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Research Article

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Sustainable Functional Finishing of Cotton Fabrics Using Acorn Shell Extract Enhanced by Cellulase Pretreatment

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Abstract Growing environmental concerns associated with synthetic textile finishing agents have driven interest in sustainable alternatives; however, the practical application of biobased finishes remains limited by poor uptake and insufficient durability. In particular, the synergistic effects of enzymatic pretreatment and phenolic-rich bioextracts have not been systematically explored. This study explores sustainable functional finishing of cotton fabrics through enzymatic pretreatment with cellulase, followed by application of acorn (*Quercus variabilis*) shell extract. The acorn shell, rich in flavonoids and phenolic acids, was extracted using a hot aqueous extraction method and applied to cotton fabrics using a pad–dry–cure process. Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR) analysis, X-ray photoelectron spectroscopy (XPS), and X-ray diffraction (XRD) analysis indicate that cellulase pretreatment modified the cotton surface and enhanced interaction with bioactive compounds. Treated fabrics demonstrated excellent antimicrobial (> 99.9% bacterial reduction) and strong antioxidant (> 92% 1,1-diphenyl-2-picrylhydrazyl (DPPH) scavenging) activities. Although antioxidant properties decreased after laundering, cellulase-pretreated samples exhibited improved retention of antibacterial effects, particularly against *K. pneumoniae*. These results suggest that acorn shell extract, when combined with enzymatic pretreatment, offers a promising natural alternative for functional textile finishing, providing enhanced antibacterial durability but limited antioxidant wash fastness.

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34 *Keywords: cotton fabric, cellulase pretreatment, acorn shell extract, phenolic compounds,*
35 *antimicrobial activity, sustainable textile finishing*

36

37 Abbreviations: attenuated total reflectance, ATR; carbohydrate-binding modules, CBMs;
38 catechin equivalent, CE; cellobiohydrolases, CBHs; color strength, K/S; crystallinity index,
39 CrI; 1,1-diphenyl-2-picrylhydrazyl, DPPH; endoglucanases, EG; Fourier transform infrared
40 spectroscopy, FTIR; gallic acid equivalents, GAE; infrared, IR; scanning electron
41 microscopy, SEM; thermogravimetric analysis, TGA; total flavonoid content, TFC; total
42 phenolic content, TPC; ultraviolet, UV; visible, Vis; X-ray diffraction, XRD; X-ray
43 photoelectron spectroscopy, XPS

44

Introduction

The textile industry is a major contributor to global environmental degradation, characterized by high water and energy consumption and the generation of substantial greenhouse gas emissions and solid waste. Of particular concern is the widespread use of synthetic dyes and hazardous chemicals, which frequently lead to the release of untreated effluents into natural ecosystems. In response to escalating environmental and sustainability challenges, the industry faces increasing pressure to adopt greener alternatives, including the use of biobased materials, green chemistry approaches, and closed-loop production systems (Haji and Naebe 2020; Leal Filho et al. 2022). Among these strategies, the development of ecofriendly functional finishing agents derived from renewable natural resources has garnered significant research interest. In particular, the valorization of agricultural and food processing byproducts offers a promising pathway for reducing waste and advancing circular economy principles (Jajpura et al. 2020; Brudzyńska et al. 2023).

Acorns, the nut-like fruits of *Quercus* species, have long been used as a nutritional resource for both human consumption and livestock feed due to their high content of proteins, carbohydrates, and lipids. Beyond their nutritional value, acorns are rich in phenolic compounds, including flavonoids, tannins, and phenolic acids, which exhibit a broad spectrum of biological activities, including antioxidant, antibacterial, anti-inflammatory, and antifungal effects (Vinha et al. 2016; Huang et al. 2016; Martins et al. 2022). Recent research has drawn attention to the bioactive potential of acorn shells, which contain even higher concentrations of secondary metabolites than the edible kernel. Notably, a study by Vinha et al. (2020) demonstrated the angiogenic and therapeutic potential of acorn shell extracts in vivo, underscoring their value as a functional bioresource. With growing interest in waste valorization, acorn shells, typically discarded during processing, are increasingly recognized as a promising underutilized material. Previous studies have explored their application as biosorbents for environmental remediation (Altıntaş et al. 2017) and as biochar for soil enhancement (Seow et al. 2022). However, their rich phenolic composition and diverse bioactivities indicate strong potential for acorn shell extracts to serve as natural functional agents in sustainable textile finishing applications.

Recent research has increasingly focused on the use of agricultural waste materials as natural colorants and functional agents to promote sustainable textile production (Koh and Hong 2014, 2017; Hong 2021; Rahman et al. 2022, 2024). Despite growing interest, the practical

application of biobased finishing agents remains limited due to challenges such as poor uptake during the finishing process and insufficient durability against light, heat, and repeated laundering (Harsito et al. 2021). To address these limitations, various additives and processing strategies have been explored to enhance both the coloration and functionality of treated fabrics.

