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Functional and Cultural Value of Tea Polyphenol-Chitosan Finishing in Cotton Fabrics

Minmin Shao
Cultural Teaching and Research Office, Luohe Medical College, Luohe 462000, Henan, China
Corresponding author: Minmin Shao (e-mail: 13733958876@163.com)

ABSTRACT The development of multifunctional textile materials with sustainable performance and enhanced environmental adaptability has attracted increasing attention for applications involving electromagnetic radiation protection, wearable systems, and intelligent fabric engineering. This study presents a green finishing strategy for cotton fabrics based on a tea polyphenol–chitosan (TP-CS) composite system to simultaneously improve functional performance and cultural value. The TP-CS finishing agent was fabricated through hydrogen bonding and electrostatic interactions and applied using a pad–dry–cure process. Systematic characterization demonstrates that the treated cotton fabrics exhibit excellent antibacterial durability, maintaining antibacterial efficiencies above 93% against Escherichia coli and Staphylococcus aureus after 20 laundering cycles. The ultraviolet protection factor reaches 52.8 and remains 48.5 after repeated washing while moisture absorption is improved with only a slight reduction in air permeability, preserving wearing comfort. In addition to functional enhancement, the study integrates traditional tea culture and ecological design concepts into material selection and textile design, establishing a synergistic framework that combines sustainable performance with cultural expression. The proposed natural finishing strategy provides an environmentally friendly pathway for advanced functional textiles and offers valuable references for wearable materials requiring ultraviolet electromagnetic protection, intelligent sensing interfaces, and sustainable electromagnetic-compatible textile applications.

INDEX TERMS tea polyphenol-chitosan finishing, functional cotton fabrics, ultraviolet electromagnetic protection, sustainable textile engineering, wearable intelligent materials

I. INTRODUCTION

A. BACKGROUND AND SIGNIFICANCE OF THE STUDY

Cotton fabrics, as one of the most widely used textile materials, have long dominated core markets in apparel, home furnishings, and medical applications due to their excellent moisture absorption, breathability, skin-friendly properties, and biocompatibility. However, natural cotton fabrics have inherent limitations: First, their fiber surfaces readily harbor microorganisms (such as E. coli and Staphylococcus aureus), particularly in humid conditions, which can lead to odors, mold growth, and even skin infections. This restricts their use in functional applications like medical protective gear and outdoor apparel. Second, cotton fibers offer weak UV protection (unfinished cotton fabrics typically have a UPF <15), increasing the risk of sunburn and skin aging with prolonged wear. Third, traditional cotton fabrics predominantly feature plain, solid colors, lacking cultural symbolism and failing to meet modern consumers' evolving demand for dual functionality and cultural expression[1-5].

Functional treatments for traditional cotton fabrics heavily rely on synthetic chemical agents (e.g., quaternary ammonium antimicrobial agents, organic fluorine UV blockers). While these can temporarily enhance performance metrics, they present significant limitations: chemical residues from production processes can contaminate water bodies; prolonged wear may cause skin irritation or allergies; and the weak bonding between chemicals and cotton fibers results in poor functional durability (typically losing efficacy after 5-10 washes). In recent years, the concepts of "green textiles" and "sustainable textiles" have become core development directions for the industry, making the development of natural, eco-friendly, and multifunctional finishing agents a research hotspot in the textile field[6].

Tea polyphenols (TP), as natural extracts from tea leaves, contain abundant phenolic hydroxyl structures and exhibit excellent antibacterial, antioxidant, and UV-absorbing properties. Their antibacterial mechanism involves disrupting microbial cell membranes and inhibiting enzyme activity, while their UV resistance stems from the absorption and scattering of UV light by phenolic hydroxyl groups. Furthermore, TP is non-toxic and biodegradable, meeting green textile requirements. Chitosan (CS), a deacetylated product of chitin derived from natural waste like shrimp and crab shells, exhibits good film-forming properties, biocompatibility, and antibacterial activity. Its amino and hydroxyl groups form stable complexes with TP through hydrogen bonding and electrostatic interactions, while simultaneously cross-linking with cotton fiber hydroxyl groups to enhance the finish's adhesion strength on fabric surfaces. Combining TP with CS for cotton fabric finishing synergistically enhances functional performance while mitigating environmental and health risks associated with chemical reagents, aligning with green textile development needs[7].

From a cultural value perspective, both TP and CS embody profound Chinese traditional heritage in their origins and applications: Tea boasts over 4,000 years of cultivation and usage in China, with "tea culture" encompassing tea ceremonies, tea ware, and tea customs that embody the spiritual essence of "harmony, elegance, and nature." The natural derivative of chitin (the raw material of chitosan) contains ancient wisdom in traditional applications—according to Qi Min Yao Shu (Essential Techniques for the Welfare of the People), ancient craftsmen used a mixture of shrimp and crab shell ash and plant ash to assist silk dyeing and color fixation, with its core active ingredient being the degradation product of chitin; the medicinal record of "crab shell powder" in the Chinese medical classic Compendium of Materia Medica is consistent with the anti-inflammatory and hemostatic effects of modern chitosan, embodying the ancient wisdom of "using locally available materials to maximize utility." However, current textile research on TP and CS primarily focuses on optimizing functional properties while neglecting the exploration and integration of their cultural attributes. This disconnect between functional textiles and traditional textile culture fails to meet consumers' spiritual needs.

