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Cleaner Production of Mulberry Spun Silk Yarns via a Shortened and Gassing-free Production Route

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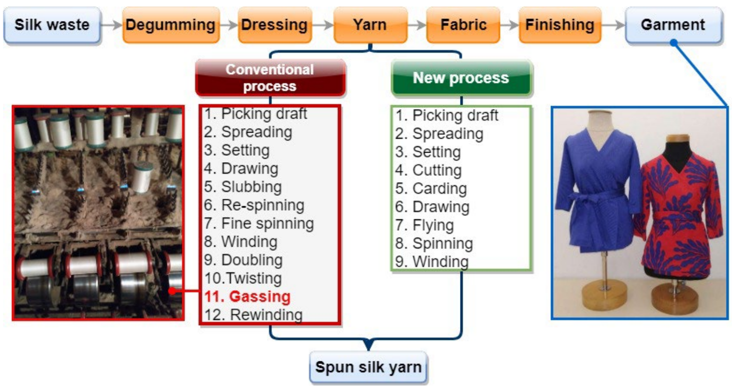
Highlights

- An eco-friendly production process to manufacture mulberry spun silk yarns
- Excellent properties of yarns and fabrics comparable with conventional ones
- Elimination of greenhouse gas emission, odor, and dust pollution due to gassing
- Significant savings achieved in materials, manpower, and energy

Graphical abstract



Abstract

The green production of textiles via an eco-friendly approach has recently gained considerable interest. As a derivative industry of silk manufacturing, spun silk utilizes waste materials generated in different processes of silk production, which is considered as the re-use of silk waste. The spun silk industry is facing several problems now, including environmental pollution, low production efficiency, increased labor intensity, significant material waste, and excessive energy consumption. This study presents an environment-friendly production route to produce mulberry spun silk yarns, by eliminating the gassing process that burns away surface hairs and neps. The gassing process not only generates odors, dust, and gas discharges but also results in significant material wastage and high production cost. The key is a modified ring spinning technology to achieve low yarn hairiness and neps; thus the yarn produced no longer requires gassing. The number of processing steps is also reduced to nine from twelve compared to the traditional silk spinning system. The modified 60 Nm mulberry spun silk yarns show a comparable tenacity of 26.33 cN/tex, evenness of 9.96%, neps (+200%) of 18 per 1 km, and a slightly worse hairiness S3 value of 74 per 100 m, compared with the conventional gassed ones. The plain knitted fabrics made by the modified yarns also reveal a 1.5 grade higher pilling resistance, similar mechanical and thermal properties, and a slightly hairier surface appearance than the conventional ones. The new processing route greatly reduces carbon footprint and achieves significant savings in materials, manpower, and energy, which may shed new light on the industrial manufacturing of mulberry spun silk yarns.

Keywords

mulberry spun silk, yarn properties, gassing process, modified ring spinning, 3D structural configuration

1. Introduction

Silk is a natural fiber used in textiles for more than 5000 years (Astudillo et al., 2014). It has been regarded as a highly valued textile fiber, which exhibits properties unrivaled by any other natural fiber such as high tensile strength, elasticity, absorbency, and great dyeing properties (Murugesh Babu, 2013a). Despite facing keen competition from man-made fibers, silk has maintained its supremacy in the production of luxury apparel and other high-quality goods (Robson, 1998). Nowadays, silk has also been used as a biomaterial (da Silva et al., 2016), bio-ink (Jose et al., 2015), and in bioactive scaffolds (Jose et al., 2015) widely employed in medical and tissue engineering fields.

It is known that the textile and clothing industry is one the most polluting industries and a major source of greenhouse gas emissions due to its production technologies and supply-chain transportation (Giacomin et al., 2017). According to the comparative research carried out by the

Waste & Resources Action Program (Thomas et al., 2012), silk yarn production produces a carbon footprint of 6,964 kg of CO_2 equivalent (CO_2e) per metric ton, which is 2.58 times that of polyester yarns. The higher carbon footprint of silk yarn production is associated with the larger consumption of water and energy. It is, therefore, important to develop green yarn technologies to alleviate the carbon footprint in the silk yarn production process.

As a derivative industry of silk manufacturing, spun silk utilizes waste material created in different processes of silk production. The main source of raw material is the waste of floss generated in the reeling of the cocoons (Armitage, 1956). Silk waste is considered as a valuable material for its supreme properties and good spinnability that can be made into spun silk textiles (Murugesh Babu, 2013b). However, the variances among raw material quality lead to a complicated production process, wherein large material wastage, heavy energy consumption, and serious environmental pollution take place.

Production of spun silk yarn can be broadly divided into three main divisions: degumming, dressing, and spinning (Zhang, 1991), as shown in Fig. 1. The main task of degumming is to remove a certain part of sericin, grease and other contaminants from the raw material, so that the fiber can be easily loosened, facilitating mechanical processing in the later stage. The dressing process is to further loosen, mix, and remove impurities from the degummed raw material, and carefully comb them to make combed drafts. The traditional draft-making process is mainly based on the circular dressing machine, i.e., circular dressing draft-making process. Three grades of drafts are extracted through the circular dressing. The first dressing yields the longest fibers, 65-78 mm in length, and is known as 1st grade draft. The remaining silk is re-dressed to produce 2nd grade draft, 50-65 mm in length. The last dressing yields 3rd grade draft, 40-50 mm in length. The spinning stage can be divided into pre-spinning and post-spinning: the task of pre-spinning is to process the combed drafts into a continuous and uniform combed sliver, and then draw and spin into roving; the post-spinning is to further draw and twist the roving into yarn, and then ply and gas the yarn into the final product. Towards a cleaner production, some efforts have been made by using eco-friendly methods, such as hydrated lime water (Zhao et al., 2018), steam treatment (Wang et al., 2018), ultrasound and enzymes (Mahmoodi et al., 2010) to replace the conventional degumming process. Some mills have used a worsted gilling machine (Zhang, 1991) to comb the silk fibers to replace the conventional dressing process. However, few studies investigated the problems existing in the spinning process. One major concern is the gassing procedure which is applied to burn away protruding fibers, neps, and other impurities from the yarn body by a gas flame and imparts a gloss to the silk (Murugesh Babu, 2013b), as displayed in Fig. S1. Gassing is a key step in the conventional spun silk yarn production because it greatly improves yarn surface appearance by largely removing neps and protruding fibers, meanwhile reducing the quality control for previous production processes. However, gassing not only generates dust, gas discharges, and odors, resulting in excessive energy consumption and carbon emissions, but also poses a great threat to workers' health which may lead to respiratory and heart diseases in cases of long-term persistent inhaling silk dust, volatile organic compounds, and carbon monoxide (Xiang et al., 2019). According to statistical data from Hailing Spun Silk Mill, one of the largest spun silk mills in China, 0.275 ton fuel gas is consumed and 0.82 ton CO_2 is released per metric ton of spun silk yarns. In addition, gassing leads to 6-8% weight loss (Armitage, 1956), and silk yarns undergoing gassing appear in color as uneven yellowness, which may cause difficulties in dyeing bright color and color matching among different batches (Tao and Yin, 2019). It can be clearly seen in Fig. S1 that the heavy accumulation of dust is formed and deposited on the gassing machine. However, insufficient research and data on air pollution and energy consumption during gassing can be found in the literature.

Some earlier attempts have been made within the traditional spun silk frame to improve yarn properties and productivity. Siro-spun has been introduced to reduce the gassing loss and shorten the production steps, however no data regarding material and energy savings have been disclosed (Zhou et al., 2006). Compact has also been employed, and it was reported that the weight loss due to gassing has been improved by 4.48% (Wang et al., 2016). For the above attempts, gassing was always required because, in the traditional process, gill boxes are employed in each process from spreading to roving. Spun silk yarns are gassed to remove neps which is likely to be created in the gilling processes because of the fineness of the fiber (Armitage, 1956).