Recent investigations have identified enzyme pretreatment, specifically using cellulase, as a promising approach to improve the processability and binding efficiency of natural finishing agents on cotton textiles (Yoo and Hong 2025). Cellulase is a multicomponent enzyme system composed of endoglucanases, exoglucanases, and β -glucosidases, which act synergistically to hydrolyze β -1,4-glucosidic bonds in the amorphous regions of cellulose. This enzymatic activity results in partial degradation of fiber surfaces, leading to weight reduction, surface smoothing, and improved hand and luster. Consequently, dyeability, wettability, and the aesthetic appearance of textiles improve. Cellulase has been widely applied in the textile industry for biopolishing and bioscouring of cellulose-based fibers such as cotton, flax, and rayon (Buschle-Diller et al. 1994; Hao et al. 2012; Jabasingh et al. 2016; Sankarraj and Nallathambi 2018). Moreover, cellulase-based processes are increasingly recognized as ecofriendly alternatives to conventional chemical treatments in sustainable textile finishing. Few studies have systematically investigated the synergistic effects of enzymatic pretreatment and phenolic-rich bioextracts derived from acorn shells on the functional performance and durability of cotton textiles.

Accordingly, this study aims to bridge this gap by evaluating the combined influence of cellulase-assisted modification and natural polyphenol-based finishing. Cotton fabrics were pretreated with cellulase for varying durations and subsequently finished with acorn shell extract at an optimized concentration identified in preliminary experiments. The finishing process was conducted using the pad-dry-cure method, and the treated fabrics were comprehensively evaluated for processability and functional performance, including surface morphology and roughness (scanning electron microscopy; SEM), crystallinity (X-ray diffraction; XRD), surface chemical composition (X-ray photoelectron spectroscopy; XPS), thermal stability (thermogravimetric analysis; TGA), molecular structure (Fourier transform infrared spectroscopy; FTIR), color properties (CIELab and K/S), antimicrobial activity, and antioxidant capacity (1,1-diphenyl-2-picrylhydrazyl (DPPH) assay).

Materials and Methods

Materials and precursors

Scoured cotton fabric (No. 400; plain woven) was purchased from Testfabrics Inc. (West Pittston, PA, USA). Cellulase enzyme was purchased from Biozoa Biological Supply Company (Seoul, South Korea) and used as received, as a 1% enzyme solution (pH 5), without further dilution or modification. Acorn (*Quercus variabilis*) shells were collected in October 2023 from Ansan, South Korea. Sodium carbonate, gallic acid ($\geq 97\%$), (+)-catechin hydrate ($\geq 98\%$), and the Folin–Ciocalteu reagent were purchased from Sigma-Aldrich (Seoul, South Korea). Additionally, DPPH was acquired from Alfa Aesar (Haverhill, MA, USA). All reagents were used as received without further purification.

Acorn shell extraction

Acorn shells were thoroughly cleaned to remove surface impurities and subsequently air-dried at ambient room temperature. A total of 100 g of dried acorn shells was subjected to hot aqueous extraction by boiling in 1.5 L of distilled water for 2 h to obtain a crude extract. The resulting extract was filtered to remove solid residues and then freeze-dried to yield a stable powdered form. The freeze-dried material was further pulverized using a laboratory mill to achieve a uniform particle size suitable for subsequent applications.

Cellulase pretreatment

Cotton fabrics were thoroughly impregnated with a cellulase enzyme solution at a liquor ratio of 1:4 (fabric:enzyme solution, w/w), followed by incubation at 55 °C for varying durations of 1, 2, 3, 6, 12, and 24 h. To terminate the enzymatic reaction, the treated samples were immersed in distilled water at 80 °C for 10 min. The fabrics were then rinsed twice with distilled water at room temperature and dried in a convection oven at 65 °C for 24 h. Cotton fabrics pretreated with cellulase for different durations were designated as CP_1h_COTTON, CP_2h_COTTON, CP_3h_COTTON, CP_6h_COTTON, CP_12h_COTTON, and CP_24h_COTTON, corresponding to cellulase pretreatment durations of 1, 2, 3, 6, 12, and 24 h, respectively.

Acorn shell extract finishing

Each cotton fabric specimen was immersed in an aqueous solution containing 10 wt% acorn shell extract for 30 min, with a bath ratio maintained at 1:20 (fabric weight to solution volume). The above conditions, including the concentration of acorn shell extract, were determined based on preliminary screening (data not shown). Following immersion, the treated fabrics were passed through a laboratory-scale padding mangle until a wet pick-up rate of approximately 100% was achieved. The impregnated fabrics were subsequently dried in a convection oven at 85 °C and then cured at 160 °C for 3 min to promote fixation of the extract onto the fiber surface. After curing, the samples were thoroughly rinsed with distilled water to remove unbound residues and then air-dried. Fabric samples subjected to varying durations of cellulase pretreatment followed by finishing with acorn shell extract were designated as CP_0h_AE_COTTON, CP_1h_AE_COTTON, CP_2h_AE_COTTON, CP_3h_AE_COTTON, CP_6h_AE_COTTON, CP_12h_AE_COTTON, and CP_24h_AE_COTTON. These labels correspond to samples pretreated with cellulase for 0 h (no enzymatic treatment), 1 h, 2 h, 3 h, 6 h, 12 h, and 24 h, respectively, prior to finishing with acorn shell extract.

Analysis of acorn shell extract

Total flavonoid content

The total flavonoid content (TFC) of the extracts was determined using a colorimetric method. Specifically, 200 µL of the extract was added to 1 mL of distilled water in an amber bottle. Next, 50 µL of NaNO₂ (5% w/v) was added and thoroughly mixed. After 6 min, 150 µL of AlCl₃·6H₂O (10% w/v) was added, followed by 0.5 mL of NaOH (1 mol/L) after 5 min. The absorbance was immediately measured at 510 nm using an ultraviolet (UV)–visible (Vis) spectrophotometer (Biomate 5, Thermo Fisher Scientific, Waltham, MA, USA). Catechin was used as the standard for the calibration curve, and the results were expressed as mg of catechin equivalent (CE) per 1 g of sample (mg CE/g).