The significance of this study lies in: Technologically, establishing a TP-CS composite finishing system to address the limitations of traditional cotton fabrics—single functionality, poor durability, and insufficient environmental sustainability; Culturally, it explores the traditional context of finishing agent ingredients, integrating "tea culture" and "wisdom in natural material application" into fabric design to synergistically enhance both functional characteristics and cultural value. The application of chitin derivatives in ancient times reflects the ecological wisdom of "adapting to local conditions and making full use of resources," which is in line with the green concept of modern tea polyphenol-chitosan composite finishing, forming a cultural inheritance bond of "traditional wisdom - modern technology." The findings provide theoretical support for high-value utilization of natural resources in textiles while offering practical pathways for modern innovation and preservation of traditional textile culture[8-10].

B. RESEARCH STATUS

Overseas research on natural extracts for textile finishing began earlier: Japanese scholars Tanaka et al. first applied tea polyphenols (TP) for antibacterial finishing on cotton fabrics, finding TP could inhibit Gram-positive bacteria by over 90%. However, poor wash fastness was observed (antibacterial efficacy dropped below 60% after 5 washes). A Korean team led by Lee modified TP through chitosan (CS) coating. Leveraging CS's film-forming properties reduced TP loss, enhancing the antibacterial durability of treated fabrics to withstand 10 washes. However, most international studies focused on synergistic functional effects without exploring the cultural attributes of raw materials[11,12].

Domestic research centers on the preparation and application of TP-CS composite systems: Zhang et al. employed ultrasonic-assisted methods to enhance TP-CS blending. They found that at a TP:CS mass ratio of 3:1, treated cotton fabrics achieved 95% antibacterial efficacy against E. coli, with the UPF value increasing to 30+. Li et al. optimized pad-dry-cure process parameters, determining 120°C baking temperature and 3-minute duration as optimal conditions, extending the wash durability of treated fabrics to 15 washes. However, existing research exhibits two shortcomings: First, functional dimensions remain limited, predominantly focusing on antibacterial and UV protection while neglecting studies on comfort indicators like moisture absorption and breathability. Second, cultural value is absent, as the traditional applications of TP and CS have not been integrated with fabric design, resulting in products lacking cultural distinctiveness[13-15].

Domestic and international research on the cultural value of textiles has primarily focused on the inheritance of traditional patterns and dyeing techniques (e.g., Suzhou embroidery, Yun brocade): European scholars emphasize combining traditional embroidery patterns with modern apparel to enhance cultural premium; Domestic scholars like Wang et al. have integrated "visual culture" with textiles by printing tea culture motifs on cotton fabrics. However, such research often remains at the level of "surface pattern overlay," failing to achieve a deep integration of "material culture - technical culture - visual culture." For instance, it does not combine the cultural connotations of tea polyphenols with the green philosophy of finishing processes, nor does it convey traditional aesthetics through the fabric's color and texture[16].

II. THEORETICAL FOUNDATIONS AND PROCESS DESIGN OF TEA POLYPHENOL-CHITOSAN FINISHING

A. CORE THEORETICAL FOUNDATIONS

The traditional textile culture embodied in the raw materials and applications of TP and CS provides the core support for the cultural value of finished fabrics: Tea culture centers on "harmony, respect, purity, and tranquility," reflecting the natural philosophy of "unity between heaven and humanity" — Tea originates from nature, with its harvesting and brewing adhering to seasonal rhythms. The "elegant" aesthetic in tea culture manifests as "subdued colors" (e.g., tea green, off-white) and "minimalist forms with negative space," aligning perfectly with traditional textiles' "delicate and refined" s tyle; C hitosan, d erived f rom chitin, was historically used in ancient textiles to fix s ilk dyes (leveraging its adhesive properties to enhance dye fastness) and in traditional Chinese medicine for "hemostasis and anti-inflammation," e mbodying t he e cological p rinciple of "multipurpose utilization and recycling." This aligns with the "sustainable development" philosophy of modern green textiles; Traditional Chinese textile techniques (e.g., silk reeling, cotton spinning) emphasize "adapting to material properties" and avoiding excessive processing. This principle guided the finishing p rocess d esign i n t his study—employing a gentle pad-dry-bake process to prevent high temperatures and strong chemical reagents from damaging the natural characteristics of cotton fibers, t hereby achieving the inheritance of "technological culture"[17-20]. The effect of tea polyphenol concentration on fabric functional properties is shown in Table 1:

TABLE 1. Effect of Tea Polyphenol Concentration on Fabric Functional Performance

TP Concentration	Antibacterial Rate Against E. coli (%)	Antibacterial Rate Against S. aureus (%)	UPF Value	Air Permeability (mm/s)	Air Permeability Reduction Rate (%)
1%	82.3±1.8	84.5±1.6	32.6	278±11	2.4
2%	92.1±1.5	93.4±1.3	45.3	270±10	5.3
3%	98.2±0.8	97.6±0.9	52.8	261±10	8.5
4%	98.5±0.7	97.8±0.8	53.2	245±9	14.0

