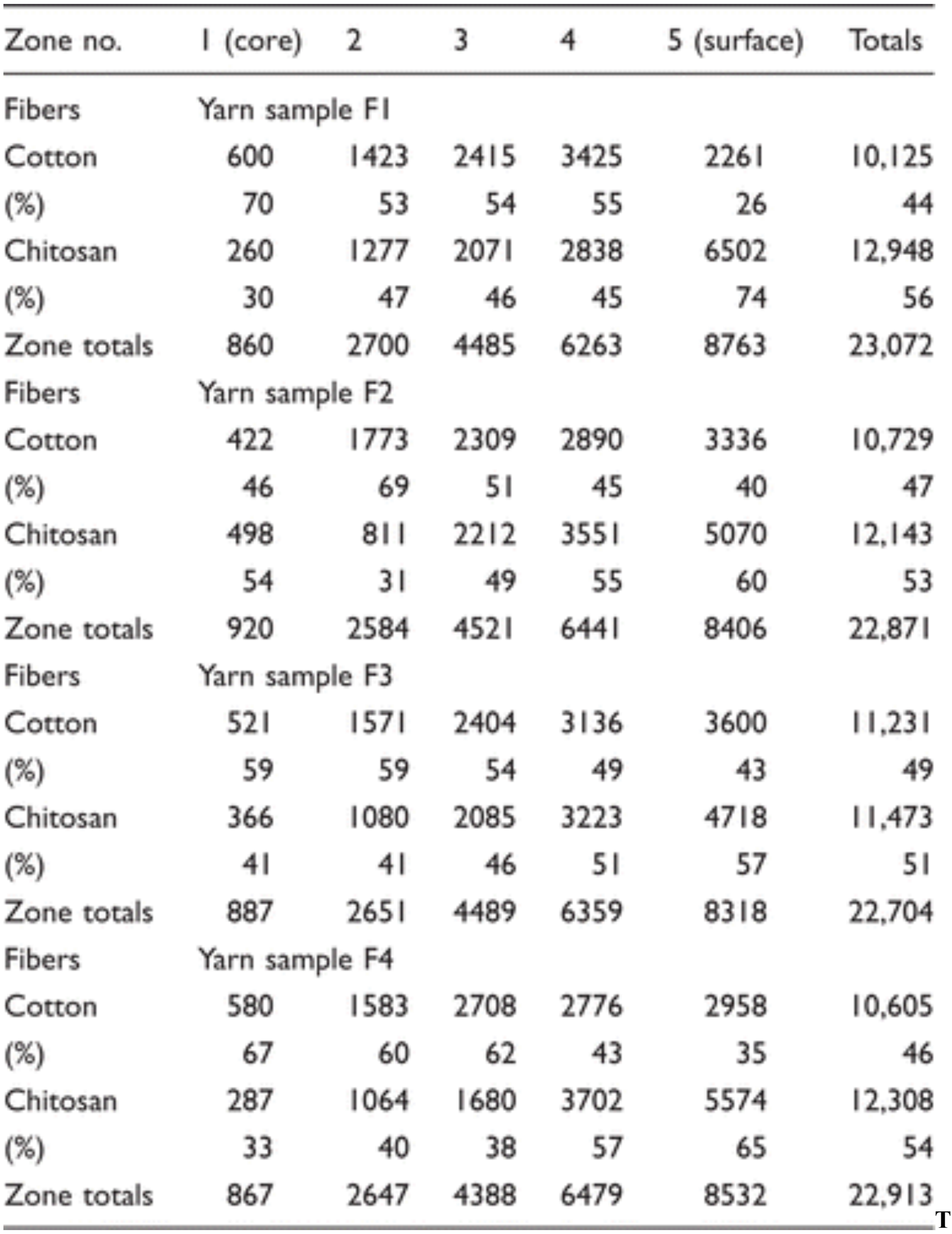


Figure 8. Fiber length distribution in 50:50 chitosan/cotton blend yarn composed of chitosan fibers with length of 46 mm, determined by manual fiber counting of untwisted yarn.