Total phenolic content

The total phenolic content (TPC) of the extract was measured using a colorimetric method. Specifically, 100 μL of the extract was added to 0.5 mL of distilled water and mixed well. Subsequently, 100 μL of the Folin–Ciocalteu reagent (diluted 1:10 in distilled water) was added. The mixture was then incubated in the dark for 3 min. Next, 1 mL of Na_2CO_3 (7 wt%) was added, followed by incubation in the dark for 30 min. The absorbance was then measured at 760 nm using a UV–Vis spectrophotometer (Biomate 5, Thermo Fisher Scientific, Waltham, MA, USA). The results were quantified using a calibration curve for gallic acid and expressed as mg of gallic acid equivalents (GAE) per 1 g of sample (mg GAE/g).

Characteristics of cotton fabrics

The surface morphologies of the cotton fabrics were observed using a high-resolution field-emission SEM (Tescan, Brno, Czech Republic). Surface roughness was evaluated from SEM micrographs using ImageJ software (Hong 2024).

Crystallinity changes in the cotton fabrics were determined by XRD analysis using an X-ray diffractometer (D/MAX2500, Rigaku, Osaka, Japan) with $\text{Cu K}\alpha$ radiation ($\lambda = 1.5405 \text{ \AA}$). A 2θ wide-angle goniometer was used, with an ultimate peak resolution of $2\theta = 0.050^\circ$. Data were recorded from 10° to 30° in steps of 0.02° . The crystallinity index (CrI; %) of the cotton fabric was calculated using Eq. (1) (Segal et al. 1959):

$$\text{CrI (\%)} = \frac{I_{200} - I_{\text{am}}}{I_{200}} \times 100 \quad (1)$$

where I_{200} represents the maximum intensity of the XRD peak at $2\theta \approx 22.6^\circ$, and I_{am} represents the minimum intensity at $2\theta \approx 18.6^\circ$.

XPS analysis was conducted using a K-Alpha spectrometer (Thermo Fisher Scientific, Waltham, MA, USA) equipped with a monochromatic $\text{Al K}\alpha$ X-ray source ($\lambda = 1486.6 \text{ eV}$). All measurements were performed under ultra-high vacuum conditions ($\sim 10^{-8} \text{ mbar}$), with an energy resolution of $\Delta E \leq 0.5 \text{ eV}$. Survey spectra were recorded with a pass energy of 200 eV and a step size of 1.0 eV, whereas high-resolution spectra for C 1s and O 1s were acquired using a pass energy of 50 eV and a step size of 0.1 eV. A constant analysis spot size of 400 μm was maintained throughout the measurements. Surface elemental compositions were

quantified based on relative peak area ratios after appropriate background subtraction and sensitivity factor correction.

The thermal properties of the cotton fabrics were determined through TGA (Pyris 1 TGA, PerkinElmer, MA, USA) under an N₂ atmosphere over a temperature range of 20 to 550 °C at a heating rate of 10 °C/min.

Molecular structure changes in the cotton fabrics treated with acorn shell extract were analyzed using FTIR spectroscopy. The FTIR instrument (Spectrum 100, PerkinElmer, MA, USA) was equipped with an attenuated total reflectance (ATR) accessory. The spectra were recorded in the mid-infrared (IR) region at a resolution of 4 cm⁻¹ with 32 scans.

Color changes in the cotton fabrics were analyzed using a photoelectric spectrophotometer (CM-2500d, Konica Minolta, Inc., Osaka, Japan) in terms of CIELab coordinates (L*, a*, b*) and color strength (K/S). The color strength (K/S) was calculated using the Kubelka–Munk Eq. (2):

$$\frac{K}{S} = \frac{(1 - R)^2}{2R} \quad (2)$$

where R represents the diffuse reflectance, K denotes the absorption coefficient, and S corresponds to the scattering coefficient.

Antimicrobial activity of the cotton fabrics was tested using *Staphylococcus aureus* (*S. aureus*; ATCC 6538; Gram-positive bacterium) and *Klebsiella pneumoniae* (*K. pneumoniae*; ATCC 4352; Gram-negative bacterium) according to the KS K 0693 protocol. Bacterial reduction was calculated using Eq. (3):

$$\text{Bacterial reduction (\%)} = \frac{(B - A)}{B} \times 100 \quad (3)$$

where A and B represent the surviving bacterial cells (colony-forming units in mL⁻¹) on plates inoculated with bacterial solutions derived from the treated fabric and the control, respectively.

Antioxidant capacity of the cotton fabrics was measured using the DPPH assay. Specifically, 500 mg of fabric was immersed in 30 mL of 0.15 mM DPPH in methanol. The absorbance was measured at 517 nm using a UV–Vis spectrophotometer after 1 h of incubation in the dark. The DPPH scavenging ability was calculated using Eq. (4):

$$\text{DPPH scavenging activity (\%)} = \frac{C - S}{C} \times 100 \quad (4)$$

where S and C represent the absorbance of the sample solutions from the treated and pristine fabrics, respectively.