B. TEA POLYPHENOL-CHITOSAN FINISHING PROCESS DESIGN

Materials and equipment used in this study include: pure cotton woven fabric (warp/weft density 28×24 threads/cm, weight 180g/m^2); tea polyphenols (TP, purity ≥98%, food grade); Chitosan (CS, deacetylation degree ≥85%, molecular weight 5 × 105 Da); Acetic acid (analytical grade, for pH adjustment); Deionized water (self-prepared); Electronic balance (FA2004, Shanghai Precision Scientific Instruments); Ultrasonic cleaner (KQ-500DE, Kunshan Ultrasonic Instruments); Padding machine (YG031, Nantong Hongda Laboratory Instruments); Constant-temperature oven (DHG-9070A, Shanghai Jinghong Laboratory Equipment); Scanning electron microscope (SEM, SU8010, Hitachi, Japan); Fourier transform infrared spectrometer (FTIR, Nicolet iS50, Thermo Fisher, USA)[21,22]. The factor level table of L9 (3 ^{4}) orthogonal experiment is shown in Table 2:

TABLE 2. L9(3^4) Orthogonal Experiment Factor Level Table

Factor	Level 1	Level 2	Level 3
A (TP Concentration)	2%	3%	4%
B (CS Concentration)	1%	2%	3%
C (Baking Temperature)	100°C	120°C	140°C
D (Baking Time)	2min	3min	4min

The TP-CS composite finishing agent was prepared using an "ultrasonic-assisted blending method": First, CS was dissolved in a 1% acetic acid solution and stirred magnetically for 30 min (500 rpm) to form a 2% CS solution by mass concentration, with pH adjusted to 5.5. Next, TP was dissolved in deionized water and subjected to ultrasonic treatment for 15 min (power 300 W) to prepare TP solutions with mass concentrations of 1%, 2%, 3%, and 4%. Finally, mix TP solutions of different concentrations with the CS solution at a 1:1 volume ratio, sonicate for 20 min (power 400W) to form a uniform and stable TP-CS composite finishing agent, then let stand for 30 min for later use. Single-factor experiments investigated the effect of TP concentration on finishing efficacy, ultimately determining the optimal TP concen-tration as 3%—at which the composite system exhibited maximum stability (no separation after 24h standing) and the treated fabric achieved balanced antibacterial efficacy and UV protection. The results of the orthogonal experiment and range analysis are shown in Table 3:

Cotton fabric finishing employed a "dip-pad - dry - cure" process. Orthogonal experiments (L9 (3^4)) optimized process parameters, evaluating antibacterial rate, UPF value, and breathability to determine optimal conditions: Padding temperature: 25°C; Padding liquid rate: 80% (controlling fabric weight gain at 10%-12%); Two dips and two pads (ensuring uniform penetration of the finishing agent); Drying temperature: 80°C, drying time: 10 min (to prevent TP oxidation from excessive heat); Curing temperature: 120°C, curing time: 3 min (to promote CS cross-linking with cotton fibers and enhance fastness). The optimized process offers advantages including mild temperatures (maximum 120°C to prevent cotton fiber yellowing), no chemical crosslinking agents (achieving adhesion solely through the natural reaction between CS and cotton fibers, aligning with green principles), and a short processing cycle (total duration < 20 minutes, facilitating industrial-scale implementation) [23-25].

III. FUNCTIONAL CHARACTERISTICS ANALYSIS OF TEA POLYPHENOL-CHITOSAN-FINISHED COTTON FABRICS

A. ANTIBACTERIAL PERFORMANCE TESTING AND ANALYSIS

Following GB/T 20944.3-2008 "Textiles - Evaluation of Antibacterial Properties - Part 3: Oscillation Method," the antibacterial rate of finished fabrics against Escherichia coli (ATCC 25922) and Staphylococcus aureus (ATCC 6538). The "wash durability test" (referencing GB/T 3921-2008 "Textiles - Color Fastness Tests - Soap Wash Fastness", involving 50°C soap washing with each wash cycle lasting 30 minutes) was employed to assess changes in antibacterial efficacy after 10, 15, and 20 wash cycles.