In order to better handle silk fibers and reduce the neps generation, the roller-apron drafting system in the cotton spinning line has been proposed in this work to replace the gill boxes. Although some patents have been disclosed by using the cotton production line for producing blended yarns with cotton (Wu et al., 2014), wool (Liu et al., 2015) or cashmere (Li et al., 2014), studies for the purpose of clean production have remained limited. Therefore, the production of silk blends on the cotton spinning line is textile-oriented, not clean product-oriented. There is no investigation on the clean production aspect as well as a comparison using spun silk yarns as a benchmark. Noil silk yarns with coarse yarn count, 60/2 Nm or above, made from silk noil, 25-30 mm in length, were produced in the cotton spinning line (Zhou, 2006), but four gassing processes were applied because of the poor quality of the raw material. Therefore, there is a lack of wide-spread fundamental knowledge on the processing of mulberry spun silk yarns by means of the eco-friendly gassing-free method. Moreover, no assessment has yet been made on the environmental performance of the production process.

In this work, an eco-friendly and shortened production process for mulberry spun silk single yarns, without the requirement of gassing was first presented. In actual practice, the cotton production line has been applied to better handle silk drafts by reducing neps generation in the pre-spinning process. The cutting process has been introduced to prepare the silk fibers suitable for the cotton production line. Meanwhile, a modified ring spinning method has been proposed to substantially improve yarn properties, thus the yarn produced no longer requires gassing. In the new process, doubling and twisting have also been eliminated because they are essential for preparing processes for gassing. Thus, the proposed production approach follows a more sustainable and cleaner route than the conventional one.

Under the proposed production route, it is very important to understand the effects of different grades of silk drafts and key spinning parameters on the yarn quality, and therefore on the performance of the resultant knitted fabrics. The internal structure of the modified yarns, 3D structural configuration of the fibers, was then characterized. Moreover, fabric objective and subjective properties were evaluated. In addition, the chemical structure of the modified yarns and fabrics were tested. Finally, an environmental assessment was conducted to investigate the air pollution, consumptions in material, manpower, and energy generated or consumed in this work as well as the conventional spun silk yarn production. With the present study, it is expected to provide the feasibility assessment of using the new approach to replace the conventional spun silk yarn production, and simultaneously assess the clean production aspect, which may shed new light on the industrial manufacturing of spun silk yarns.

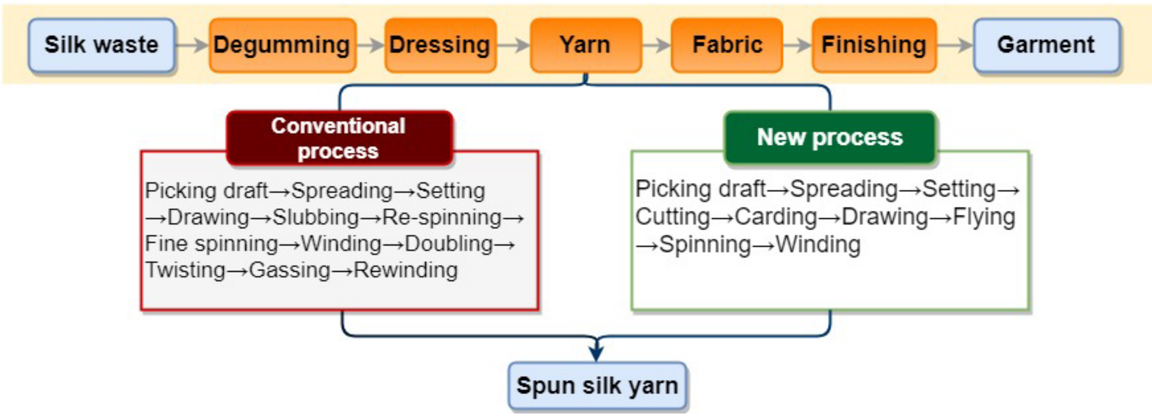


Fig. 1 Process flow of spun silk

2. Material and Methods

In this section, testing methods of different mulberry spun silk drafts, clean yarn production processes, characterization of the modified yarns and fabrics, as well as the environmental and economical assessment are introduced. Additional details can also be found in the Supplementary Information.

2.1 Material

Three kinds of mulberry silk drafts with different grades were used as the starting material, namely 1st grade, 2nd grade, and 50% 1st/50% 2nd grade silk drafts. Different grades of the silk drafts were selected to achieve a balance between quality and cost. The major difference among these drafts is fiber mean length and neps. All the materials were supplied by Hailing Spun Silk Mill. After fiber cutting, fiber mean length was measured according to the standard ASTMD1440-07(2012), Neps were tested by the standard ASTMD 1770-94, fiber strength was assessed by the standard ASTMD1445/D1445M-12, and fiber fineness was investigated based on the standard

ASTMD1577-07(2012). The pre-spinning processes were also conducted in Hailing Spun Silk Mill. After the flying process, the Uster Tester 3 was used to test roving evenness performance.

2.2 Production Process

Fig. 1 illustrates the novel approach for mulberry spun silk yarn production (Tao and Yin, 2019). Details of pre-spinning and after-spinning processes are described in Supplementary Information. A novel modified spinning method was first proposed to minimize yarn faults including hairiness and neps. A combination of Siro-spun (Plate and Lappage, 1982) and Nu-torque (Yin et al., 2016) technologies were applied on the ring spinning machine (Zinser 351) to substantially improve yarn properties. As displayed in Fig. 2, two rovings were fed simultaneously through the drafting zone with a controlled spacing called Siro gap between each other. The two strands of drafted fibers passed through the front rollers and formed a spinning triangle, then joined to a convergence point to form a single yarn with two-ply structure by high twists generated from both false and real twists. In the downstream of the false twister, the reverse twists were immediately introduced until the final twist remaining was that of the original yarn. Finally, the yarn was wound onto a bobbin mounted on a driven spindle.

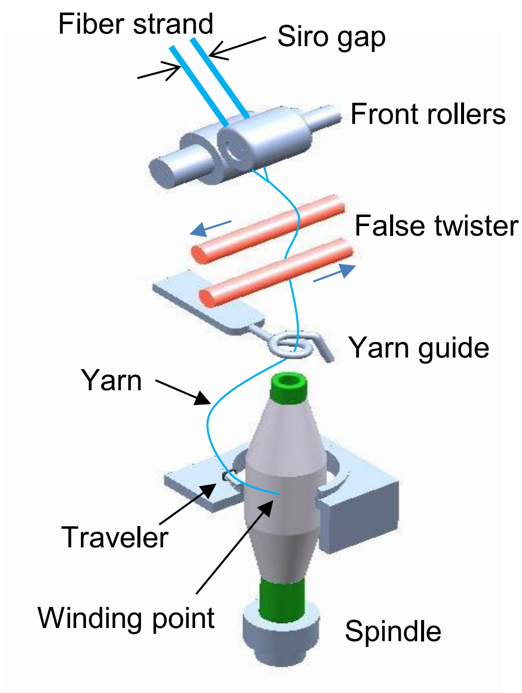


Fig. 2 A modified spinning method for spun silk yarn production

2.3 Experimental design

For the new approach, 60 Nm single yarns were produced on Zinser 351 by the proposed method. As the key parameters for the proposed method: Siro gap (the gap between two roving strands) and speed ratio (the ratio of the belt moving speed to the yarn delivery speed), the effects of three different levels of these two parameters on the quality of the resultant yarns were evaluated. Moreover, the effects of three different grades of silk drafts on the quality of the resultant yarns were also assessed. In addition, yarns produced by the traditional ring spinning method (Fraser, 1993), modified ring-based methods including Siro-spun, Compact (Nikolic et al., 2003), and Nu-Torque (Tao et al., 2013) were also tested and compared with the modified yarns. For all methods, the spindle speed was 13,000 rpm, the twist factor was 3.3, and the traveler was R+F 4/0. For Compact, the mechanical compact device (Rotorcraft RoCoS) was adopted. For Siro-spun, the gap between the two roving strands was 10 mm. For Nu-torque, the speed ratio of the false twister was 1.0. The conventional 120/2 Nm spun silk yarns before (Y-CBG) and after gassing (Y-CAG) were used as the benchmark against the yarns produced on the cotton spinning line. The raw material used for conventional spun silk yarns was 50% 1st/50% 2nd grade silk draft. The specified experimental plan is shown in Table 1.