Results and Discussion

Enzymatic pretreatment of cotton fabrics using cellulase

Figure 1 presents representative surface morphologies and corresponding azimuthal images of cotton fibers subjected to cellulase treatment as a function of treatment time. A substantial reduction in surface roughness was observed after enzymatic treatment, with the roughness values (R_q) decreasing within the first 2 h. Although a slight increase occurred at longer treatment times, the surface roughness remained consistently lower than that of untreated (pristine) cotton fibers. Notably, prolonged treatment resulted in increasingly prominent submicron-scale fibrillation features on the fiber surface, as illustrated in **Fig. 1(d)**. These findings suggest that cellulase initially degraded prominent surface structures and subsequently induced finer-scale morphological modifications through fibrillation during extended exposure.

Figure 2 further demonstrates that cellulase treatment influenced not only the amorphous regions but also the crystalline domains of cotton cellulose. The CrI showed an overall decrease relative to pristine cotton, with a marked reduction observed during the early stages, whereas the lowest CrI was obtained after 24 h of treatment (**Table 1**). This trend contrasts with earlier findings by Sankarraj and Nallathambi (2018), who reported that free cellulase primarily hydrolyzes amorphous regions, resulting in an increase in the relative crystallinity index of cotton fabrics. The observed decrease in crystallinity over time may be attributed to the catalytic action of endoglucanases (EG; endo-1,4- β -D-glucan 4-glucanohydrolase, EC 3.2.1.4), which cleaved internal β -1,4-glycosidic bonds within the amorphous zones of cellulose chains in a random manner. This cleavage generated new chain ends that were further degraded by cellobiohydrolases (CBHs). Notably, endoglucanases contain carbohydrate-binding modules (CBMs), which facilitate their interaction with cellulose substrates and are known to disrupt crystalline domains under certain conditions (Gomez del Pulgar and Saadeddin 2014; Srivastava et al. 2018). Although enzymatic degradation

typically initiates in amorphous regions, prolonged exposure to cellulase may enable enzyme access to and hydrolysis of crystalline regions. This extended enzymatic activity may stem from the inherent structural heterogeneity of cellulose. As a naturally occurring polymer, cellulose exhibits imperfect crystallinity, where amorphous regions often occur near or extend through crystalline domains. Moreover, even within highly ordered crystalline regions, concealed chain ends, in other words, those not exposed at the surface, may exist and serve as additional enzymatic targets (Hoshino et al. 1997).

This mechanistic interpretation is further supported by surface compositional changes observed through XPS (**Fig. 3**). The atomic percentage of oxygen in cellulase-treated cotton fabrics increased from 30.54% in the control (a) to 31.84% in the treated sample (b). Correspondingly, the O/C atomic ratio increased from 0.44 (a) to 0.47 (b), indicating an enrichment of oxygen-containing functional groups on the fiber surface. These changes suggest an increased exposure or relative abundance of oxygen-containing functionalities after cellulase treatment, likely associated with enhanced surface polarity and/or greater accessibility of existing hydroxyl-containing cellulose structures.

Figure 4 presents the thermal properties of cotton fabrics following cellulase treatment, as determined by TGA. Compared with pristine cotton, the cellulase-treated samples exhibited increased mass loss at lower temperatures. This behavior suggests that enzymatic hydrolysis by cellulase disrupted the ordered structure of cotton cellulose, resulting in a more open and thermally less stable configuration. Notably, within the first 6 h of treatment, a marked shift in the peak decomposition temperature to lower values was observed, along with a pronounced decrease in peak area. These results indicate that cellulase treatment altered the thermal stability of cotton cellulose during the early stages, likely due to preferential hydrolysis of less ordered regions and potential modification of crystalline domains. Although thermal decomposition behavior continued to change thereafter, the XRD results indicate that crystallinity did not decrease monotonically with treatment time (**Table 1**).

