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Research article

Structure, properties, and fabric applicability of sustainable paper yarn with high washing stability

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ABSTRACT

This research provides an in-depth assessment of two paper yarn variants, examining their structural, functional, and performance characteristics. These yarns demonstrated favorable properties, including suitable linear density, twist, typical cellulosic functional groups as confirmed by Infrared spectroscopy, minimal hairiness, moisture transfer, and creditable mechanical strength. These yarns have flat layered cross-sections and grooved longitudinal surfaces. In addition, a low hairiness index (1.3–1.33) further acknowledged their smooth surface. Their remarkable evenness (15.86% and 7.08%) supported their effective wicking properties. Despite average breaking strength (0.77 cN/dTex and 1.05 cN/dTex) and moderate elongation, these yarns exhibited exceptional water-washing resistance and retained over 89% breaking strength after 15 washes. This study ranks these paper yarns as highly suitable for durable clothing fabrics, providing promising sustainable alternatives in the textile industry.

1. Introduction

The constraint for environmental sustainability in the textiles and apparel industry has risen due to alarming statistics surrounding global chemical fiber production and the expanding use of cellulosic fibers. This has prompted a reevaluation of conventional materials to address the environmental impact associated with these practices [1–3]. The environmental concerns of cellulosic and oil-based fibers, reliant on extensive fertilizers and toxic pesticides, have led to a critical need for eco-conscious substitutes [1]. Intensive cotton farming technologies have faced challenges from soil pollution and labor shortages, necessitating reforms for sustainable cotton production [2]. Additionally, proposals for reshoring the fashion value chain aim to contribute to sustainable economic growth by challenging the reliance on overseas supply chains [3]. The evaluation of the environmental impact of natural and synthetic fibers through a life cycle assessment underscores the importance of eco-conscious alternatives, such as bio-based fibers or recycled materials, to mitigate the environmental challenges posed by conventional textile materials [4]. This compelling evidence collectively emphasizes the demanding need for sustainable alternatives in the industry.

The sustainable textile material holds immense promise in reshaping the landscape of eco-conscious fashion and textile industries

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[5,6]. Furthermore, the persistent issue of plastic pollution, worsened by microfibers shedding of these synthetic textiles [7,8], reinforces the imperative for innovative, eco-conscious approaches within the textiles and apparel sector. The research by Ladewig et al. [9] underscores the urgent need to investigate the rates of release of chemical pollutants, and the potential harm to both marine and terrestrial life caused by textile fibers, and comprehend their roles in aquatic environments' chemical pollutant transport.

Amid this context, paper yarn emerges as an increasingly appealing substitute, crafted from cellulose-based paper sheets twisted into yarn, offering renewable and eco-friendly properties [10]. Paper yarn production offers a promising avenue for sustainability by countering the ecological impact of traditional fibers [11,12]. There is a growing interest in paper yarn as a textile material, acknowledging its inherent properties like moisture retention, absorbency, and antibacterial features while addressing its limitations in flexibility and knitting processes. Park et al. [13] explored hybrid yarns with synthetic filaments to enhance the paper yarn's tensile properties, aiming to overcome its drawbacks in flexibility and elongation. Peterson et al. [10] delve into the potential of Manila-hemp paper yarn, emphasizing its low shrinkage and suitability for textiles despite challenges in handling and stiffness. Felicia et al. [14] discuss methods to improve the knittability of paper yarn through surface treatments, evaluating the effects on friction coefficients and tensile properties. Furthermore, Park et al. [15] examined the development of a special kind of denim fabric using paper yarn, highlighting its unique physical properties and potential for summer-oriented products. Lastly, Hiroki et al. [16] focus on the high cool touch feeling of fabrics woven with paper yarn, examining their transverse heat conduction properties compared to conventional cotton yarn fabrics.

