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Study on the Characteristics of Kapok Yarn and Its Antibacterial and Constant-temperature Properties

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Abstract: **-** This study aims to explore the physical, chemical, and thermal properties of kapok fiber, as well as its antibacterial and constant-temperature properties via experiments. The cross-sectional structure of kapok fiber was observed using a microscope, and its thermal property was determined using thermogravimetric analysis (TG) and differential scanning calorimetry (DSC). Additionally, antibacterial tests were conducted using Escherichia coli (E. coli) and Staphylococcus aureus (S. aureus), while changes in the physical properties of kapok fiber after blending were analyzed. It was found that kapok fiber possesses a unique hollow structure and excellent warmth retention property, with an initial decomposition temperature of 296℃, indicating good thermal stability. Kapok fiber exhibited significant antibacterial effects against both E. coli and S. aureus. Blending kapok fiber with cotton fiber significantly enhanced the moisture absorption and conduction, and warmth retention properties of the fabric. In conclusion, kapok fiber is a natural and eco-friendly fiber with excellent antibacterial and warmth retention properties. When blending with cotton fiber, it improves the physical and hygienic properties of textiles.

Keywords: kapok fiber; antibacterial textiles; physical property; thermal property; chemical composition

1 Introduction

Textiles play a crucial role in bacterial spread due to their porous and loose structure, which easily absorbs various contaminants. This makes them an ideal breeding ground for microbial growth. The presence of these microorganisms not only causes textiles to become dirty and damaged but also significantly increases the risk of infection in public spaces, which may lead to various diseases. As living standards rise, there is a growing concern for hygiene and health issues. Therefore, antibacterial textiles are gaining significant attention.

This study focuses on kapok fiber to explore its textile properties, antibacterial and constant-temperature properties. As a natural non-cotton fiber, kapok fiber, with its unique hollow structure and low density, exhibit outstanding warmth retention and buoyancy. The physical, chemical, and thermal properties of kapok fiber are thoroughly analyzed with the help of detailed experiment. The study investigates its potential applications in antibacterial textiles, aiming to support the conceptual development of low-carbon and eco-friendly antibacterial textiles.

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2 Materials and methods

2.1 Physical experiment of kapok fiber

Kapok fiber is a natural non-cotton fiber that grows in tropical and subtropical regions, originating from the fruits of kapok trees. It is widely distributed in southern China, including Guangdong, Fujian, Guangxi, Hainan, Sichuan, Yunnan, and central and southern Taiwan. Kapok is also known as "mian," "banzhihua," "gubei," or "panzhihua" in Chinese. Globally, there are approximately 20 genera and 180 species, with China alone having 7 genera and 9 species.

Although kapok and cotton fibers are both single-cell fibers, their growth origins differ. Kapok fibers come from the fruit pods of the kapok tree, whereas cotton fibers originate from the seeds. Kapok fibers attach to the inner walls of the fruit pods with relatively weak adhesion, making them easy to detach from the pods. During initial processing, only the seeds need to be removed from the kapok wadding, often by shaking them in a sieve to settle the seeds, yielding the kapok fibers. In contrast, cotton fibers require ginning before they can proceed to subsequent processing.

Due to its unique hollow structure, kapok fiber possesses excellent warmth retention and softness. As early as the Jin Dynasty, kapok wadding was used as filling material and was one of the important raw materials for weaving in ancient times. However, with the introduction of cotton and advancements in the cultivation techniques, cotton gradually replaced kapok fiber as the primary textile material, leading to a reduction in the use of kapok fiber. Nevertheless, kapok fiber still finds applications as an oil-absorbing material, filling material, or thermal insulator, demonstrating its unique potential uses.

Figure 1 Kapok fruit **Figure 2 Kapok wadding**

2.1.1 Observing the structure of fiber under a microscope

Under the microscopic, kapok fiber reveals a distinct porous structure with exceptionally thin walls and air-filled cavities inside. The hollowness can reach as high as 80% to 90%, far exceeding the approximately 40% found in synthetic fiber. This makes kapok fiber potentially one of the fibers with the highest hollowness. Due to its hollow and thin-walled characteristics, kapok fiber has a low relative density, providing excellent buoyancy. Even buoyancy blocks made from kapok fiber can withstand loads 20 to 36 times their own weight without sinking.

In addition, kapok fiber has a smooth appearance and a cylindrical shape without the twisting characteristic similar to cotton fiber. The fiber is thicker in the middle and taper gradually towards the ends, which are sealed.