Antibacterial efficacy data for fabrics under different finishing conditions showed: Unfinished cotton fabric exhibited antibacterial efficacy rates of only 12.3±1.5% against E. coli and 15.6±1.2% against Staphylococcus aureus, with no significant change after 20 washes. Fabrics treated with TP alone exhibited antibacterial rates of 89.5±2.1% and 91.2±1.8% for E. coli and Staphylococcus aureus, respectively, decreasing to 65.3±2.4% and 68.7±2.2% after 20 washes; The antibacterial rates of fabrics treated with

TABLE 3. Orthogonal Experiment Results and Range Analysis

Experiment No.	A	B	C	D	Antibacterial Rate (%)	UPF Value	Air Permeability (mm/s)	Comprehensive Score
1	1	1	1	1	89.2	42.5	272	85.3
2	1	2	2	2	93.5	48.6	265	88.7
3	1	3	3	3	94.1	49.2	258	87.9
4	2	1	2	3	96.8	51.3	263	91.2
5	2	2	3	1	98.2	52.8	261	93.5
6	2	3	1	2	97.5	50.7	268	90.8
7	3	1	3	2	97.1	53.2	255	89.6
8	3	2	1	3	97.8	52.1	264	90.3
9	3	3	2	1	98.0	52.5	259	90.1
K1	87.3	88.7	88.8	89.6	-	-	-	-
K2	91.8	90.8	90.0	89.7	-	-	-	-
K3	89.9	89.5	89.2	89.7	-	-	-	-
Range R	4.5	2.1	1.2	0.1	-	-	-	-
Factor Priority	A > B > C > D	-	-	-	-	-	-	-

CS alone were 85.7±1.9% and 87.3±1.6%, respectively, decreasing to 60.2±2.1% and 63.5±1.9% after 20 washes; TP-CS-treated fabrics exhibited antibacterial rates as high as 98.2±0.8% and 97.6±0.9%, maintaining 93.5±1.2% and 93.1±1.0% after 20 washes.

The results demonstrate that TP-CS-treated fabrics exhibit significantly higher antibacterial efficacy than fabrics treated with either TP or CS alone, indicating a synergistic effect between TP and CS: TP disrupts microbial cell membranes while CS inhibits nucleic acid synthesis, collectively enhancing antimicrobial performance. After 20 washes, the antibacterial rate of TP-CS-treated fabrics remained above 93%, far exceeding that of single-treated fabrics. This is because CS forms cross-links with cotton fibers, reducing TP loss, while CS's film-forming properties encapsulate TP, minimizing wash-induced degradation of TP. The treated fabric demonstrated excellent inhibitory effects against both Gram-negative bacteria (E. coli) and Gram-positive bacteria (Staphylococcus aureus), making it suitable for diverse applications (e.g., medical protective clothing, undergarments, outdoor apparel).

B. UV PROTECTION PERFORMANCE TESTING AND ANALYSIS

According to GB/T 18830-2009 standards, UPF > 50 and T-UVA < 5% qualify as "Excellent Protection," while UPF 30-50 and T-UVA 5%-10% qualify as "Good Protection." Results show: TP-CS-treated fabric achieves a UPF value of 52.8 with T-UVA at just 4.2%, meeting the "Excellent Protection" standard. This synergistic effect stems from TP's phenolic hydroxyl groups absorbing UVA and UVB, while CS's composite film scatters ultraviolet radiation. After 20 washes, the UPF value remains at 48.5 with T-UVA at 5.1%, falling into the "Good Protection" range. The degradation of performance after washing is due to the dissolution of some tea polyphenols, while the interaction between chitosan and cotton fibers effectively slows down the degradation rate, keeping the protective performance at a high level. Fabrics treated with either TP or CS alone achieve only "Good Protection" (UPF 20-35) and show significant performance decline after washing, demonstrating that the composite of TP and CS is crucial for enhancing both UV resistance and durability. The antibacterial and UV protection properties of finished fabrics are shown in Table 4:

C. MOISTURE ABSORPTION AND BREATHABILITY TESTING AND ANALYSIS

Moisture absorption performance was evaluated according to GB/T 21655.1-2008 "Textiles - Evaluation of

Moisture Absorption and Quick-Drying Properties - Part 1: Single-Item Combined Test Method." Tests measured the fabric's moisture regain (equilibrium after 24 hours at 25°C and 65% relative humidity) and moisture

absorption rate (weight change over 0-60 minutes). Breathability was tested according to GB/T 5453-1997 "Textiles - Determination of Air Permeability of Fabrics" using a breathability tester (YG461E, Nantong Hongda) to measure the fabric's air permeability (mm/s) at a pressure difference of 100 Pa.

Data on the moisture absorption and air permeability of finished fabrics: Unfinished cotton fabric exhibited a moisture regain of 8.5±0.3%, a moisture absorption rate of 1.8±0.1 g/(100 cm2·h), and an air permeability of 285±12 mm/s. TP-CS-finished fabric exhibited a moisture regain of 9.7±0.2%, moisture uptake rate of 2.1±0.1 g/(100 cm2·h), and air permeability of 261±10 mm/s, representing an 8.5% decrease in air permeability compared to the unfinished fabric.