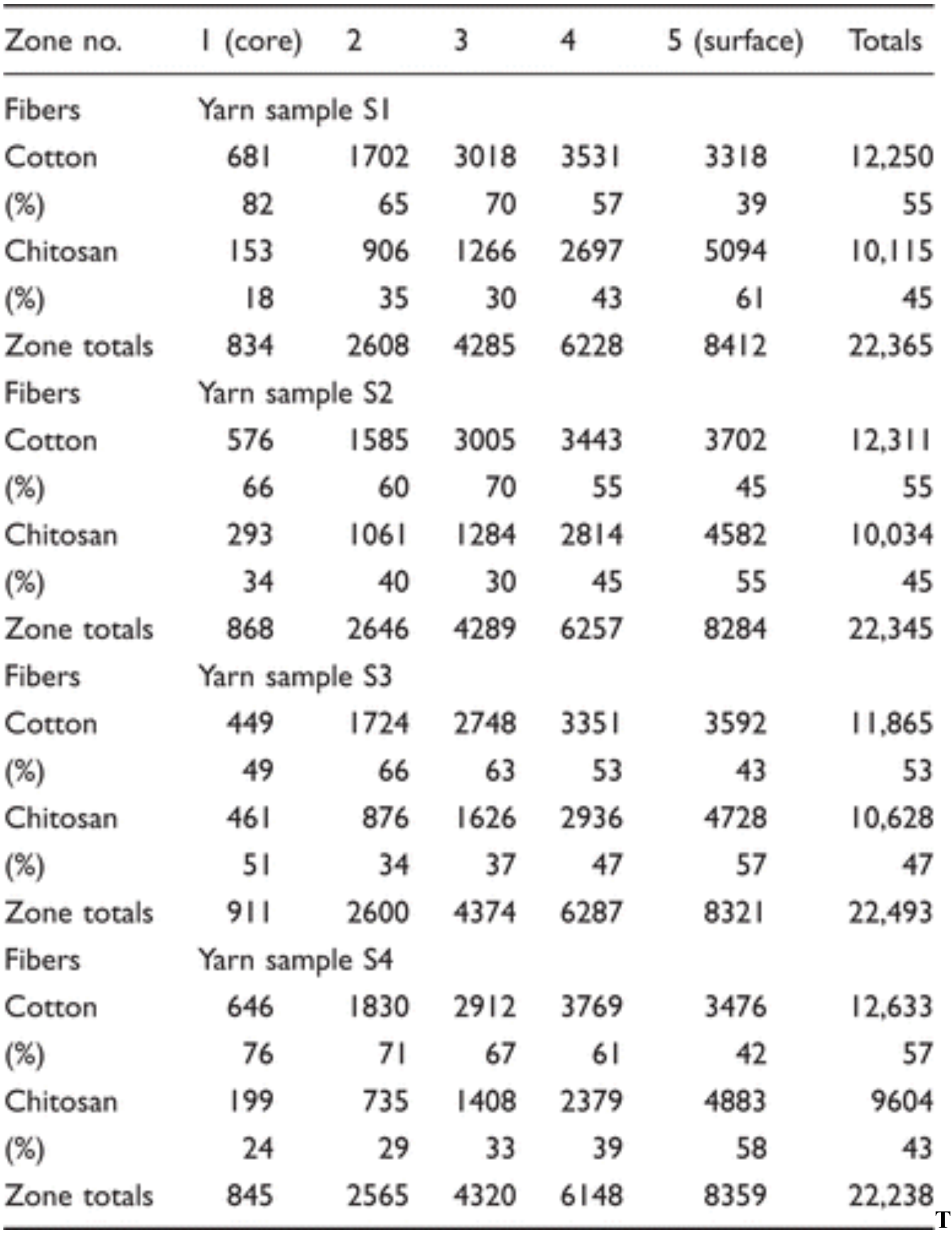
Fiber distribution in the blended yarns

In order to study the influence of chitosan fiber parameters on the yarn properties, the migration index of the fiber-blended and sliver-blended chitosan/cotton yarn samples was determined (Tables 8 and 9), and the results are shown in Table 10.The formation and the structure of the yarns are the key factors that define the mechanical properties of the yarn, such as yarn bulkiness, tensile properties and abrasion. Due to different blending methods and fiber lengths, the yarns would have different radial distributions of the fiber components. According to Hamilton and Cooper,[31] fibers that are short and coarse tend to migrate outwards towards the yarn surface, which improves the strength of yarns. Meanwhile, if the fineness and length of the fibers are consistent, fibers with higher tenacity are expected to migrate to the inner surface of yarns.