Leonard Y.M. conducted a study using scanning electron microscopy to examine both the longitudinal and cross-sectional views of kapok fiber, comparing them with cotton fiber. Refer to Figure 3 and 4 for details.

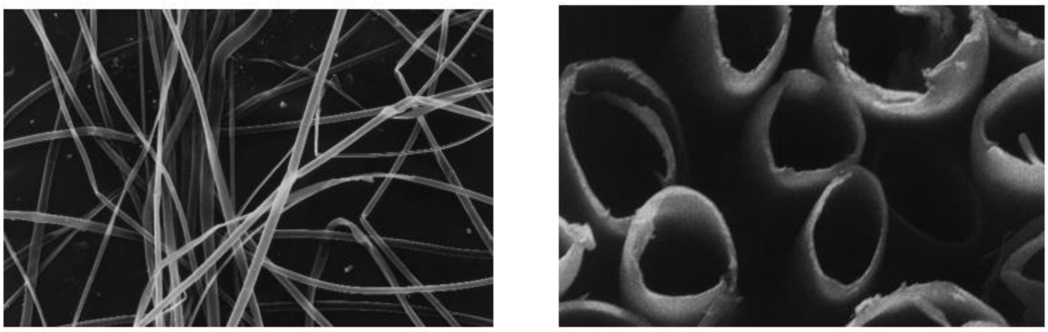

Figure 3 Electron microscopy scanning image of kapok fiber

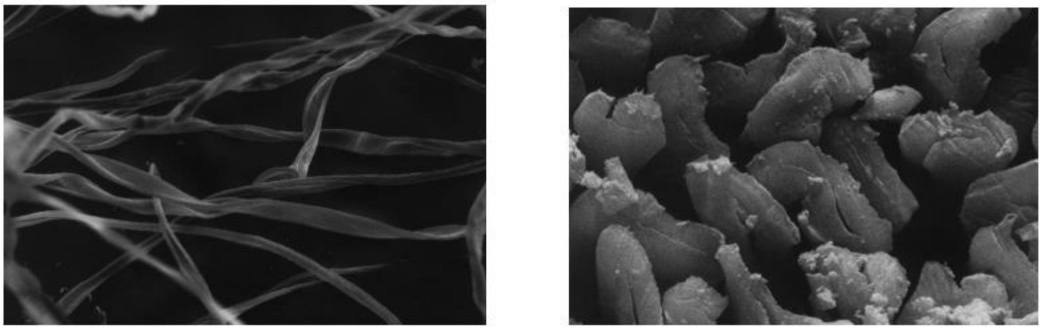

Figure 4 Electron microscopy scanning image of cotton fiber

From Figure 3 and 4, it is observable that despite both kapok and cotton fibers being single-cell fibers, their morphological structures exhibit significant differences. Cotton fiber has a round waist-shaped cross-section with a dense structure and very few gaps; longitudinally, it display a natural spiral shape. In contrast, kapok fiber has a highly thin-walled hollow structure in cross-section; longitudinally, it appears smooth without a spiral shape, resembling smooth cylinders.

The hollow structure of kapok fiber allows it to store a large amount of air. With thin walls, kapok fiber is lightweight and possesses excellent warmth retention and isolation properties. Consequently, kapok fiber finds wide application in buoyancy, warmth retention, and soundproofing and thermal insulation.

2.1.2 Molecular weight and crystallinity of kapok fiber

In 1991, Sunmanu O.K. conducted a molecular characteristics study on kapok fibers produced in Nigeria. This involved measuring the viscosity of fiber solutions, determining their average relative molecular weight to be approximately 2.96×10^6. Based on this, and considering the relative molecular weight of the 323 elemental chain segment, he estimated the polymerization degree of kapok fiber to be around 10,000, similar to the average polymerization degree of cotton fiber.

In 1981, Kunio N. and his team utilized X-ray diffraction technology to study the crystal lattice structure of kapok fiber. They discovered that the crystallinity of kapok fiber was 33%, which is significantly lower compared to linen fiber (69%) and cotton fiber (54%).

2.1.3 Other physical and mechanical properties of kapok fiber

Due to regional variations in the source of kapok fibers, their properties exhibit differences. Through a literature review, this study has summarized other properties of kapok fibers, detailed in Table 1-1.