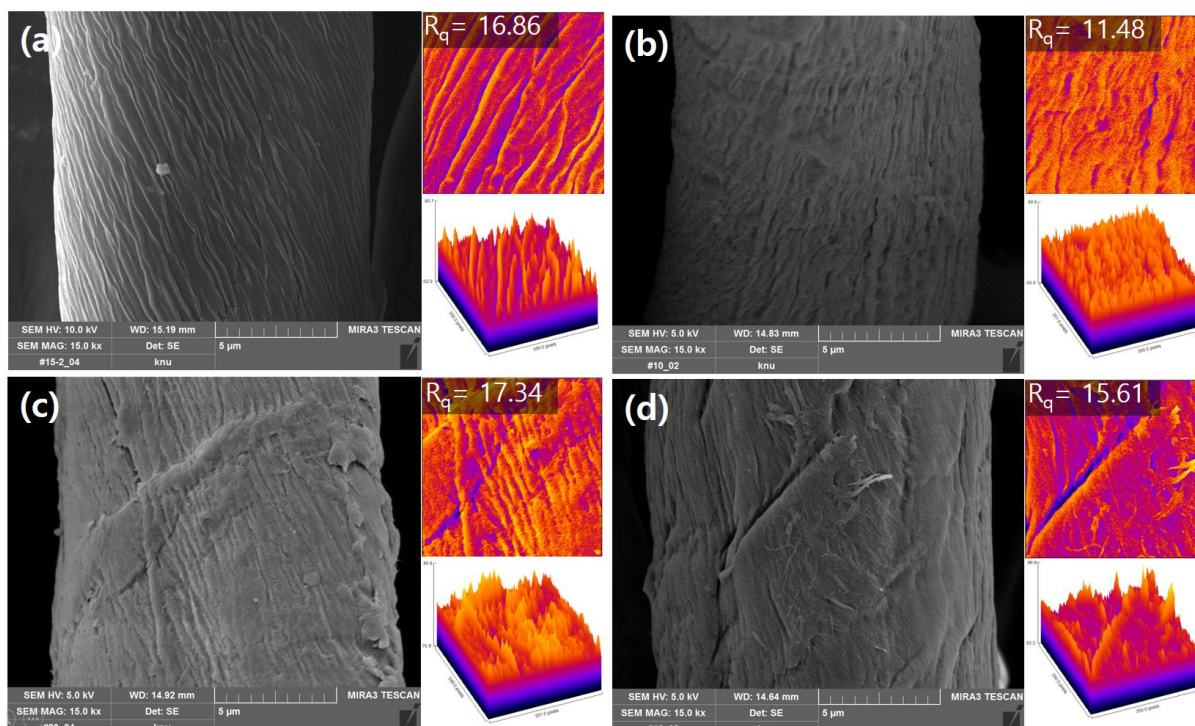


Fig. 1 SEM and azimuthal images of cotton fibers after cellulase treatment (R_q : root-mean-square roughness): (a) CP_0h_COTTON, (b) CP_1h_COTTON, (c) CP_6h_COTTON, and (d) CP_24h_COTTON

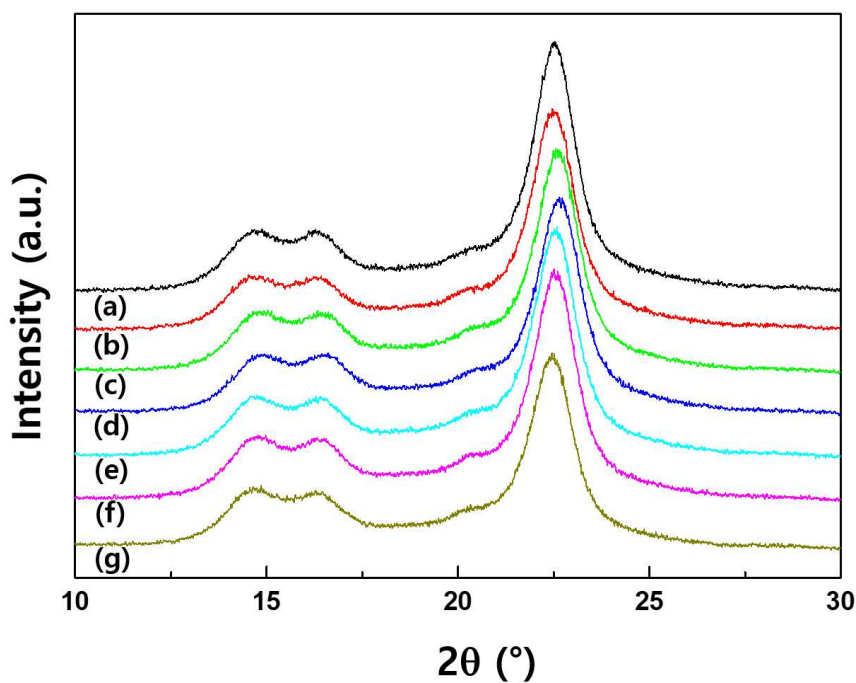


Fig. 2 XRD patterns of cotton fabrics after cellulase treatment: (a) pristine, (b) CP_1h_COTTON, (c) CP_2h_COTTON, (d) CP_3h_COTTON, (e) CP_6h_COTTON, (f) CP_12h_COTTON, and (g) CP_24h_COTTON

Table 1 Maximum peak intensities obtained from XRD and crystallinity index of cotton fabrics after cellulase treatment

Fabric samples	I_{am}	I_{200}	CrI (%)
Pristine	15181	77817	80.49
CP_1h_COTTON	15506	70915	78.14
CP_2h_COTTON	16018	71695	77.66
CP_3h_COTTON	17086	69176	75.30
CP_6h_COTTON	16968	73090	76.78
CP_12h_COTTON	16561	72877	77.28
CP_24h_COTTON	15528	60904	74.50