Despite its eco-friendly attributes, paper yarn faces inherent limitations, including susceptibility to wrinkling, limited stretchability, and reduced softness [17]. Yet, its rising demand in textile applications owes to its lightweight and anti-static nature, demonstrating its growing viability [17]. In the realm of sustainable material innovation, the utilization of historical Japanese practices in paper yarn production stands as evidence of the interaction between tradition and modern environmental consciousness [18]. Our previous research endeavors in developing cellulose films from Ficus Natalensis bark cloth fibers have further illuminated the potential of renewable resources in crafting textiles that not only abandon emitting harmful substances but also emphasize genuinely the present ambitions for alternative greener and healthier textile materials [19]. Moreover, the exploration of lignocellulosic materials as viable candidates for bioplastics [20,21] and the development of biobased, biodegradable synthetic fibers [22,23] present promising avenues for sustainable material engineering.

This study marks a crucial step in unraveling the potential of paper yarn within the textile domain. By systematically evaluating two distinct paper yarn types, this research offers a comprehensive analysis spanning structural characteristics, morphology, functional attributes, evenness, hairiness, wicking performance, mechanical robustness, and the critical aspect of washing stability. These findings highlight on suitability of paper yarns for fabric and garment production, paving the way for broader market acceptance and expanded applications. We recognize the challenges inherent to paper yarn, primarily due to its limited softness and stretchability and we support the roadmap for seamless integration of these paper yarns into versatile and sustainable fabric development for future research. In the pursuit of a sustainable textile industry, paper yarn emerges as an eco-friendly choice with inherent recyclability and minimal ecological impact. We believe that paper yarn achieving SDG 12 through high washing stability, SDG 9 via innovative materials, and SDG 13 with plant-based resources, leads the journey for greener and more sustainable textiles.

2. Materials and methods

2.1. Materials

Two paper yarns were provided by Zhejiang Shunpu Paper Co., Ltd. The production process of paper yarns was as follows: two pieces of paper with the areal weights of 12 g/m^2 and 18 g/m^2 were cut into 3 mm paper strips, with the composition likely incorporating plant-based wood pulp, and then the paper strips were twisted into paper yarns. The paper yarn made from 12 g/m^2 paper named as S1, and the other one named as S2.

2.2. Methods

The yarn linear density was measured by a yarn length meter (Model: YG086C, Wenzhou Darong Textile Instrument Co., Ltd, Wenzhou, China) according to GB/T 4743-2009 "Textile-Yarn from packages-Determination of linear density (mass per unit length) by the skein method". The testing length was 100 m, and the average value was taken from 5 measurements.

The twist of paper yarn was evaluated by a yarn twist machine (Model: YG155A, Wenzhou Darong Textile Instrument Co., Ltd, Wenzhou, China) according to GB/T 2543.2–2001 "Textiles-Determination of twist in yarn-Part 2: Untwist-retwist method".

The length of the paper yarn sample was 250 mm, the testing speed was 1000 r/min, and the preset twist was 900. The average value was taken from 10 measurements. The surface and cross-sectional morphology of paper yarn was observed by a field emission scanning electron microscope (Model: GeminiSEM 500, ZEISS, Oberkochen, Germany). The paper yarn was first treated in liquid nitrogen and then was cut to obtain a suitable cross-section for testing. Before testing, the paper yarn was pasted on a sample table with conductive adhesive for gold spraying treatment; since conductive adhesive and gold spraying treatment is a standard procedure to overcome the insulating nature of paper, allowing for better visualization of the surface and cross-sectional morphology under the electron microscope.

The surface of the paper yarn was also observed by a stereo microscope (Model: SteREO Discovery V12, ZEISS, Oberkochen, Germany). The functional groups of paper yarn were analyzed by a Fourier transform infrared spectrometer (Model: Nicolet iS50, ThermoFisher Scientific, Waltham, Massachusetts, USA). The evenness and hairiness of paper yarn were analyzed by a Uster Tester

(Model: Uster Tester ME6, Uster Technologies, Sonnenbergstrasse, Switzerland) according to GB/T3292.1–2008 "Textiles - Unevenness of textile strands - Capacitance method". The testing speed was 400 m/min, and the testing length of paper yarn was 400 m. The average value was taken from 10 measurements.