Tab.1-1 Basic physical properties of kapok fiber

Performance	Index
Ffineness / dtex	0.9~3.2
Length / mm	8~34
Density / $g \cdot cm^{-3}$	0.29
Regain rate / %	10.00~10.73
Compression modulus / kPa	43.63
Relative torsional stiffness / $cN \cdot cm^2 . tex^{-2}$	71.5 X 10^{-4}
Refractive index	1.71761

From Table 1-1, it is evident that kapok fiber is shorter in length compared to cotton fiber (15~64mm). Their torsional rigidity can be as high as 71.5×10^{-4} $cN \cdot cm^2/tex^2$, even exceeding that of glass fibers. Due to its short length, high torsional rigidity, and smooth surface, kapok fiber experiences poor cohesion during spinning. It is challenging to spin independently using traditional methods for cotton or wool, often requiring blending with cotton or synthetic fiber. Kapok fiber content typically ranges from 30% to 50%, thus limiting its application in the apparel industry.

Kapok fiber has a moisture absorption rate of 10.73%, slightly higher than typical cotton fiber. Additionally, kapok fiber exhibits a brighter luster due to its average refractive index of 1.71761, which is slightly higher than the 1.59614 observed in cotton fiber.

2.1.4 Thermal property of kapok fiber

Xiao Hong's research team utilized a thermogravimetric analyzer (TG) and differential scanning calorimeter (DSC) to investigate the thermal property of kapok fiber, comparing it with cotton fiber. The results can be seen in Figure 5 and 6.

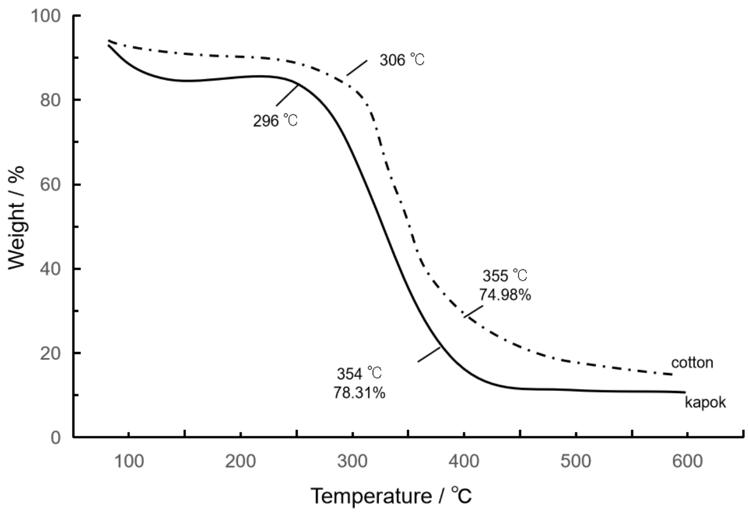

Figure 5 TG of kapok and cotton fiber

2.1.5 Spinnability of kapok fiber

Due to the short length, tendency to generate lint, high rigidity, difficulty in twisting, smooth surface, and poor cohesion, spinning kapok fibers presents challenges. According to studies by Sun Jingxia et al., kapok fiber is not suitable for spinning alone and is typically blended with over 40% cotton fiber. However, blending reduces the strength of the yarn.

2.1.6 Dyeing property of kapok fiber

Regarding the dyeing property of kapok fiber, there is limited research available. According to Misha S.P., kapok fiber can be dyed directly, but the dye uptake efficiency is only 63%. In contrast, under similar conditions, cotton fiber achieves a dye uptake efficiency as high as 90%.