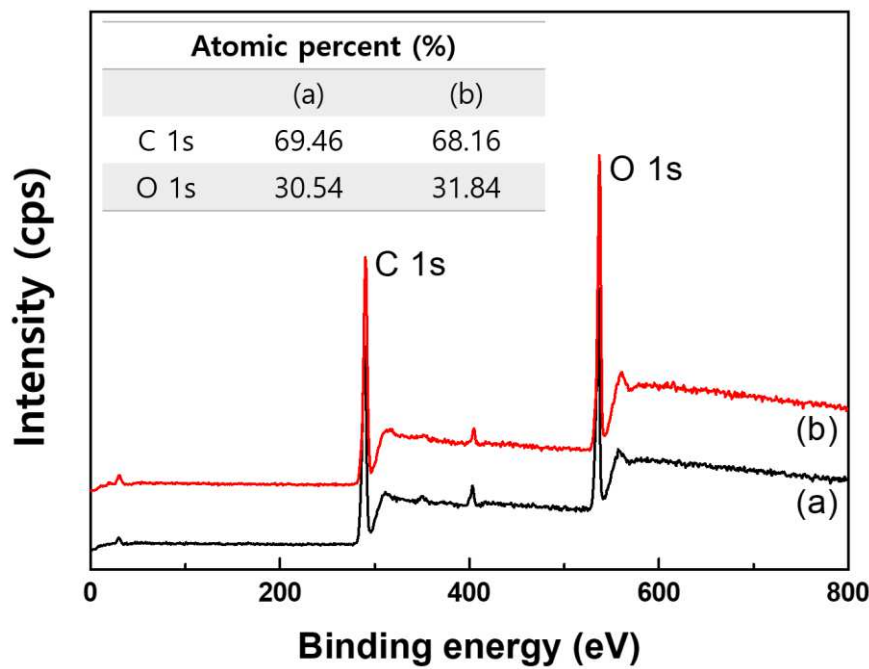


Fig. 3 XPS survey spectra of cotton fabrics (a) before and (b) after cellulase treatment for 24 h, illustrating changes in surface elemental composition

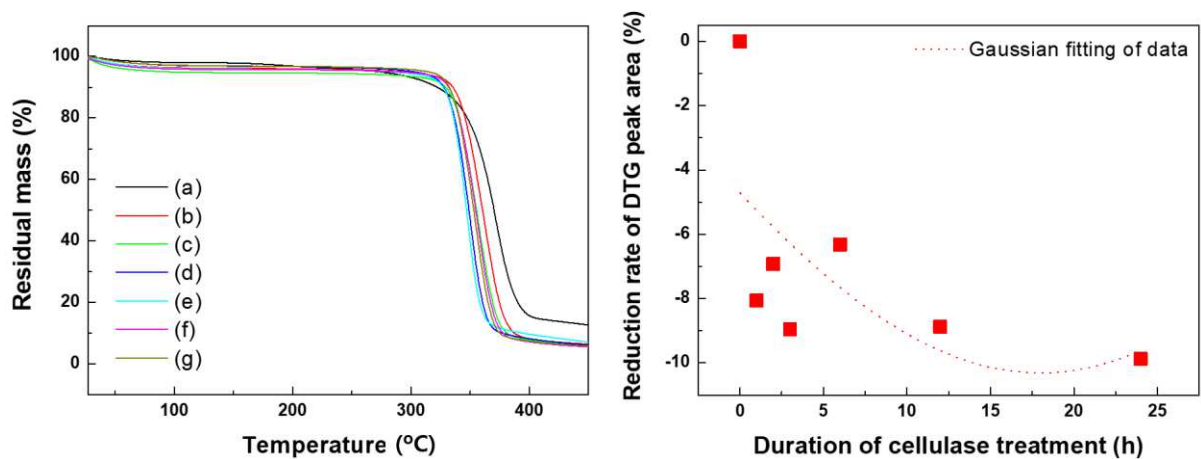


Fig. 4 TGA curves and reduction rates derived from derivative thermogravimetric (DTG) peak areas of cotton fabrics after cellulase treatment: (a) pristine, (b) CP_1h_COTTON, (c) CP_2h_COTTON, (d) CP_3h_COTTON, (e) CP_6h_COTTON, (f) CP_12h_COTTON, and (g) CP_24h_COTTON

Finishing of cellulase pretreated cotton fabrics with acorn shell extract

Color characteristics

Table 2 and **Fig. 5** illustrate the colorimetric changes observed in cotton fabrics that were pretreated with cellulase and subsequently finished with acorn shell extract as a function of enzyme treatment duration. As shown in **Table 2**, cellulase pretreatment alone resulted in negligible changes in the color parameters (L^* , a^* , and b^* values), regardless of exposure time, indicating that the enzymatic action itself did not produce appreciable chromatic modification of the cotton substrate.

However, following the application of acorn shell extract, all enzyme-treated fabrics exhibited a noticeable brownish tint, characterized by a decrease in L^* values and corresponding increases in a^* and b^* values. This chromatic shift is consistent with the incorporation of phenolic compounds derived from the acorn shell extract, which are known for their inherent color, antioxidant activity, and bioactive functionalities (Alasalvar et al. 2025). Additionally, the total color difference (ΔE^*_{ab}) was generally higher in cellulase-pretreated and extract-finished samples, with the highest value observed at 24 h, suggesting that cellulase pretreatment enhanced the interaction between phenolic constituents and the cotton substrate.

This improvement in finishing performance may be attributed to cellulase-induced surface modifications. Specifically, cellulase catalyzed the hydrolysis of β -1,4-glycosidic bonds within the amorphous regions of cellulose, resulting in partial depolymerization and an increase in reactive chain ends bearing hydroxyl ($-OH$) groups (Srivastava et al. 2018). The introduction of these functional groups likely enhanced the chemical affinity between the cotton fibers and phenolic compounds in the extract, thereby promoting stronger interactions and greater retention. Furthermore, the enzymatic treatment disrupted the ordered supramolecular structure of cellulose, leading to an overall reduction in crystallinity relative to pristine cotton, as reflected in **Table 1**. This structural loosening may have increased fiber surface accessibility, facilitating enhanced interactions with the finishing agent. These findings are consistent with earlier studies that reported improved dyeability and finishability

of cellulose-based fabrics due to cellulase-induced enhancement in surface reactivity (Ibrahim et al. 2005; Ibrahim et al. 2011; Kuhad et al. 2011).