Table 1 General experimental plan

Factor	Yarn code	Spinning method	Siro gap (mm)	Speed ratio	Roving
Siro gap	Y-Sg6Sr1-RV3	Siro + Nu-Torque	6	1	RV3
	Y-Sg8Sr1-RV3	Siro + Nu-Torque	8	1	RV3
	Y-Sg10Sr1-RV3	Siro + Nu-Torque	10	1	RV3
Speed ratio	Y-Sg10Sr1-RV3	Siro + Nu-Torque	10	1	RV3
	Y-Sg10Sr1.5-RV3	Siro + Nu-Torque	10	1.5	RV3
	Y-Sg10Sr2-RV3	Siro + Nu-Torque	10	2	RV3
Silk drafts	Y-Sg10Sr1-RV1	Siro + Nu-Torque	10	1	RV1
	Y-Sg10Sr1-RV2	Siro + Nu-Torque	10	1	RV2

	Y-Sg10Sr1-RV3	Siro + Nu-Torque	10	1	RV3
Benchmark	Y-Ring	Ring	/	/	RV3
	Y-Comp	Compact	/	/	RV3
	Y-Siro	Siro	10	/	RV3
	Y-NT	Nu-Torque	/	1	RV3
	Y-CBG	Conventional before gassing	/	/	RV2
	Y-CAG	Conventional after gassing	/	/	RV2

2.4 Yarn measurements

For each yarn sample, the properties of the three cops were tested. Yarn tenacity, evenness, and hairiness were evaluated according to the standards described in Supplementary Information. Yarn internal structure, 3D configuration of fiber trajectory in a yarn, was studied by using trace fiber technology (Morton and Yen, 1952). Preparation and image acquisition of these trace fibers are described in Supplementary Information.

2.5 Fabric measurements

Fabric objective properties such as surface morphology, dimensional stability, pilling resistance, and physical properties were tested. Fabric subjective measurements, the handle feelings of stiffness, smoothness, fullness, softness, and crispness, were carried out. Details of fabric objective and subjective measurements are provided in Supplementary Information.

2.6 Chemical structure variation before and after gassing

Infrared spectra of yarns and fabrics before and after gassing were collected using a Perkin Elmer Spectrum 100 FTIR spectrometer, while their surface elements were analyzed by the JEOL Model JSM-6490 tungsten thermionic emission SEM system with energy-dispersive X-ray spectroscopy (EDX) detector. Both yarn and fabric samples before and after gassing were employed for the measurement and comparison.

2.7 Air quality measurements

All air quality data were collected at Hailing Spun Silk Mill. In the mill, the gassing process is separated from the other processes. In order to evaluate air pollution due to gassing, the air quality data of both the gassing workshop and non-gassing workshop were collected separately and then compared and analyzed. Data of PM2.5, PM10, CO_2, and TVOC were captured by an environment air quality tester (SMART SENSOR, Model ST-8312), while CO data was captured by a gas detector (Jing Xun Chang Tong Ltd., Model YDBS-4001-4IN1X). The resolutions of PM2.5, PM10, CO_2, TVOC, and CO are 1ug/m^3, 1ug/m^3, 1ppm, 0.01 mg/m^3, and 0.1 ppm, respectively, while the accuracy of these data is ±10%, ±10%, ±5%, ±20%, and ±3%, respectively. The testing instruments were located 1.2 m above the ground. The sampling frequency was one record per minute and the acquisition time was 160 minutes. Details of each air quality index and its standard are listed in Table 2.

Table 2 Air quality index

Item	Excellent	Mild pollution	Heavy pollution	Standards
PM2.5	≤75ug/m^3	75~150 ug/m^3	>150 mg/m^3	GB3095-2012
PM10	≤150ug/m^3	150~250 ug/m^3	>150 mg/m^3	GB3095-2012
CO_2	≤700ppm	700~1500ppm	>1500ppm	GB18883-2002
TVOC	≤0.5mg/m^3	0.5~3.0 mg/m^3	>3.0 mg/m^3	GB50325-2010
CO	≤1ppm	1~9ppm	>9ppm	ASHRAE62-1989

2.8 Calculation of savings in materials, manpower, and energy consumption

For the conventional process, the cleaning wastage is caused by two processes: winding and gassing. The mass of the yarn samples was measured before winding and after gassing, and the cleaning wastage percent was calculated according to Eq. (1), where *Wc* is the cleaning wastage percent, *M1* is the mass before winding process and *M2* is the mass after the gassing process.

$$W_c = \frac{M1-M2}{M1} x100\% \tag{1}$$

For the new process, the cleaning wastage results from the winding process. Thus, the mass of the yarn samples was measured before and after winding, and the cleaning wastage percent was calculated according to Eq. (2), where *Wn* is the cleaning wastage percent, *M1* is the mass before winding process and *M3* is the mass after winding process.

$$W_n = \frac{M1-M3}{M1} x100\% \quad (2)$$

Manpower and energy consumption for both conventional process and new process were provided by Hailing Spun Silk Mill, in which a mill-scale trial has been conducted. The data were calculated based on the production of one ton of spun silk yarns. The manpower of each process was given, and the total manpower is the sum of each process plus welfare and social insurance. Likewise, the energy consumption of each process was provided, and the total value is the sum of each process.

3 Results and discussion

In this section, the experimental results of the fibers, yarns, and fabrics are displayed. Specifications of fiber and roving properties were tested. Moreover, yarn properties produced by the proposed process including strength, evenness, hairiness, surface appearance, and structure were measured. In addition, knitted fabrics made by the modified yarns were produced and tested. Finally, environmental and economical assessments were conducted and discussed.

3.1 Material characterization

Specifications of fiber and roving properties are listed in Table 3. Fiber mean length and neps are major differences among different grades of silk drafts. As expected, the fiber mean length and neps content of the 1st grade silk draft (RV1) are superior to those of the 2nd grade silk draft (RV3). The 50% 1st /50% 2nd grade draft (RV2) has the longest fiber mean length and the worst neps content, which may be caused by the uneven blending of the two materials. Moreover, silk fiber acquired from RV1 has the highest tensile strength (53.96 cN/tex) and finest fiber fineness (68.12µm^2) among three drafts, while RV3 shows the lowest results by comparison (48.81 cN/tex; 71.19µm^2 respectively). In addition, three types of roving are very similar in the roving count. The roving evenness of RV2 (4.18Um%) is slightly better than the other two (RV1 4.58Um%; RV3 4.57Um%) probably due to a slightly coarse roving count.

Table 3 Specifications of silk fiber and roving

Roving code	Silk draft	Fiber mean length (mm) [CV %]	Neps (No./0.1g) [CV %]	Fiber strength (cN/tex) [CV%]	Fiber fineness (μm^2) [CV%]	Roving count (tex) [CV %]	Roving evenness Um% [CV %]
RV1	1st grade draft	33.09 [31.45]	11.20 [15.97]	53.96 [5.69]	68.12 [32.98]	374.67 [1.08]	4.58 [3.28]
RV2	50% 1st /50% 2nd grade draft	33.48 [27.55]	21.60 [15.21]	49.33 [1.39]	69.78 [34.12]	385.00 [2.34]	4.18 [2.64]
RV3	2nd grade draft	31.45 [30.87]	19.8 [13.07]	48.81 [2.42]	71.19 [29.59]	380.67 [2.63]	4.57 [2.49]

3.2 Yarn properties

Spinning is a vital process to determine the staple yarn structure and performances like tenacity, elongation, evenness, and hairiness (Yin et al., 2019a). Unless otherwise stated, the roving used for the experiment was RV3. As important parameters for the proposed spinning method, the effects of the Siro gap and speed ratio on the properties of the resultant yarns were studied, as shown in Table 4. The effect of the Siro gap on the hairiness S3 value (the number of protruding fibers longer than 3 mm) was found to be significant, at a constant speed ratio of 1.0. The hairiness value is greatly reduced by 58.43% as the Siro gap is increased from 6 to 10 mm. A wider gap increases the probability of fiber trapping by the neighboring fiber strands, thus obviously improves yarn hairiness (Plate, 1983). Further increasing the Siro gap leads to poor spinnability because it is hard for the two fiber strands to converge with a larger gap.