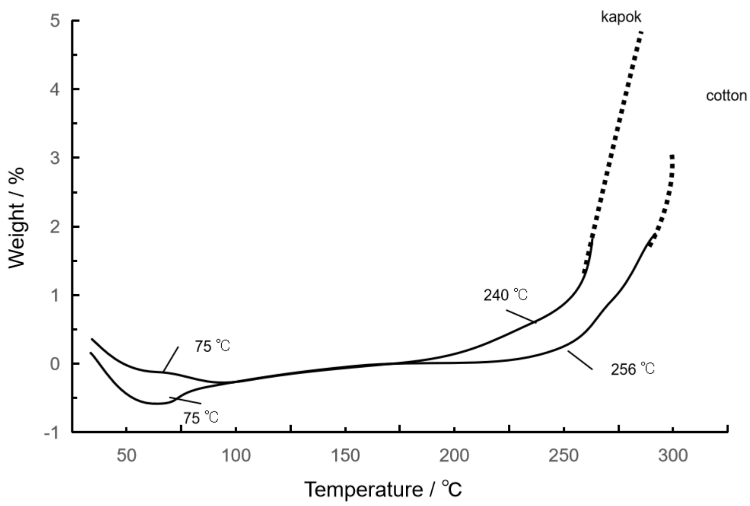

Figure 6 DSC of the kapok and cotton fiber

According to Figure 6, the initial decomposition temperature of kapok fiber is approximately 296℃, which is close to that of cotton fiber at 306℃. At 354℃, kapok fiber ceases its primary decomposition process, and between 354 and 600℃, its rate of mass loss is nearly zero. In contrast, cotton fiber begins to slow its decomposition around 355℃ and continue to decrease in mass until 600℃, indicating a significant difference compared to kapok fiber.

According to Figure 6, both kapok fiber and cotton fiber exhibit similar trends in their thermal analysis curves, with endothermic peak at around 75℃ due to melting crystalline water. As shown in Table 1-1, kapok fiber has a slightly higher moisture regain rate compared to cotton fiber, hence its endothermic peak area is slightly more pronounced. Kapok fiber continues to absorb heat during heating above 240℃, similar to cotton fiber continuing to absorb heat after 256℃. The heat absorption property of both fibers are similar. Kapok fiber crystallizes and melts between 75℃ and 240℃ (compared to cotton fiber between 75℃ and 256℃).

2.1.7 Chemical composition of kapok fiber

Leonard Y.M., Fengel D., and Alka G. conducted research on the chemical composition of kapok fiber using a reagent dissolution method, and their findings are consistent. For detailed information on the main components of kapok fiber, please refer to Table 1-2. For comparative purposes, Table 1-2 displays the primary components of various natural celluloses.

Tab. 1-2 The chemical composition ofnatural cellulose fiber

Variety	Cellulose / %	Hemicellulose / %	Lignin / %	Pectin / %
Cotton fiber	92	6	0	< 1
Kapok fiber	35~50	22~45	15~22	< 1
Ramie fiber	76	15	1	2
Linen fiber	81	14	3	4
Sisal fiber	73	13	11	2

According to Table 1-2, kapok fiber shares similarities in chemical composition with natural cellulose fibers like cotton and flax, but there are notable differences in their content. Specifically, the amount of cellulose in kapok fiber is only about half that found in cotton or flax fibers. Since dyes typically interact with cellulose during dyeing, the dyeing method for kapok fiber differs slightly from that used for cotton and flax cellulose fibers.

Among the five types of fibers mentioned above, kapok fiber has the highest hemicellulose content, exceeding 20%. Flax fiber contains approximately 15% hemicellulose, while cotton fiber has only about 6%. Kapok fiber also contains approximately 20% lignin, significantly higher than other fibers. Natural cotton fiber contains almost no lignin. Lignin is a polymer composed of highly substituted phenylpropane units, and its methoxy groups help prevent fiber-water interaction, giving kapok fiber hydrophobicity.

To explore the feasibility of dyeing kapok fiber with reactive dyes, infrared spectroscopy scans and compared spectra between pre-treated kapok fiber and cotton fiber were conducted.

According to Figure 7, the comparison of infrared spectra between kapok fiber and cotton fiber reveals that aside from slight adjustments in absorption intensity, the characteristic absorption peaks remain largely unchanged. There are no distinct absorption peaks typical of hemicellulose and lignin visible in the spectra. This is because pre-treatment of kapok fiber removes hemicellulose and lignin, presenting typical cellulose absorption peak similar to that of cotton fiber. Particularly notable is the hydroxyl absorption peak around 3417cm^{-1}, indicating that dyeing kapok fibers with reactive dyes is feasible.