The wicking properties of paper yarns were assessed by a capillary effect tester (Model: YG(B)871, Wenzhou Darong Textile Instrument Co., Ltd, Wenzhou, China) according to FZT 01071-2008 "Textiles - Test method for capillary effect". The paper yarn with a length of 250 mm was hung vertically, and the bottom end of the paper yarn was applied 3 g of tension. The bottom end of paper yarn with a length of 15 mm was immersed in grade III water with an appropriate amount of black ink. The wicking height was recorded after 1 min, 5 min, 10 min, 20 min, 25 min, 30 min, and 35 min.

The paper yarn was washed in a fully automatic washing shrinkage tester (Model: Y089D, Wenzhou Fangyuan Instrument Co., Ltd, Wenzhou, China) according to GB/T 3921-2008 "Textiles-Tests for color fastness-Color fastness to washing with soap or soap and soda". The concentration of soap solution was 0.5 %, and the mass ratio of paper yarn to soap solution was 1:20. The paper yarn was washed for 40 min at 30 °C in the washing shrinkage tester. After washing, the paper yarn was put into an oven at 60 °C for 24 h. The dried paper yarn was ready for further processing or testing.

The mechanical property of paper yarn was tested by an automatic single yarn strength tester (Model: YG023B, Wenzhou Darong Textile Instrument Co., Ltd, Wenzhou, China) according to GB/T 3916-2013 "Textiles-Yarns from packages-Determination of single-end breaking force and elongation at break using constant rate of extension (CRE) tester". The clamping distance of paper yarn was 500 mm, the pretension was 0.2cN/dTex, and the testing speed was 500 mm/min. The average value was taken from 10 measurements.

3. Results and discussion

3.1. Structure characteristics

The linear density or diameter and twist are the critical parameters influencing the properties of paper yarn. The specifications of paper yarns are given in Table 1.

The linear densities of two kinds of paper yarns were measured in Tex (grams per 1000 m), with values of 42.2 Tex and 59 Tex, corresponding to the diameter of 0.11 mm and 0.12 mm, which are a little bit thick but still suitable for weaving or knitting [18]. It is well known that a suitable twist of yarn is important for fabric manufacturing as well as the final properties of the fabric formed by those yarns. As the paper yarn was designed for knitting, therefore, the twists of paper yarns were 46.4 twist/10 cm and 47.5 ± 2.22 twist/10 cm, which had a small difference. The twist irregularity of the two paper yarns was small, which was 3.7% and 3.8% respectively, which fulfills the requirement that the twist unevenness of the yarn should be controlled below ±8%.

3.2. Surface morphology

The paper yarn had a rough surface and demonstrated a stripe structure with small grooves (Fig. 1A). The cross-section of the paper yarn showed a layered stack structure (Fig. 1B) which is owing to the rotation of the paper strip. Besides, there was hardly any hairiness on the paper yarn surfaces since the surface of the papers was smooth (Fig. 1C and D).

3.3. Infrared spectra

The FTIR spectra of the paper yarn reveal distinct infrared characteristic peaks that provide valuable insights into its composition as shown in Fig. 2. The peak at 3335 cm^{-1} corresponds to the oxygen-hydrogen stretching vibration, primarily originating from cellulose and hemicellulose. This suggests a high content of –OH groups, indicating good hydrophilicity in the paper yarn. The peak at 2907 cm^{-1} is attributed to carbon-hydrogen stretching vibrations, associated with CH_3- and –CH_2- groups. The presence of the C]O stretching vibration peak at 1641 cm^{-1} is indicative of hemicellulose and lignin in the composition. The range between 1425 cm^{-1} and 1315 cm^{-1} corresponds to the carbon-hydrogen bending vibration peak. Characteristic absorption peaks of cellulose are observed between 1157 cm^{-1} and 1106 cm^{-1}, while the carbon-oxygen stretching vibration peak is evident at around 1030 cm^{-1} [24]. The C–H characteristic absorption peak is identified at 897 cm^{-1}, and the out-of-plane deformation vibration of –OH occurs at 664 cm^{-1}. The strong absorption peaks at –OH, C–H, and C–O stretching vibrations collectively signify that the paper yarn is predominantly composed of plant cellulose, highlighting its strong polarity and hydrophilic nature. This detailed interpretation underscores the rich information provided by the FTIR spectra, offering a comprehensive understanding of the paper yarn's chemical composition.