Based on the constant Siro gap of 10 mm, the effect of the speed ratio on the yarn properties was investigated. It was observed that the speed ratio affects the yarn hairiness. When the speed ratio is reduced from 1.5 to 1, the hairiness is greatly improved from 184 to 74. This is because a higher speed ratio gives rise to a higher false twist level, which pulls up the convergence point to the nip lines, thus reducing the chance of fiber trapping, causing undesirable results. Further reducing speed ratio results in yarn breakage due to the twist blockage of the belt on the yarn. The effects of these two parameters on yarn tenacity, evenness, thin places (-40%), thick places (+50%), and neps (+200%) are not remarkable, although there are some variances.

Different grades of the silk drafts were investigated to achieve a balance between quality and cost. The major advantage of RV1 reflecting on yarns is less thick places (+50%) and neps (+200%) compared with those made by RV2 and RV3, which is consistent with the results in silk fibers (Table 3). Considering the yarn properties made by different silk drafts, RV3 was chosen for the following study due to a fair performance and low material cost.

The proposed method outweighs the other ring-based methods, especially in neps (+200%) and hairiness, as displayed in Fig. S2 (a) and (b). The Y-NT yarns show the best result of neps (+200%) among other yarns, probably due to the rearrangement of surface fibers along the yarn length (Yin et al., 2019b). Then neps (+200%) values of the Y-Comp and Y-Siro yarns are similar to the Y-Conv yarns, which means no effect played by these methods to reduce yarn neps (+200%) for silk fibers. Moreover, the Siro-spun (Y-Siro) plays an important role in hairiness reduction, as discussed previously. The combination of Siro and Nu-Torque technology (Y-Sg10Sr1-RV3) further reduces yarn hairiness. The Nu-Torque (Y-NT) and Compact (Y-Comp) methods also demonstrate hairiness reduction function compared with the Y-Conv yarns, but their level is not as good as the proposed method.

Gassing is critical in the conventional spun silk yarn production because it greatly improves yarn properties. After gassing, the yarn defects have been greatly enhanced, especially the thick places (+50%), neps (+200%), and hairiness, as shown in Table 4. When a comparison is made between the Y-Sg10Sr1-RV3 and Y-CAG yarns, the Y-Sg10Sr1-RV3 yarns still show more neps (+200%) and long hairs than the Y-CAG yarns, which should be further explored and improved.

Table 4 Test results of the yarns produced by the proposed spinning method against benchmark yarns

Factor	Yarn code	Tenacity (cN/Tex)	Evenness CVm%	Thin places	Thick places	Neps (+200%)	Hairiness S3

		[cv%]	[cv%]	(-40%) [cv%]	(+50%) [cv%]	[cv%]	[cv%]
Siro gap	Y-Sg6Sr1-RV3	26.29 [5.42]	10.25 [1.25]	2 [173.21]	12 [32.43]	23 [46.60]	178 [24.31]
	Y-Sg8Sr1-RV3	26.32 [5.22]	10.2 [0.89]	3 [57.75]	11 [47.32]	23 [36.75]	134 [22.28]
	Y-Sg10Sr1-RV3	26.33 [5.31]	9.96 [2.22]	1 [173.21]	13 [36.46]	18 [41.66]	74 [19.02]
Speed ratio	Y-Sg10Sr1-RV3	26.33 [5.31]	9.96 [2.22]	1 [173.21]	13 [36.46]	18 [41.66]	74 [19.02]
	Y-Sg10Sr1.5-RV3	26.58 [5.47]	9.99 [0.95]	2 [173.21]	13 [78.07]	14 [93.68]	184 [32.26]
	Y-Sg10Sr2-RV3	26.34 [6.88]	9.92 [2.46]	2 [173.21]	12 [60.86]	19 [52.07]	173 [12.34]
Silk drafts	Y-Sg10Sr1-RV1	25.47 [5.66]	10.41 [1.89]	3 [57.75]	3 [124.90]	12 [65.47]	116 [3.99]
	Y-Sg10Sr1-RV2	26.18 [5.31]	9.75 [3.06]	0 [0.00]	12 [30.10]	13 [36.46]	121 [5.96]
	Y-Sg10Sr1-RV3	26.33 [5.31]	9.96 [2.22]	1 [173.21]	13 [36.46]	18 [41.66]	74 [19.02]
Benchmark	Y-Ring	25.60 [5.19]	9.40 [0.70]	0 [0.00]	32 [51.16]	32 [64.12]	815 [31.55]
	Y-Comp	26.26 [5.01]	9.78 [0.41]	3 [173.21]	22 [52.28]	31 [35.92]	227 [11.85]
	Y-Siro	26.92 [5.13]	9.66 [0.16]	1 [173.21]	15 [59.25]	30 [35.56]	99 [18.73]
	Y-NT	24.56 [5.78]	9.81 [0.59]	0 [0.00]	15 [37.65]	17 [69.28]	381 [17.32]
	Y-CBG	26.28 [6.80]	12.17	10	138	308	453 [4.07]
	Y-CAG	30.28	10.60	0	5	10	4

	[6.82]	[58.08]

The tenacity, evenness, imperfections, and hairiness values of the spun silk yarns with various modified production routes evaluated in this study and previously reported in the literature are presented in Table S1. Overall, the yarn properties of this work show better hairiness (S3) and Neps (+200%) than those produced by previously reported work, which also meet the basic requirements for high-speed circular knitting machines (Basu, 2015).

Fig. 3 and Fig. S3 display representative SEM images of the modified 60 Nm single yarns (Y-Sg10Sr1-RV3) as well as the conventional 120/2 Nm spun silk ply yarns before (Y-CBG) and after gassing (Y-CAG). It can be clearly seen that the Y-Sg10Sr1-RV3 yarns show a single yarn structure while the Y-CBG and Y-CAG yarns demonstrate a typical 2-ply yarn structure. The Y-CBG yarns have many long protruding fibers outside the yarn body and plenty of loose fibers entangled around the yarn body, while the Y-CAG yarns are less hairy and have a clean surface because of gassing. When the comparison is made between the Y-Sg10Sr1-RV3 and Y-CBG yarns, it can be clearly found that the Y-Sg10Sr1-RV3 yarns show much less hairiness and some fibers on yarn surface have opposite inclination angle to the yarn axis, which hold yarn body tightly. However, the SEM images demonstrate that the Y-Sg10Sr1-RV3 yarns still have more protruding long fibers than the Y-CAG yarns, which should be further improved.