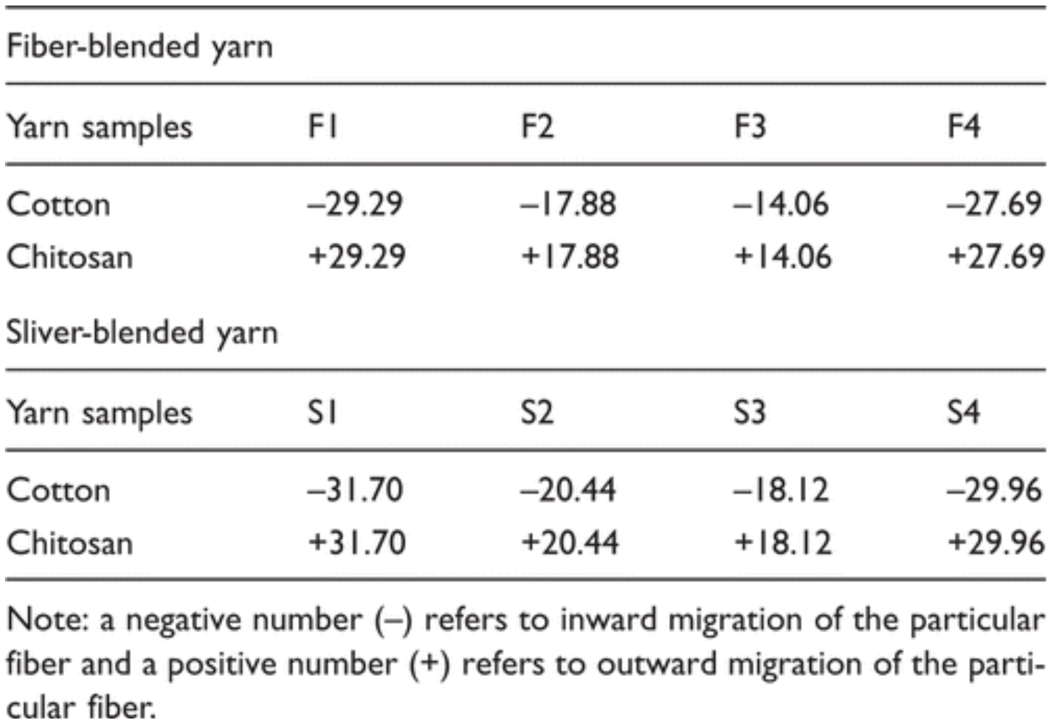
Zone no.	I (core)	2	3	4	5 (surface)	Totals
Fibers	Yarn sample F1					
Cotton	600	1423	2415	3425	2261	10,125
(%)	70	53	54	55	26	44
Chitosan	260	1277	2071	2838	6502	12,948
(%)	30	47	46	45	74	56
Zone totals	860	2700	4485	6263	8763	23,072
Fibers	Yarn sample F2					
Cotton	422	1773	2309	2890	3336	10,729
(%)	46	69	51	45	40	47
Chitosan	498	811	2212	3551	5070	12,143
(%)	54	31	49	55	60	53
Zone totals	920	2584	4521	6441	8406	22,871
Fibers	Yarn sample F3					
Cotton	521	1571	2404	3136	3600	11,231
(%)	59	59	54	49	43	49
Chitosan	366	1080	2085	3223	4718	11,473
(%)	41	41	46	51	57	51
Zone totals	887	2651	4489	6359	8318	22,704
Fibers	Yarn sample F4					
Cotton	580	1583	2708	2776	2958	10,605
(%)	67	60	62	43	35	46
Chitosan	287	1064	1680	3702	5574	12,308
(%)	33	40	38	57	65	54
Zone totals	867	2647	4388	6479	8532	22,913

Table 8. Fiber volume distribution of fiber-blended 50:50 chitosan/cotton yarn



Zone no.	1 (core)	2	3	4	5 (surface)	Totals
Fibers	Yarn sample S1					
Cotton	681	1702	3018	3531	3318	12,250
(%)	82	65	70	57	39	55
Chitosan	153	906	1266	2697	5094	10,115
(%)	18	35	30	43	61	45
Zone totals	834	2608	4285	6228	8412	22,365
Fibers	Yarn sample S2					
Cotton	576	1585	3005	3443	3702	12,311
(%)	66	60	70	55	45	55
Chitosan	293	1061	1284	2814	4582	10,034
(%)	34	40	30	45	55	45
Zone totals	868	2646	4289	6257	8284	22,345
Fibers	Yarn sample S3					
Cotton	449	1724	2748	3351	3592	11,865
(%)	49	66	63	53	43	53
Chitosan	461	876	1626	2936	4728	10,628
(%)	51	34	37	47	57	47
Zone totals	911	2600	4374	6287	8321	22,493
Fibers	Yarn sample S4					
Cotton	646	1830	2912	3769	3476	12,633
(%)	76	71	67	61	42	57
Chitosan	199	735	1408	2379	4883	9604
(%)	24	29	33	39	58	43
Zone totals	845	2565	4320	6148	8359	22,238

Table 9. Fiber volume distribution of sliver-blended 50:50 chitosan/cotton yarn



Fiber-blended yarn

Yarn samples	F1	F2	F3	F4
Cotton	–29.29	–17.88	–14.06	–27.69
Chitosan	+29.29	+17.88	+14.06	+27.69

Sliver-blended yarn

Yarn samples	S1	S2	S3	S4
Cotton	–31.70	–20.44	–18.12	–29.96
Chitosan	+31.70	+20.44	+18.12	+29.96

Note: a negative number (–) refers to inward migration of the particular fiber and a positive number (+) refers to outward migration of the particular fiber.

Table 10. Migration index of 50:50 chitosan/cotton blend yarn

The migration of the fibers is induced by the centripetal force produced during the twisting process (Figure 3(a)). As shown in Equations (4) and (5), the stress applied onto the outward migrating fibers is

$$N = 2\pi\varepsilon \, \mathrm{ATL}(1 - \cos\beta)\sin\beta \tag{4}$$

$$N \propto \varepsilon, L \tag{5}$$

where ε is the initial tensile modulus, *A* is the cross-section area of the fiber, *T* is the twist of the yarn, *L* is the length of the fiber and β is the twist angle of the yarn. It can be qualitatively concluded that the centripetal force is proportional to the length and initial modulus of the fibers.