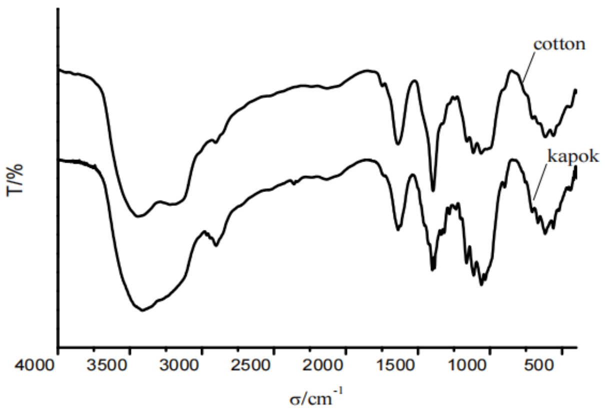

Figure 7 Infrared spectra of kapok fiber and cotton fiber

2.2 Thermal property of kapok fiber

2.2.1 Tensile property

Using the YG026MG electronic fabric strength tester, experiments were conducted where five samples of each fabric type were cut into dimensions of 200mm×50mm, both along the longitudinal and transverse directions. The clamping stretch distance was set to 100mm, with a preset stretching force of 1N and a stretching rate of 100mm/min. The experiments were conducted at a temperature of (20±2)℃ and a relative humidity of (65±2)%. Under stable temperature and humidity, the samples underwent moisture conditioning for over 24 hours before testing.

Table 1-3 Mechanical property of fabrics containing kapok fiber

Fabric number	Fabric raw materials	Fabric thickness (mm)	Area density (g·m^{-2})	Vertical density Column·(5cm)$^{-1}$	Horizontal density Horizontal column·(5cm)$^{-1}$	Fabric organization
1-1	16.0 tex kapok/cotton (20:80)+30D Xiaoxing spandex (9%)	0.770	180	124	79	Weft needle
1-2	14.2tex kapok/cotton (20:80)+30D Xiaoxing spandex (9%)	0.704	175	131	90	Weft needle
1-3	11.1 tex kapok/cotton (20:80)+30D Ebon spandex (15%)	0.770	180	121	70	Ribbed pattern
1-4	9.1tex kapok/cotton (20:80)	0.817	180	73	80	Interlock
2-1	14.2 tex cotton+30D Xiaoxing spandex (9%)	0.694	175	130	88	Weft needle

This paper studies the tensile breaking property and bursting strength of kapok fiber textile fabrics. To visually compare the mechanical properties of kapok fiber textile fabrics with pure cotton fabrics, a 14.2tex plain weft-knitted fabric of pure cotton (see the 2-1) and kapok fiber fabric (see the 1-2) with the same linear density are selected for comparison. The results show the longitudinal and transverse tensile breaking strengths of kapok textile fabrics as depicted in Figure 1-3, while the elongation at break is also presented in Figure 8.

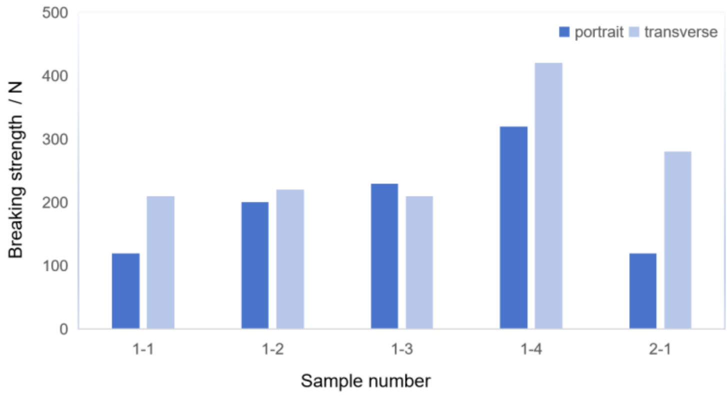

Figure 8 Longitudinal and transverse tensile fracture strength of fabric

According to Table 1-4 and Figure 8, ribbed fabrics containing spandex and kapok/cotton blends exhibit lower tensile strength compared to double-ribbed kapok blends without spandex. Fabric strength correlates closely with its structure since double-ribbed fabrics have finer yarns, yet maintain consistent strength in both longitudinal and transverse directions.