Figure 5 also presents the color strength curves (K/S spectra) of the finished cotton fabrics. The maximum K/S values were observed at approximately 370 nm, within the UV region. This peak absorption is likely due to the phenolic compounds present in the acorn shell extract, which contained conjugated π -electron systems capable of absorbing UV radiation. These findings align with known UV-absorbing properties of polyphenol-rich natural extracts. Similarly, Grifoni et al. (2011) reported that cellulose fabrics treated with tannin-based mordants, such as *Quercus infectoria* galls, exhibited markedly enhanced UV protection, reaching very high to excellent UV protection categories. Accordingly, the UV-region absorption observed in the treated cotton fabrics suggests potential UV-shielding functionality; however, direct evaluation of UV protection performance (e.g., UPF measurement) is required to confirm this effect.

Table 2 Colorimetric data of cotton fabrics after cellulase pretreatment and acorn shell extract finishing

Duration of cellulase treatment (h)	Cotton fabrics pretreated with cellulase				Cotton fabrics pretreated with cellulase and finished with acorn shell extract			
	L*	a*	b*	ΔE^*_{ab}	L*	a*	b*	ΔE^*_{ab}
0	91.55	0.13	1.20	-	66.89	7.08	24.56	34.67
1	91.49	0.12	1.58	0.38	64.74	7.68	24.80	36.51
2	91.50	0.11	1.56	0.36	66.15	7.46	24.97	35.55
3	91.26	0.13	1.53	0.44	64.99	7.59	25.11	36.51
6	91.32	0.10	1.56	0.43	65.10	7.12	24.74	36.09
12	91.52	0.11	1.42	0.22	64.44	7.69	25.27	37.03
24	91.55	0.12	1.32	0.12	63.34	7.85	25.73	38.17

$$\Delta E^*_{ab}(\text{total color difference value}) = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$$

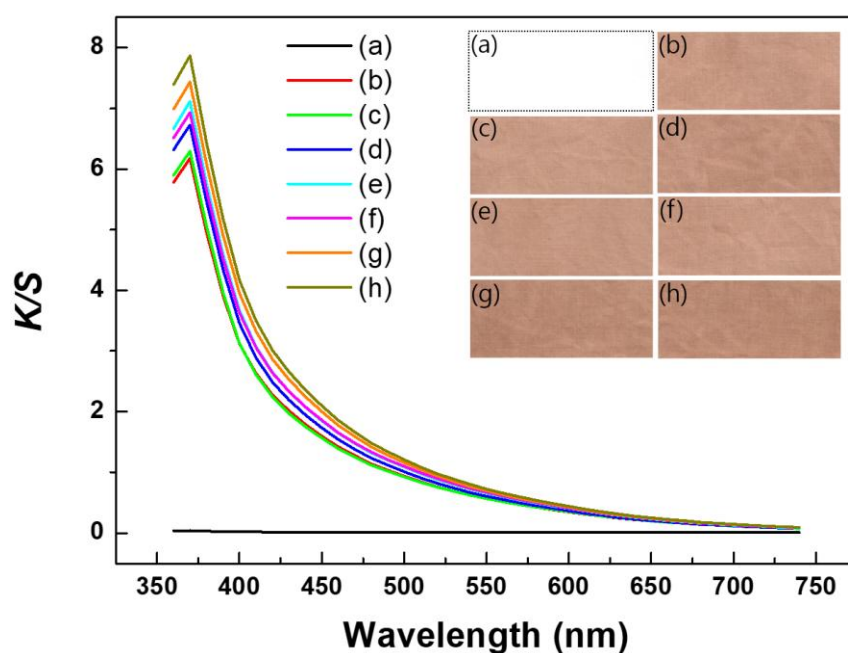


Fig. 5 K/S values of cotton fabrics pretreated with cellulase and finished with acorn shell extract: (a) pristine, (b) CP_0h_AE_COTTON, (c) CP_1h_AE_COTTON, (d) CP_2h_AE_COTTON, (e) CP_3h_AE_COTTON, (f) CP_6h_AE_COTTON, (g) CP_12h_AE_COTTON, and (h) CP_24h_AE_COTTON

Chemical modification

Figure 6 displays the FTIR spectra of (left) cotton fabrics pretreated with cellulase and subsequently finished with acorn shell extract and (right) the pure acorn shell extract. The spectra of the cotton fabrics (**Fig. 6, left**) consistently exhibited characteristic absorption bands associated with cellulose, including O–H stretching near 3400 cm^{-1} , C–H stretching around 2900 cm^{-1} , and C–O stretching at approximately 1060 cm^{-1} .

In addition to these cellulose-specific features, a distinct absorption band appeared near 1730 cm^{-1} in samples treated with acorn shell extract. This peak corresponds to the stretching vibration of carbonyl (C=O) and/or carboxyl ($-\text{COOH}$) groups and may also reflect the presence of flavone backbones derived from phenolic compounds in the extract (Şahin and Saka 2013; Mateus et al. 2025). In the spectrum of the pure acorn shell extract (**Fig. 6, right**), a corresponding carbonyl-associated peak was identified at 1726 cm^{-1} .