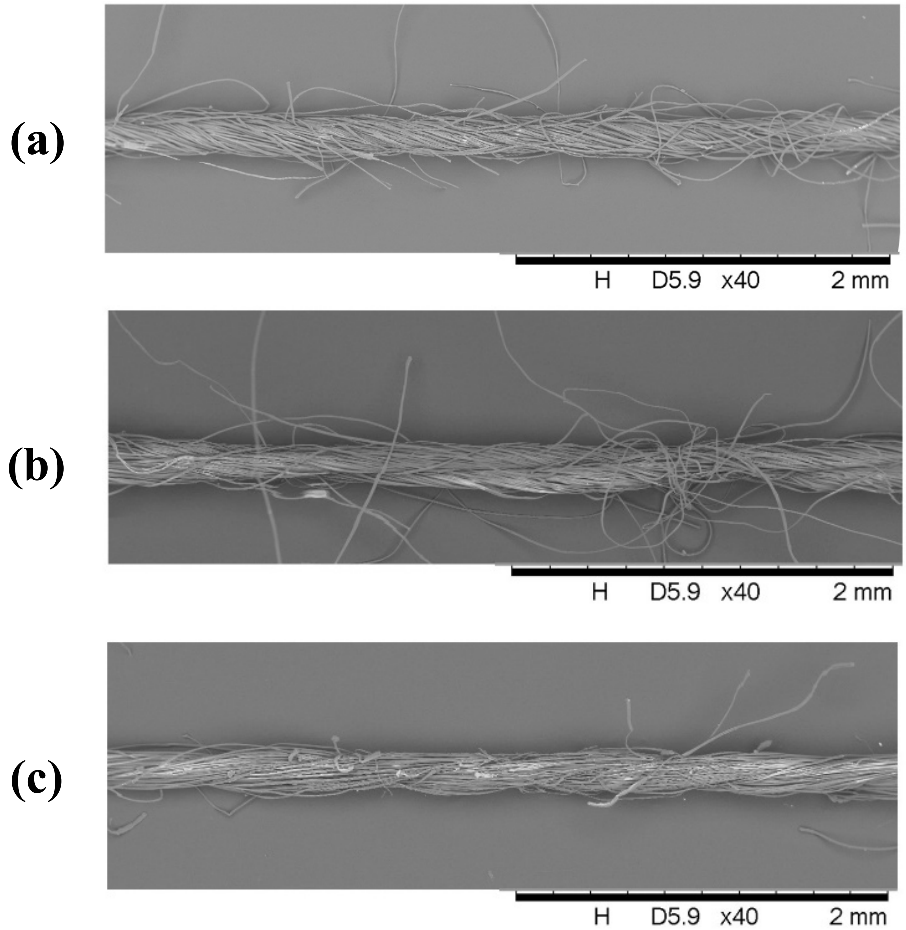


Fig. 3 SEM images of yarn surface (a) 60 Nm modified single yarns (Y-Sg10Sr1-RV3) (b) 120/2 Nm spun silk ply yarns before gassing (Y-CBG) (c) 120/2 Nm spun silk ply yarns after gassing (Y-CAG)

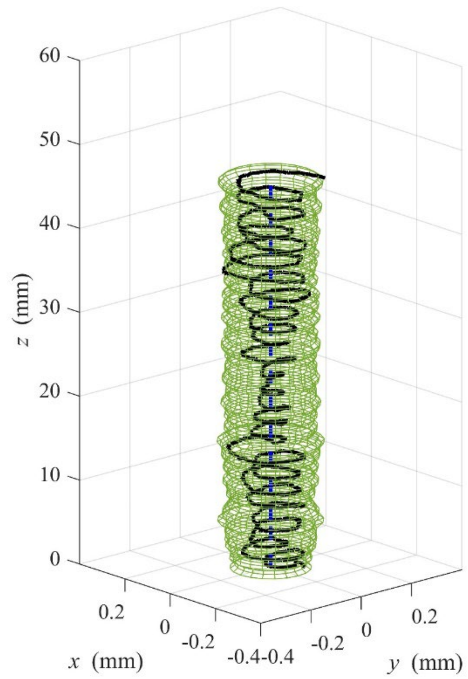
3.3 3D structural configuration

Fig. 4 displays some typical examples of yarn configuration for the Y-Conv, Y-Siro, and Y-Sg10Sr1-RV3 yarns. The length of tracer fiber varies from 20 to 60 mm, which affects the longitude view of the 3D yarn configuration. For different spinning methods, the geometrical paths and distribution of tracer fibers are distinct from each other.

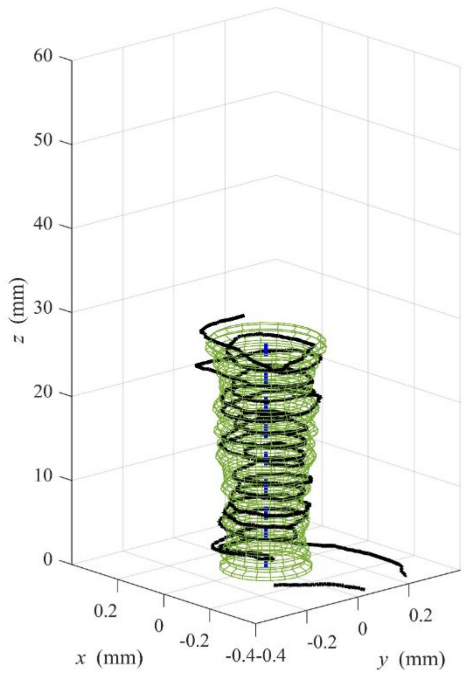
The differences in structural features reflect the spinning features of modifications applied in spinning methods. The Y-Conv yarns have an identical cylindrical helix path (Y-Conv-Sample 2), and the majority tracer fibers of the tested samples are distributed towards the outer cycle of the yarn, even with sections protruding away from the yarn body. An exception like Y-Conv-Sample 1 shows a combination of inner and outer distribution, which forms a conical helical trajectory.

The Y-Siro samples have a bulkier structure and larger yarn diameter. The special characteristics of Siro-spun yarns are that the fiber within the yarn is involved in two forms of twists: self-twisting and rotation along with the formation of the yarn. It is an effective spinning method to constrain the fiber migrated outside the main yarn body.

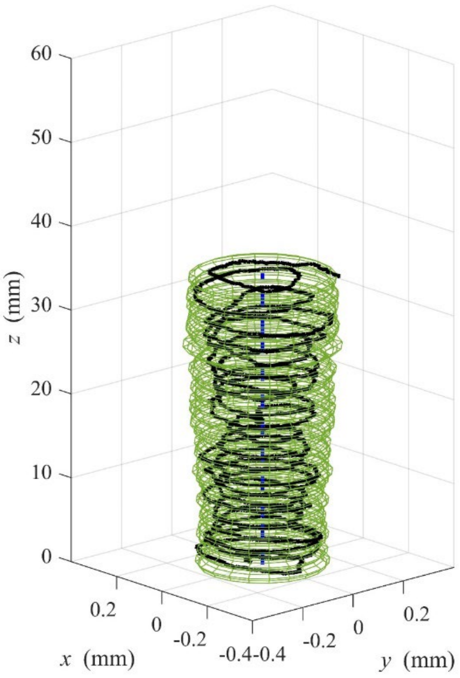
For the proposed spinning method, the yarn structure is much compact and leaner than Siro-spun yarns with an identical twist and count. Fibers have larger migration from the yarn center to the surface (Y-Sg10Sr1-RV3-Sample 1), and local reversion of twists occurs which means the fiber rotates in an opposite direction in a small section (Y-Sg10Sr1-RV3-Sample 2). Thus, larger migration, and a more compact structure, and less protruding sections from the yarn body can be achieved by the modified yarns.