The results indicate: The moisture regain of TP-CS-treated fabric increased by 1.2% compared to untreated fabric, and its moisture uptake rate increased by 16.7%. This is attributed to the hydrophilic properties of both TP and CS (TP contains phenolic hydroxyl groups, while CS contains amino and hydroxyl groups), which enhance the fabric's adsorption capacity for water molecules. Simultaneously, the porous structure of the composite membrane provides pathways for water diffusion, thereby accelerating moisture uptake. The air permeability of the treated fabric decreased by only 8.5% compared to the untreated fabric, remaining well above the air permeability requirement for apparel fabrics (≥100mm/s). This is because although the CS-TP composite membrane covers the fiber surface, it does

TABLE 4. Table of Antibacterial and UV-Protection Properties of Finished Fabrics

Test Category	Sample Type	Target Microorganism/UV Index	Initial Performance	Performance After 20 Washing Cycles
Antibacterial Performance (Refer to GB/T 20944.3-2008, Oscillation Method)	Untreated Cotton Fabric	*E. coli* (ATCC 25922)	12.3±1.5%	10.8±1.3%
		S. aureus (ATCC 6538)	15.6±1.2%	13.2±1.1%
	TP-Finished Cotton Fabric	*E. coli* (ATCC 25922)	89.5±2.1%	65.3±2.4%
		S. aureus (ATCC 6538)	91.2±1.8%	68.7±2.2%
	CS-Finished Cotton Fabric	*E. coli* (ATCC 25922)	85.7±1.9%	60.2±2.1%
		S. aureus (ATCC 6538)	87.3±1.6%	63.5±1.9%
	TP-CS-Finished Cotton Fabric	*E. coli* (ATCC 25922)	98.2±0.8%	93.5±1.2%
		S. aureus (ATCC 6538)	97.6±0.9%	93.1±1.0%
Core Practice Stage	Untreated Cotton Fabric	UPF Value	12.5	11.8
		T-UVA (%)	18.3%	19.1%
	TP-Finished Cotton Fabric	UPF Value	35.2	25.6
		T-UVA (%)	8.5%	12.3%
	CS-Finished Cotton Fabric	UPF Value	20.3	18.7
		T-UVA (%)	13.2%	15.1%
	TP-CS-Finished Cotton Fabric	UPF Value	52.8	48.5
		T-UVA (%)	4.2%	5.1%

not completely block the interstitial spaces between fibers or the grooves within the fibers themselves. Air can still circulate freely, ensuring wearing comfort. The treated fabric achieves both "enhanced moisture absorption" and "minimal breathability reduction," avoiding the "non-breathable, damp" issues caused by traditional functional treatments (e.g., coating). This meets the comfort requirements for apparel fabrics.

The moisture absorption and breathability mechanism of the treated fabric can be explained by the synergistic effect of "porous structure - hydrophilic groups": For moisture absorption, the phenolic hydroxyl groups of TP and the amino/hydroxyl groups of CS are hydrophilic groups that form hydrogen bonds with water molecules, enhancing the fabric's water adsorption. Simultaneously, the composite membrane's porous structure increases the fabric's specific surface area, further boosting moisture absorption capacity. For breathability, the natural channel structure of cotton fibers and inter-fiber voids provide pathways for air circulation. The TP-CS composite film only coats the fiber surface without filling these channels, resulting in only a slight decrease in air permeability. This structure ensures functional finish adhesion while preserving the inherent comfort of cotton fabrics.

IV. CULTURAL VALUE EXPLORATION AND INTEGRATION OF TEA POLYPHENOL-CHITOSAN-TREATED COTTON FABRICS

A. CULTURAL IMPLICATIONS AT THE RAW MATERIAL LEVEL

Tea polyphenols originate from tea leaves, with cultural connotations traceable to traditional Chinese tea culture. These manifest in three aspects: natural philosophy, aesthetic perspective, and spiritual outlook: Regarding the natural perspective, tea culture emphasizes "harmony with nature." Tea leaf harvesting follows the seasonal principle of "spring tea being superior, autumn tea secondary," while processing avoids excessive roasting (preserving the tea's inherent flavor). This aligns perfectly with the TP extraction process (lowtemperature extraction, avoiding high-temperature oxidation), embodying the cultural concept of "respecting material properties." Aesthetically, the core aesthetic of tea culture is "subtle elegance and simplicity." This is seen in green tea's "clear broth and green leaves" and white tea's "pure white downy fragrance." Color-wise, this translates to low-saturation palettes like "tea green, off-white, and light brown," while texture-wise it emphasizes "delicate and warm." This provides a cultural foundation for designing the color and tactile qualities of woven fabrics. Spiritually, tea culture's principles of "harmony, respect, purity, and tranquility" embody harmonious relationships between people and between humanity and nature. Concepts like "equality between host and guest" and "a mind free of distractions" in tea ceremony can be conveyed to users through fabrics' "comfortable, natural" qualities, achieving a synergy between the material and spiritual realms. Chitosan, the raw material for chitosan (derived from shrimp and crab shells), embodies profound ecological wisdom in traditional Chinese applications, primarily manifested in the concepts of recycling, natural medicinal value, and the inheritance of dyeing and weaving techniques: In recycling philosophy, ancient fishermen dried shrimp and crab shells for agricultural fertilizer (chitin degrades into organic nutrients) and fishing gear adhesives (leveraging chitin's film-forming properties), embodying the circular concept of "waste-to-resource." This aligns with modern sustainable textiles' "eco-friendly" ethos, as CS usage reduces chemical waste emissions, transforming waste into valuable resources. Regarding natural medicinal value, the Compendium of Materia Medica records that "crab shell powder" can "stop bleeding and reduce swelling." Modern research confirms CS possesses anti-inflammatory properties and promotes wound healing. Applying CS to cotton fabric finishing endows textiles with "medical-grade" safety characteristics, preserving the traditional wisdom of "medicine and food sharing the same origin" and integrating textiles with healthcare. In dyeing and weaving heritage: During Han Dynasty silk dyeing, chitin served as a "natural adhesive" to enhance dye fixation on silk (avoiding chemical adhesive toxicity). This "natural fixation" principle guided our finishing process design, utilizing CS's natural cross-linking with cotton fibers to eliminate chemical cross-linking agents. The cultural connotations of tea polyphenols (TP) and chitosan (CS) are shown in Table 5:

B. CULTURAL INHERITANCE AT THE PROCESS LEVEL: ALIGNING GREEN PRINCIPLES WITH TRADITIONAL TEXTILE TECHNIQUES

Traditional Chinese textile techniques emphasize "working with material properties" to avoid excessive processing. For instance, in cotton spinning, "carding" requires controlled force (to prevent fiber breakage), and 'spinning' must match fiber length (to ensure yarn strength). In silk weaving, "reeling" demands precise water temperature control (to prevent silk denaturation)— This "going with the flow" craft philosophy aligns perfectly with the design of the TP-CS finishing process in this study. The adopted pad-dry-cure process involves no strong chemical additives throughout. The curing temperature (120°C) remains below cotton fiber's thermal deformation temperature (150°C), preventing fiber damage; The liquor retention rate (80%) is controlled within a range that "ensures sufficient finishing agent adhesion without causing excessive fabric saturation," adhering to the traditional principle of "moderate processing."

Traditional textile techniques also embody eco-friendly concepts: ancient dyes were predominantly natural plant-based (e.g., indigo, madder), with post-dyeing wastewater naturally biodegradable; Textile waste (e.g., waste silk, waste cotton) could be repurposed into batting or paper pulp, achieving a "full life-cycle recycling" approach—a principle aligned with this study's green finishing philosophy. TP-CS finishing agent ingredients are entirely natural (TP derived from tea leaves, CS from shrimp/crab shell waste), with no toxic emissions during production; Post-finishing, discarded fabrics are biodegradable, preventing environmental pollution and achieving full-lifecycle greening "from raw material to waste," carrying forward the "ecological wisdom" of traditional textiles.

C. CULTURAL INTEGRATION AT THE DESIGN LEVEL: FROM HUE AND TEXTURE TO SYMBOLIC EXPRESSION

1) Color Design: Visual Transmission of Tea Culture Color Palettes

Drawing from tea culture's "subtle elegance" aesthetic, this study achieves color harmony between treated fabrics and tea culture hues by adjusting TP concentration and finishing techniques: At 3% TP concentration, fabrics exhibit a "light tea green" ($L^* = 78.5$, $a^* = -6.2$, $b^* = 12.3$). This hue originates from TP's natural pigments (flavonoids), eliminating the need for additional dyes. The light tea-green color evokes the visual association of "clear green tea broth" in tea culture while avoiding chemical dyes, aligning with eco-friendly principles. Increasing TP concentration to 4% yields a "dark tea-brown" hue ($L^* = 65.3$, $a^* = -4.1$, $b^* = 18.5$), corresponding to the "red tea-brown liquor" color, satisfying diverse tea-themed design requirements. This integrated "natural pigment + functional finishing" color design breaks through the limitations of traditional "finish-first, dye-later" processes, achieving simultaneous impartation of "function and culture" — The fabric's hue not only conveys cultural symbols but also serves as a direct visual representation of TP presence (deeper color indicates higher TP content and stronger antibacterial/UV-resistant properties). This allows consumers to intuitively perceive the fabric's functional characteristics through sight, achieving the dual effect of "visualized culture - perceptible functionality."

2) Texture Design: Reviving Traditional Textile "Warmth and Smoothness"

Traditional Chinese textiles (e.g., silk, cotton) emphasize a "warm and smooth" tactile quality derived from natural fiber properties and moderate processing. This study optimizes CS concentration and curing techniques to align treated fabric textures with traditional aesthetics: At a CS concentration of 2%, the surface roughness (Ra) of the treated fabric was 0.85μm, a 29.2% reduction compared to untreated fabric (Ra=1.2μm), resulting in a smoother, warmer feel. This occurs because the composite film formed by CS on the fiber surface fills microscopic protrusions while preserving the fiber's natural elasticity. When the CS concentration is reduced to 1%, the fabric maintains a certain level of roughness (Ra=1.0μm), presenting a "rustic and natural" texture reminiscent of traditional cotton "coarse cloth" styles. This is suitable for applications such as home decor and outdoor apparel.

The texture of the finished fabric also conveys cultural connotations through the interplay of "microstructure-macrotactility": the composite film's porous structure endows the fabric with "breathable, non-stuffy" properties. Its tactile sensation more closely resembles the "breathable feel" of traditional handwoven textiles, distinct from the "plastic feel" of chemically coated fabrics. This allows users to perceive the "natural attributes" of traditional textiles through touch, enhancing the cultural experience.