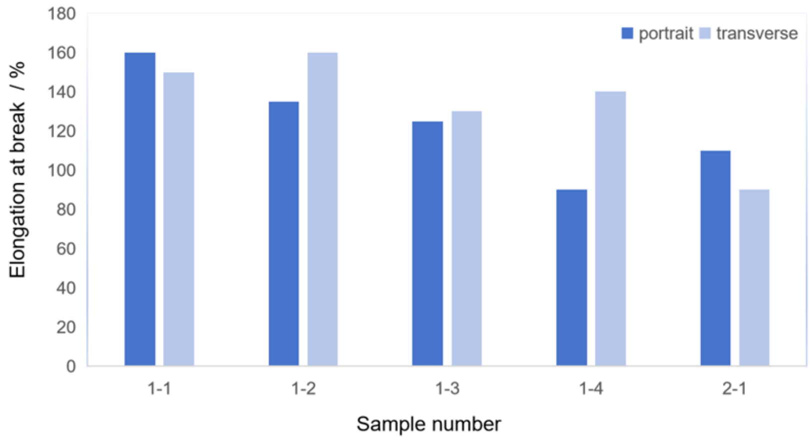

Figure 9 Longitudinal/transverse elongation at break of fabric

Based on the data presented in Table 1-3 and Figure 9, whether it is plain weft-knitted fabric of pure cotton (see Table 2-1) or fabrics containing kapok fibers (see Table 1-2), fabrics with kapok fibers show significantly higher elongation at break compared to plain weft-knitted fabric of pure cotton. Overall, the difference in elongation at break between the longitudinal and transverse directions is not significant.

2.2.2 Bursting strength

This study utilized the YG026MB-250 electronic fabric strength tester to evaluate the anti-destructive performance of fiber textiles. According to the GB/T19976-2005 standard, multiple random positions on the same fabric were selected to test circular samples with a diameter of 45mm. The experiments were conducted under stable humidity conditions with a constant temperature of (20±2)℃ and a relative humidity of (65±2)%. Prior to testing, all samples underwent at least 24 hours of preconditioning in a humid environment.

Figure 10 presents a column chart depicting the bursting strength of four types of textiles, including kapok and pure cotton fabrics. The study indicates that the bursting strength of kapok fabric clothing is related to the fabric structure, with ribbed structures showing the highest strength. Under the same fabric structure, kapok fabrics exhibit higher bursting strength compared to pure cotton fabrics.

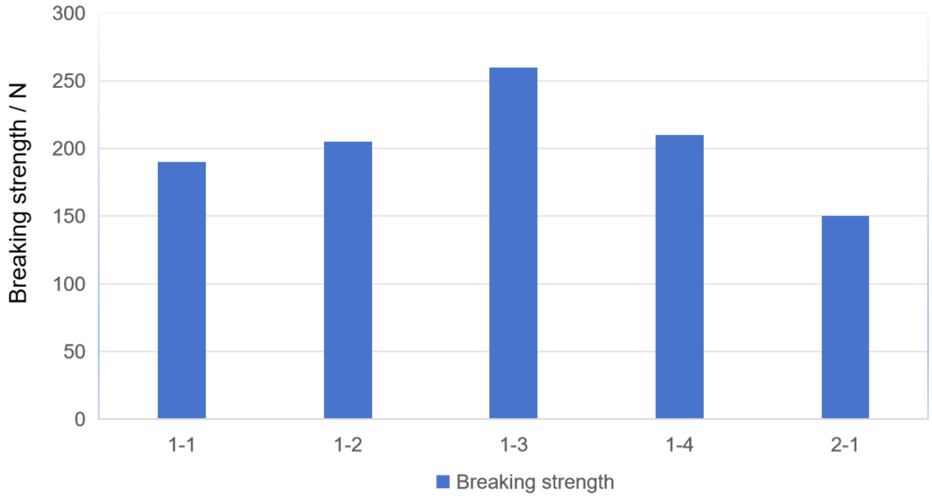

Figure 10 Fabric bursting strength

2.2.3 Mechanical properties of fabrics

Kapok blend fabrics exhibit varying mechanical properties due to differences in their textures, with kapok double-lock fabrics demonstrating superior overall mechanical properties compared to other tightly knitted fabrics. When controlling for fabric structure and yarn density, kapok blend fabric shows slightly better mechanical property than pure cotton fabric, with improved elongation at break. Kapok fiber enhance the bursting strength of ribbed fabric in clothing; within the same structure, kapok fiber enhances the bursting strength of clothing fabrics, surpassing that of pure cotton fabric.

Results from thermogravimetric analysis (TG) and differential scanning calorimetry (DSC) reveal that the initial decomposition temperature of kapok fiber is 296℃, slightly lower than that of cotton fiber at 306℃. At 354℃, kapok fiber essentially ceases decomposition, demonstrating excellent thermal stability.

2.3 Antibacterial experiment of kapok fabric

2.3.1 Experimental materials

Four circular samples of kapok flower synthetic fabric with diameters of 10mm and four with diameters of 15mm need to be prepared for the experiment. These will be used as samples for testing against Staphylococcus aureus (ATCC6538) and Escherichia coli (ATCC11229). Details regarding fabric specifications and the required drugs for the culture medium can be found in Table 1-4 and 1-5.