Chitosan fibers have the tendency to migrate towards to the surface of yarn, and the findings in this study have confirmed those of previous studies in that coarser fibers tend to migrate outwards towards the yarn surface.[19,21,32,35,36] On the other hand, cotton fibers have greater strength than any of the chitosan fibers used in the experiments in this study, so it is expected that cotton fibers would congregate in the core area rather than the surface, which is shown by our results.

Besides, one phenomenon that is worth noting is that compared with fiber-blended yarns, sliver-blended yarns have better tensile properties. The yarn samples in this study that are fiber blended have a lower migration index than the sliver-blended samples for each different length of the chitosan fibers, which means that the fibers migrate towards the inside surface compared to the fiber-blended yarns. It is considered that in spinning systems, sliver blending lacks efficiency in fiber separation compared to the fiber-blending method. It is reasonable to speculate that the fiber-blending method provides higher uniformity of fiber distribution than sliver blending. On the other hand, the sliver-blending method could be an alternative means to manipulate the migration of chitosan fibers in blended yarns.[37] In this case, the cotton fibers in sliver-blended yarns have the tendency to migrate into the core area of the yarn structure, as opposed to cotton fibers in fiber blended yarns.

Simulation

A regression analysis was conducted based on the experimental results (Figure 9 and Table 11). The regression analysis provides a possible means of predicting the migration behavior of fiber components according to the length of the chitosan fibers and blending methods. A secondary order polynomial model was used to fit the relationship between the migration index value and length of the chitosan fibers (Figure 9):

$$\mathrm{MI} = A_1 L^2 + B_1 L + C_1 \tag{6}$$

where MI is the migration index, L is the fiber length and A_1, B_1 and C_1 are coefficients of the function.

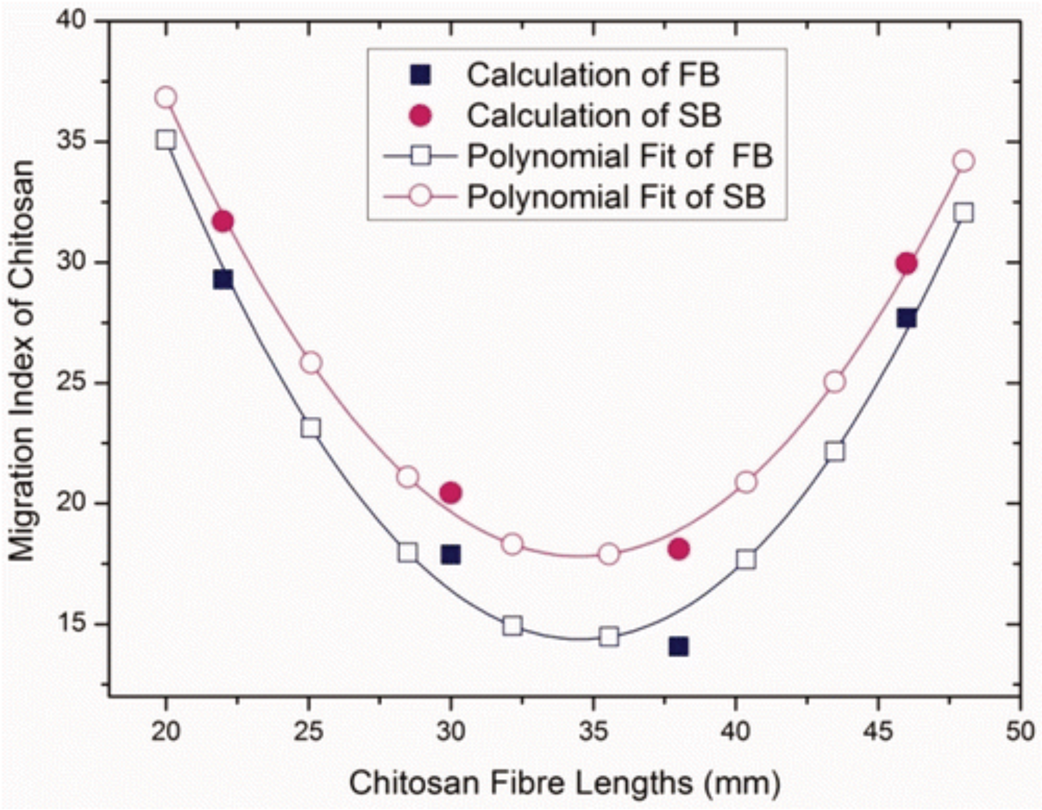
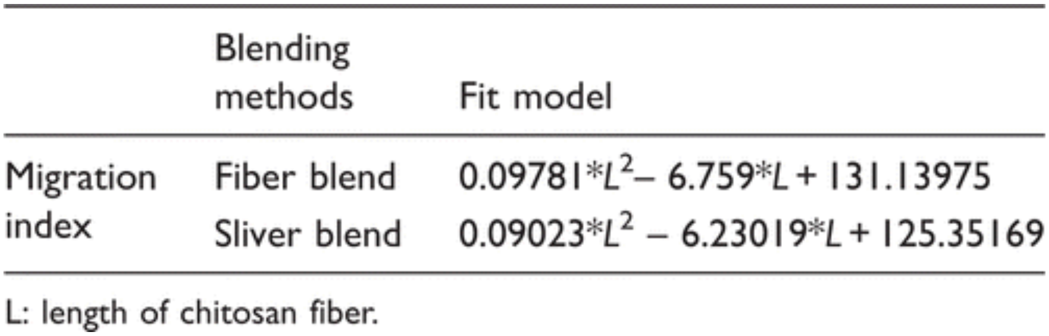