Table 1
Specifications of paper yarns.

Paper yarn	Paper areal weight (g/m^2)	Linear density (Tex)	Diameter (mm)	Twist (Twist/10 cm)	Twist factor	Twist irregularity (%)
S1	12	42.2 ± 0.10	0.11 ± 0.01	46.4 ± 2.03	301.4	3.7
S2	18	59.0 ± 0.19	0.12 ± 0.01	47.5 ± 2.22	364.8	3.8

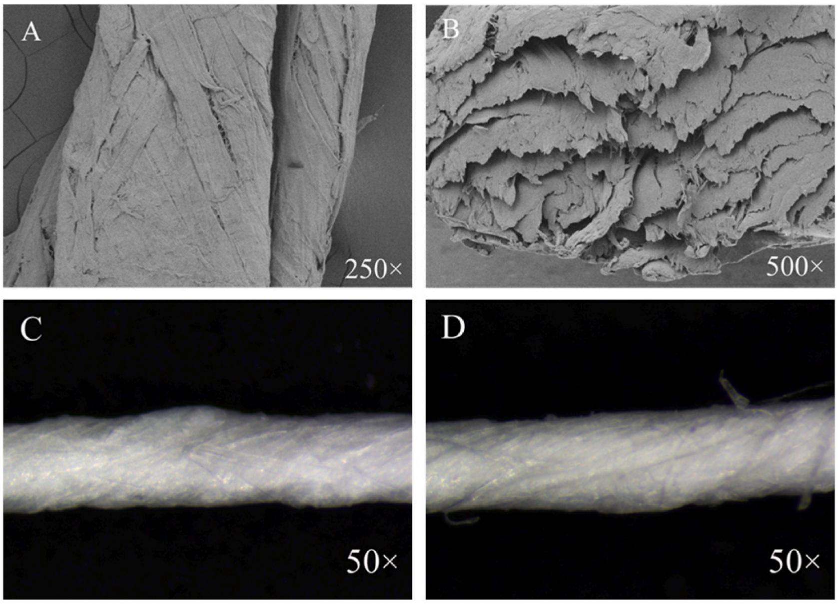

Fig. 1. Microscopic views of paper yarn: (A) Surface (250 ×) with stripe structure, (B) Cross section (500 ×) displaying layered stack structure, (C) Smooth surface of S1, and (D) S2.

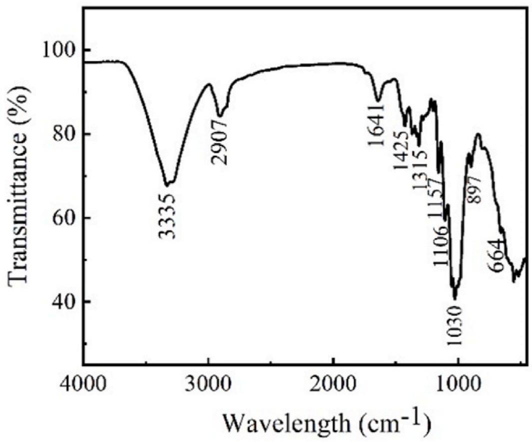

Fig. 2. Infrared spectrogram of paper yarn.

3.4. Imperfections

Yarn hairiness and unevenness are important indicators to judge the quality of paper yarn, which control their respective fabric production and their corresponding properties. The hairiness and evenness index of paper yarn are given in Table 2. The hairiness indexes of S1 and S2 were similar and were within the acceptable range of industrial standards, they can also be observed in Fig. 1c and d. The low hairiness index of both yarns was due to the smooth surfaces of the paper. However, the unevenness and yarn irregularity of S1 were much larger than those of S2. The sample S1 was made from a paper with a smaller areal weight, which signifies the thinner

Table 2
Hairiness and evenness index of paper yarn.