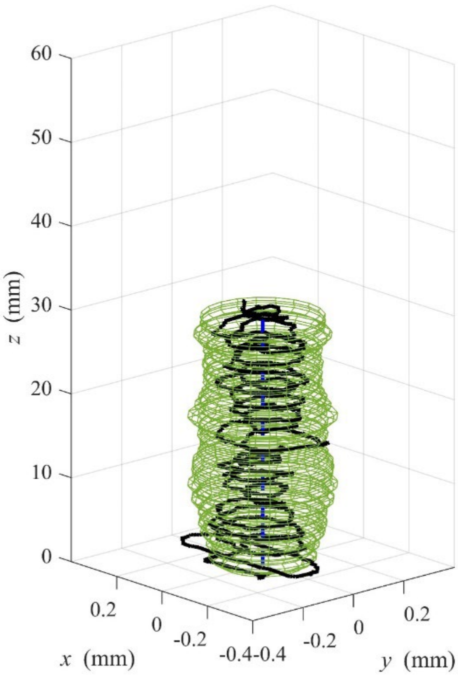
Y-Conv-Sample 1



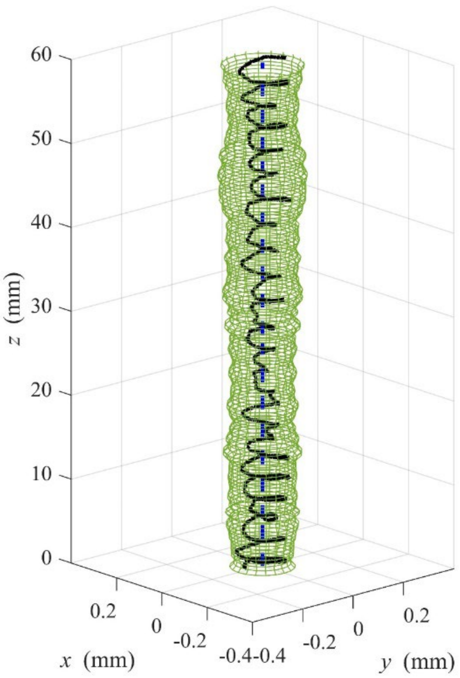
Y-Conv-Sample 2



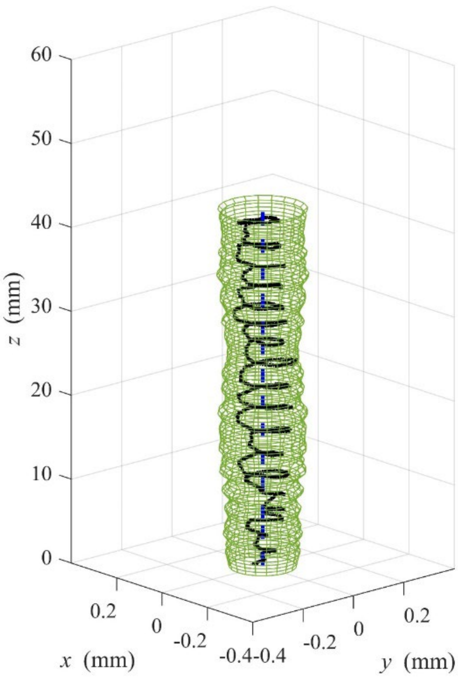
Y-Siro-Sample 1



Y-Siro-Sample 2



Y-Sg10Sr1-RV3-Sample 1



Y-Sg10Sr1-RV3-Sample 2

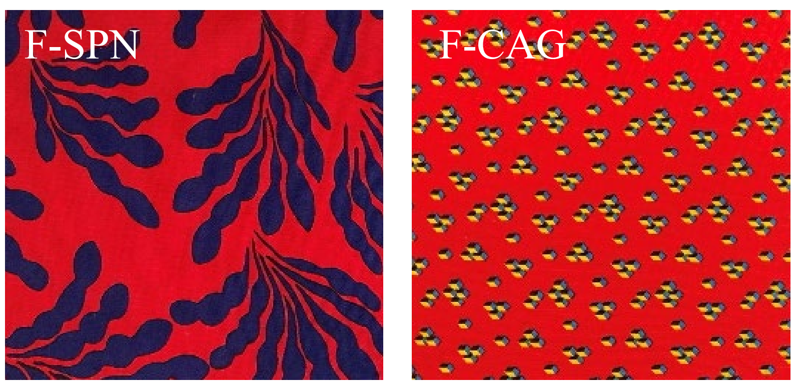
Fig. 4 3D fiber configuration of yarn samples

3.4 Fabric objective properties

The F-SPN fabrics made from the Y-Sg10Sr1-RV3 yarns and the F-CAG fabrics made from the F-CAG yarns were knitted at a density of 200 g/m^2 with single jersey structure on the same circular knitting machine by double yarn feeding, as shown in Table 5. Both fabrics were finished with prints. To explore the morphology of two fabrics, optical microscopic and SEM images were obtained for both fabrics, as shown in Fig. 5. The optical images reveal that the prints on the F-SPN fabrics are clear and even, comparable with the F-CAG fabrics, whilst the SEM images demonstrate that there are more protruding fibers on the fabric surface of the F-SPN fabrics than the F-CAG fabrics. This may be caused during the winding and knitting processes, many fiber ends coming out due to the friction with mechanical parts.

Table 5 Fabric sample specifications

Fabric code	Yarn used	Knitted structure	Fabric density (g/m^2)	Appearance
F-SPN	Y-Sg10Sr1-RV3	Single jersey	200	Print
F-CAG	Y-CAG			



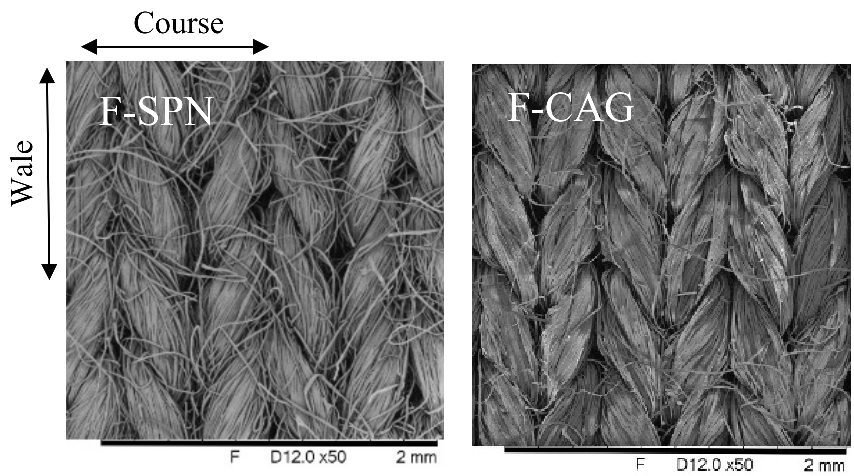


Fig. 5 Optical and SEM images of fabric appearances

Since there are more surface hairs on the F-SPN fabrics, it is important to evaluate their pilling resistance, a test to determine the resistance of textiles to the action of an applied resistive force. Unexpectedly, the F-SPN fabrics have excellent pilling resistance while the F-CAG fabrics have 1.5 lower gradings, as listed in Table 6. This may be caused by the fact that surface hairiness of the F-SPN fabrics formed fiber balls first then rubbed off during the entire testing process, whereas for the F-CAG fabrics, loose fibers came out from the yarn structure and started pilling on the surface due to repeated abrasion. It is noted that for conventional fabrics, the poor pilling grade is unable to maintain the initial fabric appearance due to friction, while the initially hairier modified fabrics can keep the surface clear for a long period.

The dimensional stability test is a standard test for any spun silk fabric. The hand wash method was adopted as knitted silk fabrics were considered delicate fabric. Both fabric samples are dimensionally stable but slightly shrunk after washing, as shown in Table 6. The shrinkage might be caused due to the tension applied during knitting. The implementation of Nu-Torque technology greatly modifies the yarn structure and reduces the residual torque (Guo et al., 2011), which also improves the dimensional performance.

Table 6 Pilling grade and dimensional stability of conventional and modified fabrics

Fabric code	Pilling grade	Spirality degree (°)	Shrinkage (%)	
			Course	Wale
F-SPN	5	0-1	-0.26 [0.82]	0.79 [0.78]
F-CAG	3.5	0-1	+/-5	+/-5

The Kawabata Evaluation System (KES) was used to measure the mechanical properties of fabrics as well as make objective measurements of hand properties (Harwood et al., 1990). Fabric properties measured by KES Testers are presented in Table S2. The p-value is the index of the significance of the test, whose value below 0.05 indicates that the difference between two fabrics is statistically significant at a 95% confidence level. The overall performance of both fabrics is quite comparable yet with some differences. The F-SPN fabrics are slightly thinner than the F-CAG fabrics. The difference can be traced back to the differences in yarn structure. The Y-Sg10Sr1-RV3 yarns have a single yarn structure while the Y-CAG yarns present a 2-ply yarn structure. For the yarn with the same count, the 2-ply yarns have a thicker yarn diameter than the single yarns, thus leading to larger fabric thickness. Due to the single jersey structure, the physical properties of as-made fabrics exhibit in-plane orthotropic behavior. The two fabrics have similar values in terms of tensile strain, bending rigidity in course direction and shear stiffness. The higher bending rigidity of the F-SPN fabrics in wale direction may be caused by the higher fabric tension during the knitting process. The compression energy of the F-SPN fabrics is 23.90% larger than the F-CAG fabrics due to a thinner thickness. The coefficient of friction of two fabrics in wale direction is similar, but in course direction the difference is significant. This may be ascribed to more surface hairs of the F-SPN fabrics, leading to higher friction when rubbing with stainless steel. Although two fabrics have statistical significance in thermal conductivity, the difference between the two is less than 6%.

3.5 Fabric subjective properties

The results of fabric subjective evaluations are listed in Table S3. The grade 1 means F-CAG feels better than F-SPN, the grade 0 means F-CAG is the same as F-SPN, and the grade -1 means F-CAG feels worse than F-SPN. All the evaluators agreed that the F-CAG fabrics feel stiffer and less smooth than the F-SPN fabrics. The stiffer feeling of the F-CAG fabrics is attributed to the high twists in the Y-CAG yarns. The smoother feeling of the F-SPN fabrics is in accordance with the KES results. Evaluators show different feels regarding the sensation of fullness, softness, and crispness. Most evaluators believe that the F-SPN fabrics are fuller and softer than the F-CAG fabrics, although the F-CAG fabrics are thinner than the F-SPN fabrics. The mean score of crispness demonstrates that both fabrics have the same feeling of crispness.