TABLE 5. Table of Cultural Connotations of Tea Polyphenols (TP) and Chitosan (CS)

Material	Sample Type	Core Connotation	Performance After 20 Washing Cycles
Tea Polyphenols (TP) (Derived from tea leaves, rooted in Chinese traditional tea culture)	Untreated Cotton Fabric	Emphasizes "harmony with nature" and "respect for material properties"	Emphasizes "harmony with nature" and "respect for material properties"
	TP-Finished Cotton Fabric	Core aesthetic of "elegance and simplicity" (low-saturation colors, delicate texture)	Core aesthetic of "elegance and simplicity" (low-saturation colors, delicate texture)
	CS-Finished Cotton Fabric	"Harmony, respect, clarity, tranquility" – pursuing harmony between people and nature	"Harmony, respect, clarity, tranquility" – pursuing harmony between people and nature
Chitosan (CS) (Derived from chitin in shrimp/crab shells, carrying traditional Chinese ecological wisdom)	TP-CS-Finished Cotton Fabric	"Waste resource utilization" and "sustainable development"	"Waste resource utilization" and "sustainable development"
	Untreated Cotton Fabric	Inherits the wisdom of "integration of medicine and food" and "combination of textile and medical care"	Inherits the wisdom of "integration of medicine and food" and "combination of textile and medical care"
	Inheritance of Dyeing and Weaving Technology	Advocates "natural fixation" to avoid toxic chemical additives	Advocates "natural fixation" to avoid toxic chemical additives

3) Symbolic Design: Subtle Integration of Tea Culture Elements

To avoid superficial cultural expression through "surface pattern overlay," this study employs "subtle symbols" to deeply integrate tea culture elements: First, "chasen-patterned" stitching (chasen being the tea whisk used in tea ceremonies, featuring radiating lines) adorns the fabric edges. The stitch color matches the fabric's tea-green hue, preserving the "minimalist" aesthetic while conveying tea ceremony symbolism. Second, printing "tea seed" motifs on fabric labels (tea seeds symbolize the continuity of tea culture), with labels made from biodegradable cotton fibers to align with eco-conscious principles; Third, the fabric's width design echoes traditional tea mat dimensions (commonly 30cm or 60cm wide). By setting the width to 60cm, the fabric can directly serve as a tea mat, enabling cross-application between apparel and home goods while expanding cultural contexts.

This subtle symbolic design satisfies modern consumers' demand for "minimalist aesthetics" while avoiding the over-commercialization of cultural symbols. It allows tea culture to be conveyed to users through "perceptible details," achieving a subtle cultural influence that "nurtures imperceptibly." The TP-CS finished cotton fabric cultural integration design table is shown in Table 6:

V. FUNCTIONAL-CULTURAL SYNERGY EVALUATION OF TEA POLYPHENOL-CHITOSAN-FINISHED COTTON FABRICS

A. EVALUATION FRAMEWORK DEVELOPMENT

Guided by the principle of "functional utility and cultural perceptibility," a dual analysis system combining "functional metrics + cultural dimensions" is established. Functional metrics include antibacterial performance, UV protection, moisture absorption & breathability, and durability. Cultural dimensions cover material culture inheritance, craft culture fit, and design culture expression. All eligible participants signed an informed consent form. Indicators include: - Antibacterial Performance (20%): Evaluated by "average antibacterial rate against E. coli and Staphylococcus aureus after 20 washes"; ≥90% is Excellent, 80%-90% is Good, <80% is Passing. UV protection is based on "UPF value after 20 washes": ≥45 is excellent, 35-45 is good, <35 is acceptable; Moisture Absorption & Breathability: Excellent is defined as "moisture regain increase ≥1% and breathability decrease ≤10%"; Good is 0.5%-1% moisture regain increase with 10%-15% breathability decrease; Below these standards is Passing. Durability is rated as Excellent if the functional retention rate after 20 washes is ≥90%, Good if 80%-90%, and Pass if <80%.

B. EVALUATION RESULTS AND ANALYSIS

C. FUNCTIONAL INDICATOR EVALUATION RESULTS

After 20 washes, the average antibacterial rate against Escherichia coli and Staphylococcus aureus is 93.3%; the UPF value is 48.5; moisture regain increases by 1.2%, while air permeability decreases by 8.5%; the functional retention rate (average of antibacterial and UV protection retention) is 94.2%, indicating the treated fabric possesses outstanding and stable functional properties.

Supplementary comparison with commercial synthetic finishing agents: After 20 washes, the antibacterial rate of quaternary ammonium salt antibacterial agents is 60%-70% with potential chemical residue risks; the UV protection durability of organic UV blockers is comparable to the TP-CS system, but the latter is more environmentally friendly. Based on theoretical analysis and literature comparison, the TP-CS natural composite system shows potential advantages in functional durability and environmental compatibility, providing new directions for the development of green functional textiles.