Paper yarn	Hairiness Index	Mass unevenness (CV %)	Unevenness (U %)	Yarn Irregularity (/km)				
				Thin place −30%	Thin place −40%	Thin place −50%	Thick place +35%	Thick place +50%
S1	1.31	15.86	12.99	6542	55	0	369	31
S2	1.33	7.08	5.61	0	0	0	5	5

paper with lower strength. Therefore, the paper strip with a smaller areal weight was easier to be influenced and damaged during the twisting process, which led to a more uneven paper yarn.

3.5. Wicking performance

The wicking height of paper yarns had a positive correlation with time as shown in Fig. 3. However, the wicking height of S1 was significantly larger than that of S2.

The wicking height of S1 and S2 reached a stable stage after 30 min, remaining at 10.9 cm and 3.4 cm, respectively (Fig. 3A). The wicking rate of paper yarns showed a remarkable decrease in the initial 5 min, and it came to equilibrium stage after 30 min (Fig. 3B). Besides, the paper yarn S1 had a much higher wicking rate than paper yarn S2 at the initial stage (Fig. 3B). The wicking performance of paper yarn could be due to two reasons, (1) the good hydrophilicity of cellulose, and (2) the groove structure on the surface and in the cross section of paper yarn (as shown in Fig. 1).

The wicking rate of the paper yarn decreased rapidly in the first 5 min, and S1 decreased much faster than that of S2 (shown in Fig. 4), indicating that the wicking effect of the paper yarn with small linear density is relatively better.

3.6. Mechanical properties before and after washing

The tensile strength and elongation of paper yarns before and after washing and soaping are given in Fig. 4. Generally, S1 had larger elongation and S2 had better tensile strength. The tensile strength and elongation of S1 before washing were 0.77 ± 0.07 cN/dTex and 3.67 ± 0.38 %, respectively. The tensile strength and elongation of S2 before washing were 1.05 ± 0.10 cN/dTex and 2.29 ± 0.29 %, respectively. The better tensile strength of S2 could be due to the better evenness (given in Table 2).

After washing and soaping, the tensile strength and elongation of paper yarn decreased gradually. After 15 washing and soaping cycles, the tensile strength of paper yarn S1 still reached 0.71 ± 0.028 cN/dTex and 0.74 ± 0.050 cN/dTex, which maintained 92.21% and 95.45% of the tensile strength of the original S1; the tensile strength of paper yarn S2 reached to 0.94 ± 0.055 cN/dTex and 0.97 ± 0.060 cN/dTex, which maintained 89.44% and 92.59% of the tensile strength of original S2. Correspondingly, after 15 washing and soaping cycles the elongation of paper yarn S1 were 1.62 ± 0.19 % and 1.66 ± 0.19 %, which maintained 56% and 55% of the elongation of original S1; the elongation of paper yarn S2 were 1.81 ± 0.42 % and 1.90 ± 0.14 %, which maintained 79% and 83% of the elongation of original S2. The experimental results indicated that the paper yarn exhibited good washing and soaping stability.

In the process of washing and soaping, the loss of tensile strength and elongation of paper yarn could be attributed to two reasons. Firstly, the mutual friction between the yarns could cause the strength loss of paper yarn. Secondly, during the washing process, water molecules could penetrate the macromolecules of wood pulp fiber, breaking some hydrogen bonds in the macromolecules of fibers, etc, water is discharged after the paper yarn is dried, so that the intermolecular force is weakened, and the breaking strength is reduced accordingly [25].

In addition, it can be seen from Fig. 4A that the breaking strength of the paper yarn after soaping is slightly higher than that after washing, which may be due to the gradual infiltration of surfactant molecules of detergent into the fiber, the paper yarn is expanded to a certain extent, and the wood pulp fibers are close to each other, thus the binding force is improved.

It can be seen from Fig. 4B that the elongation at the break of paper yarn tends to decrease with the increase of washing times. The elongation at break of 42.2tex paper yarn decreases significantly, which may be due to the loss of moisture in the yarn and the increase of brittleness caused by drying. The smaller the fineness, the greater the impact; The elongation at break of the two kinds of paper yarns after soaping is slightly higher than that after washing, which may be because the regularity of the internal structure of paper yarns is improved with the increased of the surfactant molecular groups filling between the fibers during soaping, resulting in the higher elongation at break of soaping than that of washing.