Table 1-4 Fabric specification parameters

Fabric number	Fabric raw materials	Fabric thickness (mm)	Area density $(g \cdot m^{-2})$	Vertical density Column·$(5cm)^{-1}$	Horizontal density Horizontal column·$(5cm)^{-1}$	Fabric organization
1-1	16.0 tex kapok/cotton (20:80)+30D Xiaoxing spandex (9%)	0.770	180	124	79	Weft needle
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2-1	14.2 tex cotton+30D Xiaoxing spandex (9%)	0.694	175	130	88	Weft needle

Table 1-5 Reagents required for making culture medium

Name	Model	Brand
Cotton fiber	BS216	biosharp
Kapok fiber	LP0042	OXOID
Ramie fiber	LP0042	OXOID
Linen fiber	10000561	Shanghai Trial
Sisal fiber	10019318	Shanghai Trial

2.3.2 Experimental instruments or equipment

The main equipment used in the experiment is as follows:

Table 1-6 Main experimental instruments or equipment

Name	Required conditions
Biochemical incubator	Temperature 30 ℃
Shaking water bath	Oscillation frequency of 120 beats/min
Refrigerator	Temperature 4 ℃
Vertical automatic pressure steam sterilizer	Temperature 121 ℃
Ultra clean table	Sterile

2.3.3 Experimental principle

According to GB/T 20944.1-2007 *Textiles - Evaluation for antibacterial activity - Part 1: Agar diffusion plate method*, antibacterial test was conducted on samples of kapok flower synthetic fabric. Initially, nutrient-rich broth agar medium was poured into culture dishes. Then, bacterial suspension was spread over the surface of the agar, followed by placing the samples on top. After an appropriate incubation period, the antibacterial effectiveness was evaluated, qualitatively assessing bacterial growth both underneath and around the samples.

2.3.4 Preparation before the experiment

(1) Activation of bacterial strains and preparation of test bacteria

Specific steps according to GB/T20944.1-2007 are as follows:

Take out the required bacterial strains from frozen storage.

Pre-culture them on appropriate medium to restore their vitality and promote growth.

Prepare the required bacterial suspension according to experimental requirements.

(2) Preparation method of agar medium

Prepare agar medium tailored for different bacterial strains:

① Components for cultivating Escherichia coli:

1g of tryptone

0.5g of yeast powder

1g of sodium chloride

2g of agar

Dissolve the above components in high purity water, heat until completely dissolved, sterilize, and pour into culture dishes. Allow them to solidify into agar medium.

② Components of Staphylococcus aureus medium:

1g of tryptone

0.3g of beef extract powder

0.5g of sodium chloride

2g of agar powder

Dissolve the above components in high purity water, heat until completely dissolved, sterilize, and pour into culture dishes. Allow them to solidify into agar medium.

③ Adjust the basic culture medium to a total volume of 100 ml, ensuring uniformity and quality of the agar medium.

2.3.5 Experimental steps

(1) Preparation for sterilization

Place 8 transparent glass culture dishes and agar medium for Escherichia coli and Staphylococcus aureus into a vertical automatic high-pressure steam sterilizer.

Treat them with high-pressure steam at 121°C for 15 minutes. After that, wait for 2 hours and 45 minutes in a sterile clean bench to ensure complete sterilization.

(2) UV sterilization

Place the sterilized samples on the clean bench and expose them to UV light for 30 minutes to sterilize them.

(3) Sample preparation

Use a sterile pipette, draw 100 microliters of bacterial suspension of Escherichia coli and Staphylococcus aureus, and spot them onto 8 agar mediums respectively.

After shaking to mix thoroughly, gently spread the sterilized samples evenly with sterile forceps, ensuring they adhere tightly to the agar medium.

(4) Thermostatic incubation

Place the glass culture dishes in a 30°C constant-temperature incubator and culture for 24 hours. Throughout incubation, ensure the samples remain firmly attached to the agar medium without moving.

(5) Observation

After 24 hours of incubation, remove the glass dishes and observe the growth of Escherichia coli and Staphylococcus aureus on the agar medium.

(6) Result analysis

Observe whether a annular region devoid of bacterial growth has formed around the test samples, indicating the presence of an inhibition zone.