3.6 FTIR and EDX results

It can be seen from Table 7 that the weight ratio of N element increases apparently for the surface of both silk yarns and fabrics, indicating C and O decrease with the production of CO_2 and H_2O after gassing (i.e. oxidization). Also, the C/O ratio decreases for both silk yarns and fabrics, showing that the relative content of O element on the sample surface increases after surface oxidization. The general chemical components do not show significant change for both silk yarns and fabrics after gassing from the infrared spectrum (Fig. S4), wherein there is a small decrease of peak at 2921 cm^{-1} after gassing the silk yarns and fabrics (more apparent for the yarns), illustrating a small decrease of C-H stretching (Stuart, 2000), owing to surface oxidization.

Table 7 EDX results of yarns and fabrics before and after gassing

Weight (%)	Yarn before gassing	Yarn after gassing	Fabric before gassing	Fabric after gassing
C	58.08	45.31	63.47	49.45
O	31.88	30.32	36.60	33.27
N	11.46	24.16	0.56	17.36
C/O	1.82	1.49	1.73	1.49

3.7 Air pollution due to gassing

In order to investigate the air pollution caused by the gassing process, the air quality in the gassing and non-gassing workshops were tested. Fig. 6(a) and 6(b) display the PM2.5 and PM10 data of the gassing and non-gassing processes. According to the Standard GB 3095-2012 listed in Table 2, dust pollution grade is heavy in the gassing workshop. The PM2.5 and PM10 values of the gassing process are 210.48 ug/m^3 and 327.07 ug/m^3, respectively, 11.27 and 13.74 times that of the non-gassing process. The air environment in the gassing workshop poses a great threat to workers' health, which may lead to respiratory and heart diseases owing to long-term persistent inhaling silk dust. The CO_2 data of the gassing and non-gassing processes are 909.64 ppm and 484.01 ppm, respectively, as shown in Fig. 6(c). According to the standard GB1883-2002 in Table 2, the gassing process leads to mild air pollution while the non-gassing process is considered safe. For the production per metric ton of mulberry spun silk yarns, 0.275 ton fuel gas is consumed and 0.82 ton CO_2 is released. As is known to all, the CO_2 emission is the main cause of climate change. Gassing-free production contributes to both cost reduction and environmental protection. As displayed in Fig. 6(d), the data of Total Volatile Organic Compounds (TVOC) of the gassing and non-gassing processes are below 0.5 mg/m^3, which indicates that TVOC emissions for both the gassing and non-gassing processes meet the requirement of safety standards. CO is also generated in the gassing process due to incomplete combustion of gas fuel. As shown in Fig. 6(e), 4.72 ppm of CO is discharged in the gassing workshop, whilst zero CO is measured in the non-gassing workshop. The existence of CO may lead to chronic CO poisoning of workers, causing symptoms such as headache, dizziness, limb weakness, nausea and vomiting, and mild disturbance of consciousness.

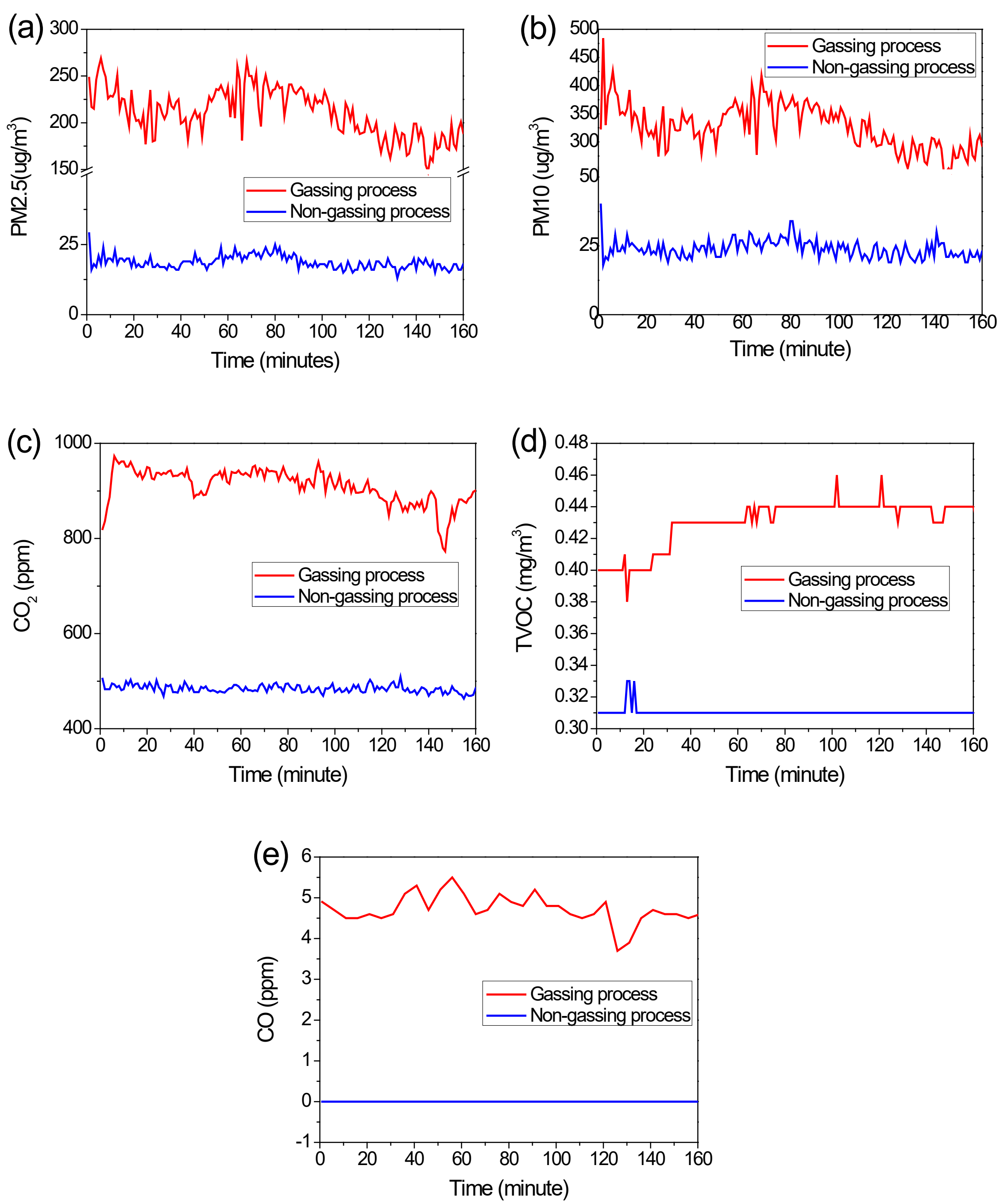


Fig. 6 Comparison of air quality data between gassing and non-gassing processes

(a) PM2.5 (b) PM10 (c) CO_2 (d) TVOC (e) CO

3.8 Savings in materials, manpower, and energy consumption

By using the new production route, significant savings in materials, manpower, and energy consumption have been achieved. For the conventional process, the material wastage mainly happens during the winding and gassing processes. For the new process, the weight loss and cleaning wastage has occurred in the winding process. As shown in Fig. 7, the wastage percentage of the modified yarns was 3.01%, while the weight loss of the conventional yarns was 8%, which means about 5% of materials can be saved. Moreover, the number of cuts of two yarns during winding was calculated. As the only cleaning step, the number of cuts for the modified yarns shows 52.27% higher than the conventional yarns, which also leads to a reduction of productivity during the winding process. But the total productivity for the new process has been improved since the number of production steps has been shortened from 12 to 9.

Fig. 8 calculates the manpower per metric ton of mulberry spun silk yarns by the conventional process and new process. By using the cotton production line, including carding, drawing, flying, and spinning, the automation level is greatly improved, thus less manpower is required in these production processes. Meanwhile, the whole production process has been shortened from 12 to 9 steps, leading to additional savings in manpower. Welfare and social insurance were calculated based on the subtotal manpower. Since the subtotal manpower of the new process has been reduced, the corresponding expenditure in these items can also be reduced accordingly. Therefore, the total manpower has greatly decreased by 39.55%, from 38,090 yuan to 23,025 yuan.