4. Conclusions

The findings explain the structural composition and performance attributes of paper yarn, revealing its distinct flat, layered structure composed of plant wood pulp fibers twisted along the axial direction, alongside notable functional groups that support plant-based cellulose composition. The yarn boasts a hairiness index ranging from 1.3 to 1.33 with a smooth surface demonstrating commendable hydrophilic traits and strong polarity. The investigation highlights that lower linear density paper yarns exhibit superior wicking abilities, as reflected in the 42.2 tex paper yarn's 10.9 cm wicking height, outperforming the 59.0 tex variant by 7.5 cm. Despite modest breaking strength and elongation, the yarns demonstrate exceptional water-washing resistance, retaining over 90% of their pre-washed strength after 15 wash cycles, underscoring their suitability for durable clothing fabrics. We believe that future research could further delve into production methods to bolster the yarn's mechanical robustness without compromising its advantageous hydrophilic properties, thereby broadening its scope for various textile applications.

Data availability statement

Data will be made available on request.

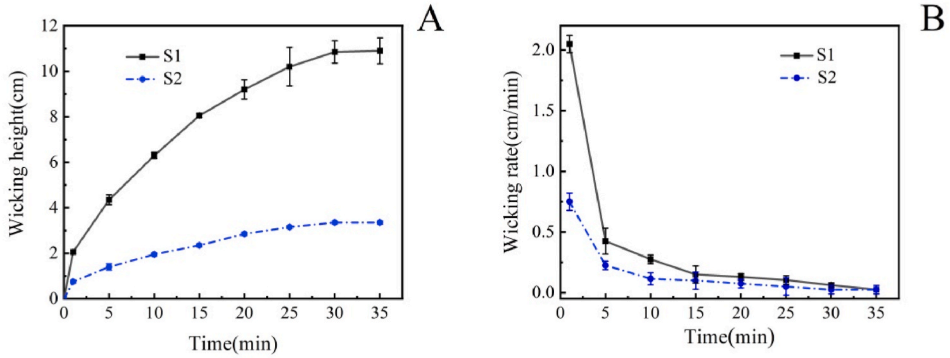

Fig. 3. Wicking performance of paper yarns (A) wicking height versus time, (B) wicking rate versus time.

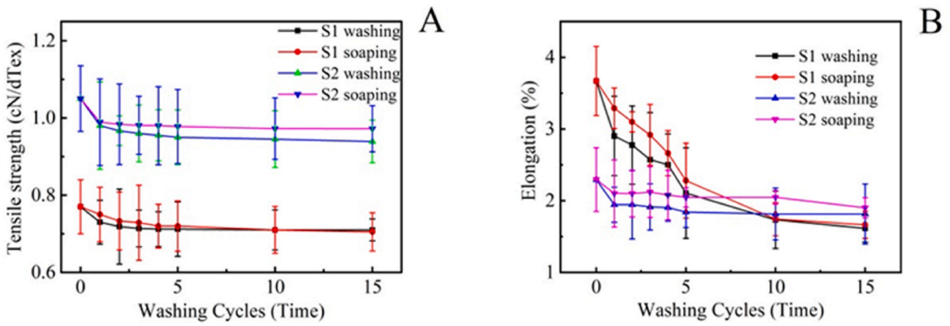

Fig. 4. Mechanical properties of paper yarn before and after washing and soaping (A) washing cycles versus tensile strength, (B) washing cycles versus elongation.

CRediT authorship contribution statement

Hafeezullah Memon: Writing – original draft, Validation, Software. **Diefei Hu:** Investigation, Formal analysis, Data curation. **Lingya Wu:** Data curation. **Yan Wang:** Visualization, Data curation. **Juming Yao:** Supervision, Resources, Project administration. **Jiri Militky:** Supervision, Resources, Funding acquisition. **Dana Kremenakova:** Project administration, Methodology, Conceptualization. **Guocheng Zhu:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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