Figure 9. Length of chitosan fibers versus migration index. FB: fiber-blend; SB: sliver-blend.



	Blending methods	Fit model
Migration index	Fiber blend	$0.09781*L^2 - 6.759*L + 131.13975$
	Sliver blend	$0.09023*L^2 - 6.23019*L + 125.35169$

L: length of chitosan fiber.

Table 11. Fit and regression equations for length of chitosan fibers and yarn properties of 50:50 chitosan/cotton blend yarn

Both the fiber-blended and sliver-blended yarns have a parabolic curve, as shown in Figures10(a) and 10(c). When the fiber length is less than the inflection point (around 35 mm), the migration index of the cotton fibers decreases with a longer fiber length. However, across the inflection point, the migration index is proportional to the fiber length, which indicates congregation of cotton fibers in the core area. It is worth noting that the long cotton fibers (UHML > 38 mm, mean length around 33 mm) used in the experiments are close to the inflection point. For the blended yarns, longer fibers have a larger ratio (around 60–75%) in the core of the yarn (Zones 1 and 2) (see Tables 8 and 9), except for the yarns spun with chitosan fibers that are 46 mm in length, which might be attributed to the increased evenness, faults, hairiness and breaking during yarn spinning.

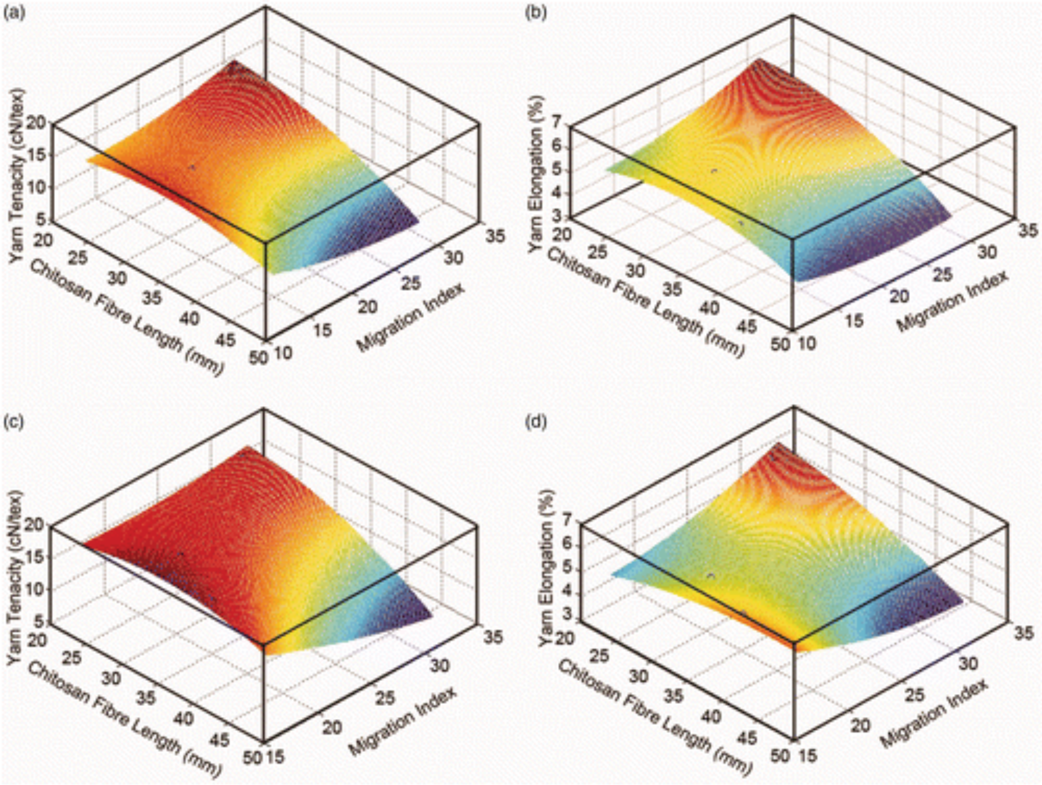


Figure 10. Effect of the length of chitosan fibers and migration index on (a) yarn tenacity and (b) elongation of fiber-blended samples; (c) yarn tenacity and (d) elongation of sliver-blended samples. (Color online only).