Note: Ensure the experiment is conducted in a completely sterile environment and strictly follow the experimental design to obtain accurate results.

$$S_{抑菌环} = \pi(R^2 - r^2)$$

Where S is the area, measured in square millimeters (mm^2)

R is the radius, measured in millimeters

The radius of the test sample is measured in millimeters

Table 1-7 Evaluation of antibacterial effect

Antibacterial ring area	Is there bacterial growth under the fabric sample	Antibacterial effect
≥0	nothing	good
0	a small amount	preferably
0	secondary	Limited
0	a large number	nothing

2.3.6 Summary of experimental results

After 24 hours of thermostatic incubation at 30℃, the growth of colonies was shown in Figure 11 and 12. The results indicate that in the antibacterial experiments involving Staphylococcus aureus and Escherichia coli, no bacterial growth was observed at the bottom of the samples, and bacteriostatic annulus was formed around with no colonies inside. According to the evaluation criteria in Table 1-7, the tests demonstrate that the cotton flower synthetic fabric sample exhibits effective antibacterial effects, capable of inhibiting bacterial growth and reproduction. In Figure 11, the boundaries of inhibition zones in (a) and (b) appear less distinct, possibly due to uneven distribution of the coating or insufficient contact between the sample and the agar medium.

The antibacterial effects of kapok textile samples originate from linen fibers, which are natural and harmless materials. Wearing fabrics made from this moisture-wicking material can partially inhibit bacterial growth, contributing to better health.

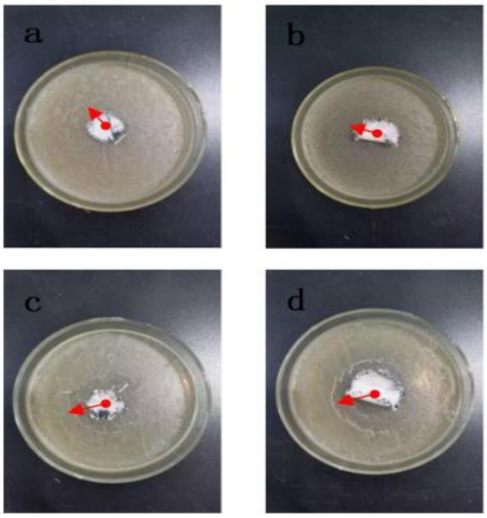

Figure 11 Antibacterial test for S.aureus

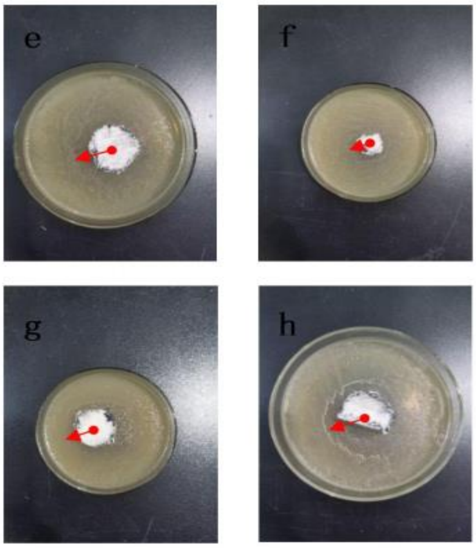

Figure 12 Antibacterial test for E.coli

After conducting antibacterial tests on kapok synthetic fabric samples, it was found that they exhibit significant inhibition of the growth of Staphylococcus aureus and Escherichia coli. Therefore, they possess antibacterial properties.

3 Summary of experimental results

3.1 Physical properties of kapok fiber

Kapok fiber is short in length with a smooth surface, making it prone to forming lint. When it blends with cotton fiber, the tensile strength of the yarn decreases slightly. However, this blend enhances warmth retention and improves moisture absorption and conduction.

3.3 Antibacterial property of kapok fiber

Through experiments, antibacterial tests were conducted on kapok fiber using Escherichia coli (E. coli) and Staphylococcus aureus (S. aureus). The results indicate that kapok fiber exhibits significant antibacterial effects against both types of bacteria, which is attributed to its lignin content.

4 Conclusion

Due to its unique hollow structure and composition, kapok fiber demonstrates excellent antibacterial and physical properties. When blended with cotton fiber, it enhances the warmth retention and moisture absorption and conduction of textiles, making it suitable for use in clothing fabrics. Its distinctive hollow structure contributes to its superior warmth retention and buoyancy, alongside its antibacterial property. Future research could further explore the applications of kapok fiber in textiles, aiming to develop low-carbon, eco-friendly, and health-promoting antibacterial textiles. This would provide more theoretical and experimental support for the development of such products.

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