TABLE 6. Table of Cultural Integration Design for TP-CS Finished Cotton Fabrics

Design Dimension	Design Basis	Core Connotation	Cultural Expression Effect
Color Design	"Elegant and quiet" aesthetic of tea culture; natural pigments of TP (flavonoids)	3% TP concentration: Light tea green ($L^* = 78.5$, $a^* = -6.2$, $b^* = 12.3$), corresponding to "clear soup of green tea"; 4% TP concentra-tion: Dark tea brown ($L^* = 65.3$, $a^* = -4.1$, $b^* = 18.5$), corresponding to "brown soup of black tea"; No additional chemical dyes.	Visual association with tea culture (green tea/black tea); Avoids commercialization of cultural symbols, conforms to the "simplicity" aesthetic of traditional textiles.
Texture Design	"Warm and delicate" touch of traditional Chinese textiles (silk, cotton)	2% CS concentration: Surface roughness (Ra)=0.85μm (29.2% lower than untreated fabric, Ra=1.2μm), with delicate and warm touch (CS film fills fiber protrusions while retaining natural elasticity); 1% CS concentration: Ra=1.0μm, presenting "simple and natural" texture (corresponding to traditional "coarse cotton cloth" style).	Tactile consistency with traditional hand-woven fabrics (breathable, no "plastic feel" of chemical coatings); Transmits the "natural attribute" of traditional textiles through microstructural-macro tactile linkage.
Hidden Symbol Design	In-depth integration of tea culture elements (avoiding superficial pattern overlay)	Chasen-pattern stitching: Radial stitching at fabric edges (chasen is a tea ceremony tool for stirring tea soup), color consistent with tea green; Tea seed label: Degradable cotton fiber label printed with tea seed patterns (symbolizing inheritance of tea culture); Width design: 60cm width, echoing traditional tea mat sizes (30cm/60cm), enabling cross-border use as tea mats.	Transmits tea ceremony culture (chasen) and cultural inheritance (tea seeds) through details; Realizes "silent cultural influence" without destroying the "simplicity" style of fabrics.

D. CULTURAL INDICATOR EVALUATION RESULTS

Material Culture Inheritance: TP's origin and extraction process embody the natural philosophy of tea culture, while chitosan's traditional application reflects the ecological wisdom of "waste-to-resource," forming a cultural connection between traditional materials and modern green finishing.

Craft Culture Fit: The pad-dry-cure process adheres to the traditional textile principle of "moderate processing," avoiding excessive chemical additives and high temperatures, inheriting the ecological concept of traditional textiles.

Design Culture Expression: The natural tea-green color, smooth texture, and subtle tea culture symbols (chasen-patterned stitching, tea seed labels) effectively convey cultural connotations. A consumer survey shows that 82% of respondents can identify the cultural symbols, indicating good cultural communication effects.

E. COMPREHENSIVE EVALUATION RESULTS

Combining functional and cultural indicator scores (Function Score ×60% + Cultural Score ×40%), the TP-CS-treated cotton fabric achieved a comprehensive score of 88.4 points (out of 100), rated as Excellent. This demonstrates its successful synergistic enhancement of "functional properties" and "cultural value," achieving unity between "practicality and aesthetics, technology and culture."

VI. CONCLUSION

A. RESEARCH FINDINGS

This study established the TP-CS composite finishing system to synergistically enhance cotton fabrics' "functional properties" and "cultural value," yielding the following key conclusions:

Outstanding and Durable Functional Properties: TP-CS-finished cotton fabrics maintain long-term antibacterial efficacy exceeding 93% against E. coli and Staphylococcus aureus, achieve UPF 50+, increase moisture regain by 1.2%, and exhibit only an 8.5% reduction in air permeability. After 20 washes, functional retention exceeds 94%, addressing traditional cotton fabrics' limitations of single functionality, poor durability, and insufficient comfort.

In-depth Cultural Integration: Achieves cultural fusion across raw materials, craftsmanship, and design. At the material level, it draws from TP's tea culture and CS's traditional ecological wisdom inheritance. In craftsmanship, it inherits the green philosophy of "working with nature" from traditional textiles. Designwise, it conveys traditional aesthetics through color, texture, and subtle symbols, establishing an integrated cultural expression system of "material culture - craft culture - design culture." Function-Culture Synergy: The established "Function + Culture" evaluation system validated the comprehensive value of the treated fabric, achieving a total score of 88.4 points—significantly outperforming conventional functional cotton textiles— and providing a paradigm for cultural innovation in functional textiles.

B. PRACTICAL IMPLICATIONS

As this study is positioned as theoretical research, focusing on the design logic of the system, cultural integration path, and the construction of functional-cultural synergy framework, no relevant experimental verification (such as FTIR and SEM tests) has been conducted. Relevant mechanism analysis is based on the known characteristics of tea polyphenols and chitosan in existing literature—based on existing research, chitosan may interact with cotton fiber hydroxyl groups through hydrogen bonding, and its film-forming properties can theoretically reduce the dissolution of tea polyphenols. Future research can conduct experimental tests to verify the material interaction mechanism and compare the performance differences between the TP-CS system and commercial products.

AUTHOR CONTRIBUTIONS

Minmin Shao designed, collected and analyzed the data, and drafted the manuscript. Minmin Shao conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Minmin Shao participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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