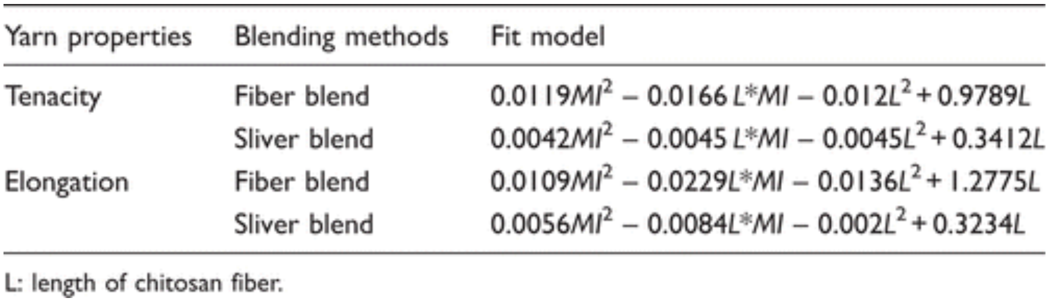
Tensile properties and fiber distribution

As shown in Figure 7, chitosan/cotton yarns with the same blend ratio have very different performances due to the different blending methods. The breaking tenacity of sliver-blended yarns is increased by 8.36%, 23.81%, 26.17% and 9.92% with fiber lengths of the chitosan of 22, 30, 38 and 46 mm, respectively. Meanwhile, the migration index of the chitosan fibers increases by 8.22%, 14.32%, 28.87% and 8.2% respectively. The preferential distributions of the chitosan/cotton yarns have a positive effect on improving the yarn strength. In this case, the tensile property of blended yarn is determined by both the length of the chitosan fiber and the migration index. The length of the chitosan fiber, *L*, and migration index, *MI*, are taken into consideration as parameters that influence the tensile properties of the yarns. By neglecting the mutual effect of these two factors, a binary quadratic model is adopted for the simulation of the length and migration versus tenacity and elongation relationships:

$$\sigma = A_2\mathrm{MI}^2 + B_2 L \bullet \mathrm{MI} + C_2 L^2 + D_2 L + E_2\mathrm{MI} + F_2 \qquad (7)$$

$$E = A_3\mathrm{MI}^2 + B_3 L \bullet \mathrm{MI} + C_3 L^2 + D_3 L + E_3\mathrm{MI} + F_3 \qquad (8)$$

where σ is the breaking tenacity of the yarn, *E* is the breaking elongation of the yarns, *L* is the length of chitosan fibers
and A_2, B_2, C_2, D_2, E_2, F_2, A_3, B_3, C_3, D_3, E_3 and F_3 are coefficients of the functions. The fitting results are shown in Table 12 and Figure 8. From these equations, the yarn tenacity and elongation can be predicted with fiber length and fiber distribution. From Figure 10, it can be speculated that in the red regions, the blended yarn would achieve the optimum performance, while the blue region indicates poor mechanical performance.



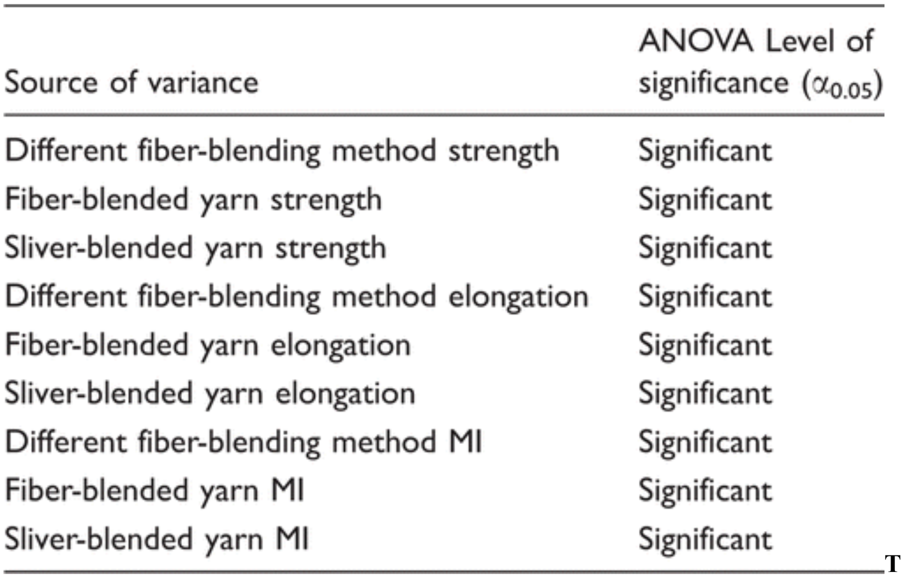
Yarn properties	Blending methods	Fit model
Tenacity	Fiber blend	$0.0119MI^2 - 0.0166\,L{*}MI - 0.012L^2 + 0.9789L$
	Sliver blend	$0.0042MI^2 - 0.0045\,L{*}MI - 0.0045L^2 + 0.3412L$
Elongation	Fiber blend	$0.0109MI^2 - 0.0229L{*}MI - 0.0136L^2 + 1.2775L$
	Sliver blend	$0.0056MI^2 - 0.0084L{*}MI - 0.002L^2 + 0.3234L$

L: length of chitosan fiber.