Fig. 9 calculates electricity consumption per metric ton of mulberry spun silk yarns by conventional and new processes. It can be found that the fine spinning and twisting occupy 77.97% of the total electricity consumption for the conventional process. By shortening the production process and producing 60 Nm single yarns directly in the ring spinning machine, the electricity consumption can be dramatically reduced by 45.01%. Therefore, by adopting the new process, 5,485 KWh electricity can be saved per metric ton of spun silk yarns. Moreover, by eliminating the gassing process, 0.275 ton gas fuel can be saved. According to the charge of utility in China: electricity 0.85 yuan per KWh, gas fuel 6,550 yuan per metric ton, the cost savings in energy consumption is 6,463.5 yuan per metric ton of spun silk yarns.

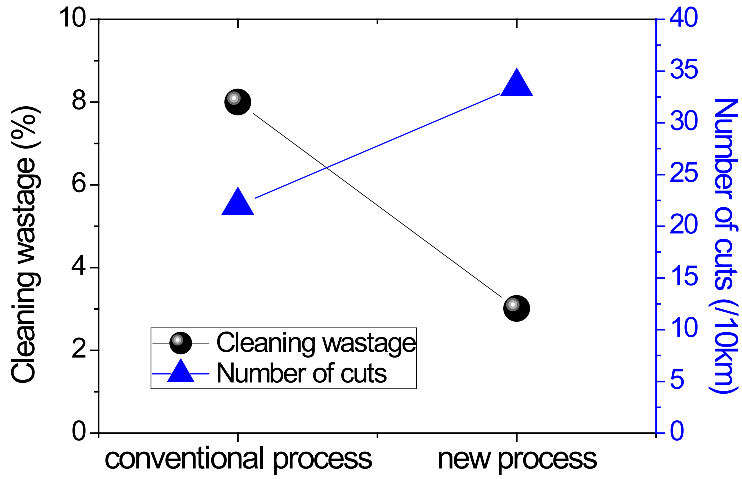


Fig. 7 Comparisons of cleaning wastage and number of cuts between conventional and new processes

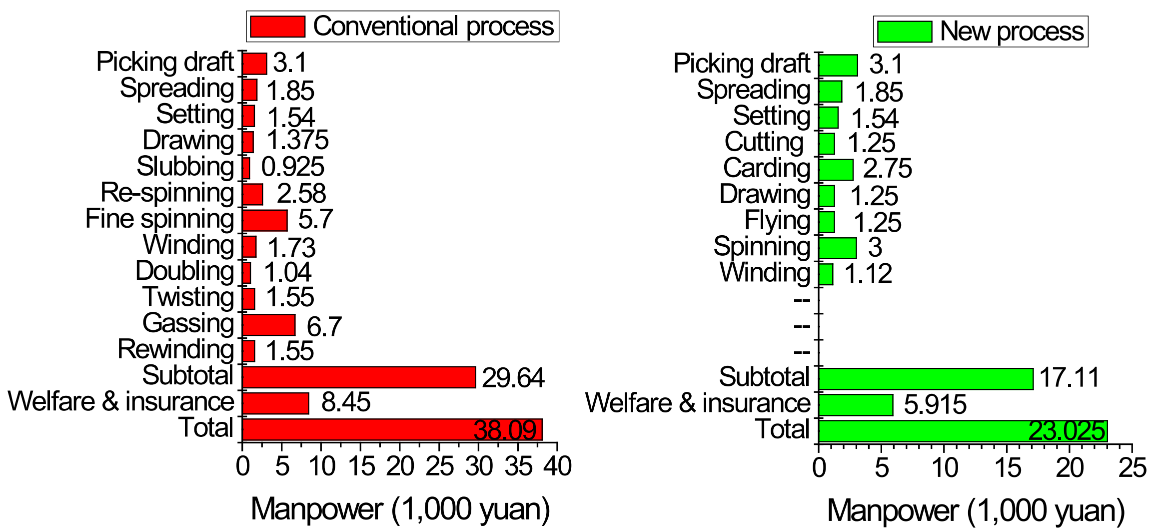


Fig. 8 Comparison of manpower per metric ton of mulberry spun silk yarns by conventional and new processes

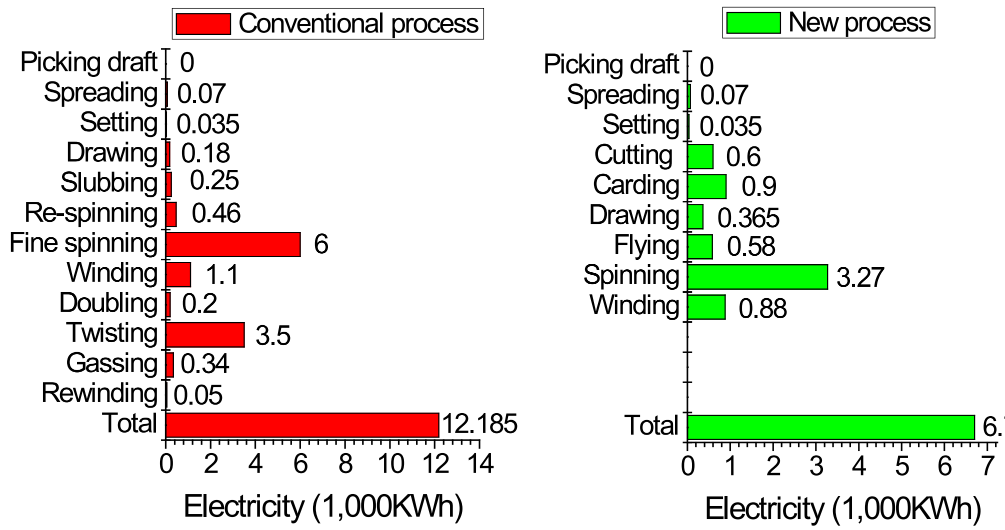


Fig. 9 Comparison of energy consumption per metric ton of mulberry spun silk yarns by conventional and new processes

3. Conclusions

This study presented an eco-friendly, shortened, and gassing-free production route for manufacturing mulberry spun silk yarns. Gassing process, which threatens workers' health and causes environmental pollution, was eliminated. The number of production steps has been shortened from 12 to 9. The tested air quality data confirmed the jeopardization of gassing to the workers and the ambient environment. The PM2.5 and PM10 values of 210.48 ug/m^3 and 327.07 ug/m^3 in the gassing workshop far exceeded the safety requirement by the Standard GB3095-2012. The tested CO_2 and CO contents of the gassing process were also much higher than the non-gassing process. The elimination of gassing significantly saved production cost, while being more environment-friendly and energy-saving. Modified mulberry spun silk single yarns using the winding process as the major cleaning process can save about 5% of materials from wastage. The proposed production route can save 100% of fuel consumption, reduce 45.01% of electricity consumption, and decrease manpower by 39.55%. The modified yarn and fabric properties were examined and compared to the conventional ones. The modified 60 Nm mulberry spun silk yarns show a comparable tenacity of 26.33 cN/tex, evenness of 9.96%, neps (+200%) of 18 per 1 km, and a slightly worse hairiness S3 value of 74 per 100 m, compared with the conventional gassed ones. The 3D fiber configurations demonstrated that the modified yarns have a more compact structure and less protruding sections from the yarn body. The modified knitted fabrics have comparable properties, dimensional stability, and excellent pilling resistance. Fabric subjective evaluations demonstrate that the modified fabrics are smoother, softer, fuller, and less stiff than the conventional fabrics.

Further studies should be conducted considering the following aspects. First, yarn and fabric properties should be further improved through the optimization of spinning parameters. Second, industry large-scale trials will be conducted for potential commercialization. Third, a carbon footprint assessment should be conducted to measure the silk yarns that are produced with the proposed production technology and comparison with the traditional process. This research may offer a new perspective for the spun silk industry towards the development and adoption of cleaner production technologies and improving environmental sustainability.

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