Table 12. Relationships among chitosan length, migration index and yarn properties of 50:50 chitosan/cotton blend yarn

Statistical analysis

To analyze the correlation between different fiber-blending methods and yarn strength, different fiber-blending methods and yarn elongation, and different fiber-blending methods and migration index within a 95% confidence limit (level of significance $\alpha_{0.05}$), a one-way analysis of variance (ANOVA) was carried out by using SPSS Statistics 22 software. The analysis reflected that the yarn strength, elongation and migration index between the different fiber-blending methods are significant (Table 13).



Source of variance	ANOVA Level of significance ($\alpha_{0.05}$)
Different fiber-blending method strength	Significant
Fiber-blended yarn strength	Significant
Sliver-blended yarn strength	Significant
Different fiber-blending method elongation	Significant
Fiber-blended yarn elongation	Significant
Sliver-blended yarn elongation	Significant
Different fiber-blending method MI	Significant
Fiber-blended yarn MI	Significant
Sliver-blended yarn MI	Significant

Table 13. Analysis of variance (ANOVA) carried out between 50:50 chitosan/cotton blend yarn and strength, elongation and migration index (MI)

Conclusions

The relationships among the length of the chitosan fibers, strength, elongation and fiber migration behaviors have been studied by producing yarn samples of four different fiber lengths of chitosan with cotton with a blending ratio of 50:50 in a ring spinning system. It is found that the yarn tenacity deteriorates with increases in the length of the chitosan fiber. Besides, chitosan fibers that are shorter in length (22 mm) or excessively long (46 mm) will bring about difficulties in yarn spinning, such as electrostaticity and fibers that stick. Chitosan fibers that are 30 and 38 mm in length are compatible for blending with long cotton fibers. It is found that, in the group of yarn samples spun by using the fiber-blending method, the yarn sample that contains chitosan fiber with a length of 30 mm provides better yarn strength and elongation among all the other lengths, while in the group of yarn samples spun by using the sliver-blending method, the yarn sample that contains chitosan fiber that is 38 mm in length has better yarn strength and elongation. Furthermore, this paper has provided evidence that the tensile properties are affected by the fiber distribution in yarn through migration index calculation. The blending method of fiber components (fiber or sliver blending) directly influences the yarn tenacity. Fiber blending offers more evenness in the fiber distribution in the spinning process as opposed to the sliver-blending method. Since the arrangement of spinning rollers can be adjusted for an optimal fiber distribution, fiber distribution can be manipulated during the yarn spinning production process. The value of this paper will be reflected by the price–performance ratio of antibacterial functionality and cost control, because it is found that there is a non-linear relationship between the inhibitory effect of chitosan and the ratio of fiber composition (in accordance with standard AATCC100, compared to the ratio of chitosan fibers in the fiber composition, the distribution of fibers has a greater influence on the antibacterial activity). In addition, the relationship between fiber distribution and the length of the chitosan fibers in the chitosan/cotton blend yarn has been studied and fitted by using polynomial modeling. It is found that the yarn tensile properties are affected by the length of each fiber component and its distribution in the yarn structure. Finally, a binary quadratic model is used to describe the relationships between length and migration versus tenacity and elongation. The proposed formula in this paper could serve as guidance for the yarn manufacturers and producers in the textile industry in terms of the effect of the length of the chitosan fibers on the fiber distribution in yarn.

Declaration of conflicting interests

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References

1. Jolle`s P and Muzzarelli RAA. *Chitin and chitinases*. Basel: Birkha¨ user, 1999.
2. Khor E. *Chitin: Fulfilling a biomaterials promise.* Waltham, MA, USA: Elsevier, 2014.
3. Nakajima M, Atsumi K and Kifune K. Development of absorbable sutures from chitin. In: Zikakis JP (ed.) *Chitin, chitosan and related enzymes.* New York, USA: Academic Press, 1984, pp.407–410.
4. Ravi Kumar MNV. Chitin and chitosan fibres: a review. *Bull Mater Sci* 1999; 22: 905–915.
5. Ravi Kumar MNV. A review of chitin and chitosan appli- cations. *React Funct Polym* 2000; 46: 1–27.
6. Wani MY, Hasan N and Malik MA. Chitosan and aloe vera: two gifts of nature. *J Dispersion Sci Technol* 2010; 31: 799–811.
7. Brine CJ, Sandford PA and Zikakis JP. *Advances in chitin and chitosan.* London: Elsevier Science Publishers, 1992.
8. Kim SK. *Chitin and chitosan derivatives: Advances in drug discovery and developments*. Boca Raton, FL, USA: CRC Press, 2013.
9. Kojima K, et al. Effects of chitin and chitosan on collagen synthesis in wound healing. *J Vet Med Sci* 2004; 66: 1595–1598.
10. Prudden JF, et al. The discovery of a potent pure chem- ical wound-healing accelerator. *Am J Surg* 1970; 119: 560–564.
11. Dresvyanina E, et al. Influence of spinning conditions on properties of chitosan fibers. *Fibre Chem* 2013; 44: 280–283.
12. Duan B, et al. Electrospinning of chitosan solutions in acetic acid with poly (ethylene oxide). *J Biomater Sci Polym Ed* 2004; 15: 797–811.
13. Kifune K, Yamaguchi Y and Tanae H. Wound dressing. Patent US4651725 A, USA, 1987.
14. Liu S, et al. A novel approach to improving the quality of chitosan blended yarns using static theory. *Text Res J* 2015; 85: 1022–1034.
15. Smorada RL. Nonwoven Fabrics. In: Mark HF and Kroschwitz JI (eds) *Encyclopedia of polymer science and engineering*. Vol. 10, New York, U.S.A: Wiley, 1985, pp.227–253.
16. O¨ ktem T. Surface treatment of cotton fabrics with chitosan. *Color Technol* 2003; 119: 241–246.
17. Kim GO, et al. An electrostatically crosslinked chitosan hydrogel as a drug carrier. *Molecules* 2012; 17: 13704–13711.
18. Batra SK and Pourdeyhimi B. *Introduction to nonwovens technology.* Lancaster, PS, USA: DEStech Publications, Inc., 2012.

19. Cyniak D, Czekalski J and Jackowski T. Influence of selected parameters of the spinning process on the state of mixing of fibres of a cotton/polyester-fibre blend yarn. *Fibres Text East Eur* 2006; 4: 36–40.
20. El-Behery HM and Batavia DH. Effect of fiber initial modulus on its migratory behavior in yarns. *Text Res J* 1971; 41: 812–820.
21. Moghassem A and Fakhrali A. Comparative study on the effect of blend ratio on tensile properties of ring and rotor cotton-polyester blended yarns using concept of the hybrid effect. *Fibers Polym* 2013; 14: 157–163.
22. Pan N, et al. Studying the mechanical properties of blended fibrous structures using a simple model. *Text Res J* 2000; 70: 502–507.
23. Cai Y, et al. A comparative study of the effects of cotton fiber length parameters on modeling yarn properties. *Text Res J* 2013; 83(9): 961–970.
24. Harlow DG and Phoenix SL. The chain-of-bundles probability model for the strength of fibrous materials I: analysis and conjectures. *J Compos Mater* 1978; 12: 195–214.
25. Pan N, Hua T and Qiu Y. Relationship between fiber and yarn strength. *Text Res J* 2001; 71: 960–964.
26. Hearle J and Goswami B. Migration of fibers in yarns part VII: further experiments on continuous filament yarns. *Text Res J* 1968; 38: 790–802.
27. Hearle J and Goswami B. Migration of fibers in yarns. Part VIII: experimental study on a 3-layer structure of 19 filaments. *Text Res J* 1970; 40: 598–607.
28. Mahmoudi MR. Blending and composite yarn spinning. In: *Lawrence CA (ed.) Advances in yarn spinning technology.* Cambridge, UK: Woodhead Publishing Limited, 2010, pp.102–118.
29. Oxtoby E. *Spun yarn technology*. London, Boston: Butterworth-Heinemann, 2013.
30. Tyagi GK. Yarn structure and properties from different spinning techniques. In: Lawrence CA (ed.) *Advances in yarn spinning technology*. Cambridge, UK: Woodhead Publishing Limited, 2010, pp.119–151.
31. Hamilton J and Cooper D. 51—The radial distribution of fibres in blended yarns part II—factors affecting the pref- erential migration of components in blends. *J Text Inst Trans* 1958; 49: T687–T698.
32. Hamilton J. 30—The radial distribution of fibres in blended yarns: part I—characterization by a Migration Index. *J Text Inst Trans* 1958; 49: T411–T423.
33. Baykal PD, Babaarslan O and Erol R. Prediction of strength and elongation properties of cotton polyester-blended OE rotor yarns. *Fibres Text East Eur* 2006; 14: 18.

34. Duckett K, Goswami B and Ramey H. Mechanical properties of cotton/polyester yarns part I: contributions of interfiber friction to breaking energy. *Text Res J* 1979; 49: 262–267.
35. Aghasian S, et al. Investigation on the properties of blended rotor-spun cotton/polyester yarn using a hybrid model. J Text Inst 2008; 99: 459–465.
36. Morton W. The arrangement of fibers in single yarns. *Text Res J* 1956; 26: 325–331.
37. Anandjiwala RD, et al. Structure-property relationship of blended cotton yarns made from low and high tenacity fibers. *Text Res J* 1999; 69: 129–138.