Additionally, a band typically attributed to the O–H bending vibration of adsorbed water in cellulose, observed at 1626 cm^{-1} in untreated samples, shifted to a lower wavenumber ($\sim 1614\text{ cm}^{-1}$) after treatment. This shift is associated with C=C stretching vibration of aromatic rings, which is characteristic of phenolic constituents such as tannins and flavonoids. A strong aromatic C=C stretching band was also evident in the acorn shell extract

spectrum, centered at approximately 1602 cm^{-1} (Wongsa et al. 2022; Yilmazer Keskin et al. 2024). Notably, the intensities of the bands near 1730 and 1614 cm^{-1} increased progressively with increasing cellulase pretreatment duration, suggesting enhanced uptake or stronger binding of phenolic compounds from the extract to the cotton substrate.

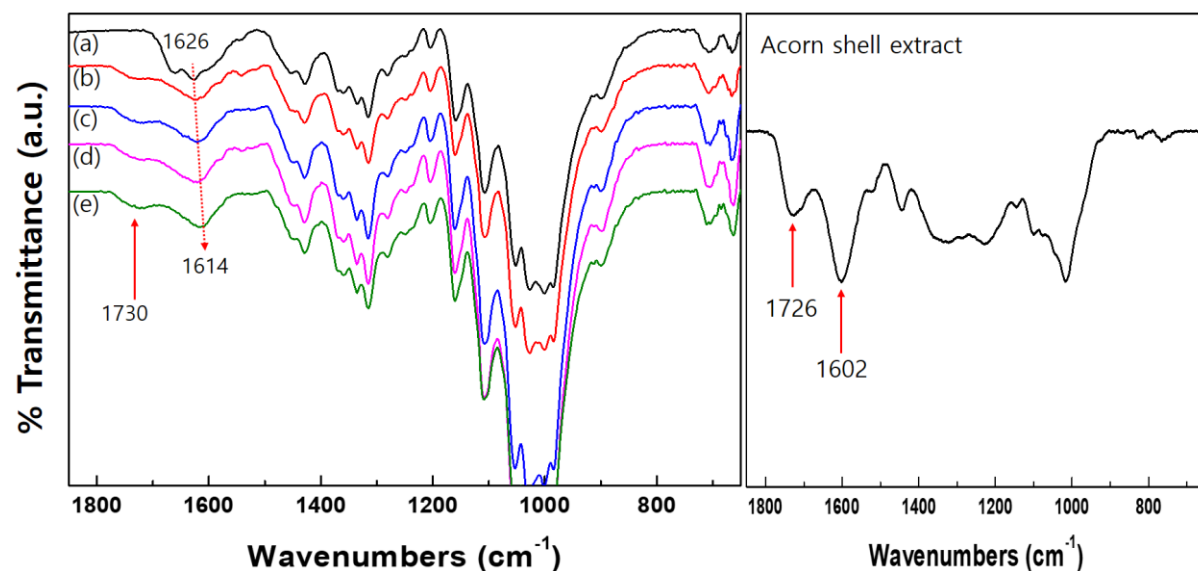


Fig. 6 FTIR spectra of acorn shell extract (right) and cotton fabrics pretreated with cellulase and finished with acorn shell extract (left): (a) pristine, (b) CP_1h_AE_COTTON, (c) CP_3h_AE_COTTON, (d) CP_6h_AE_COTTON, and (e) CP_24h_AE_COTTON

Functionalities and their wash fastness

Table 3 summarizes the antimicrobial efficacy and corresponding wash fastness of cotton fabrics pretreated with cellulase and subsequently finished with acorn shell extract, evaluated as a function of enzyme treatment duration. Chemical analysis of the acorn shell extract revealed a high concentration of bioactive compounds, with a TFC of 54.09 mg CE/g and TPC of 144.57 mg GAE/g . These concentrations were approximately 11-fold and 12-fold higher, respectively, than those reported for chestnut shell extract in a previous study (Hong 2021), highlighting the superior functional potential of acorn shell extract as a natural finishing agent.

Cotton fabrics treated with acorn shell extract exhibited excellent antimicrobial performance, achieving $> 99.9\%$ reduction rates against both Gram-negative *K. pneumoniae* and Gram-positive *S. aureus*, regardless of cellulase pretreatment. To evaluate the durability of antimicrobial functionality, treated fabrics were subjected to three laundering cycles in

accordance with KS K ISO 105 C06:2010, A2S (washing temperature: 25 ± 5 °C; washing time: 30 min; 0.14% aqueous neutral detergent solution; with 10 stainless steel balls). As shown in **Table 3**, the fabrics maintained a high level of antimicrobial efficacy against *S. aureus* after laundering. However, antimicrobial activity against *K. pneumoniae* decreased. Notably, samples with longer cellulase pretreatment retained higher antimicrobial efficacy against *K. pneumoniae*, suggesting that cellulase treatment enhanced the binding or retention of bioactive compounds during use, thereby improving wash durability.

Table 3 Antimicrobial efficacy and corresponding wash fastness of cotton fabrics.

Fabric samples	Bacteria reduction rate (%)			
	Before laundering		After three laundering cycles	
	<i>S. aureus</i>	<i>K. pneumoniae</i>	<i>S. aureus</i>	<i>K. pneumoniae</i>
CP_0h_AE_COTTON	> 99.9	> 99.9	99.7	26.8
CP_1h_AE_COTTON	> 99.9	> 99.9	> 99.9	38.5
CP_2h_AE_COTTON	> 99.9	> 99.9	> 99.9	43.3
CP_3h_AE_COTTON	> 99.9	> 99.9	> 99.9	54.6
CP_6h_AE_COTTON	> 99.9	> 99.9	> 99.9	68.3
CP_12h_AE_COTTON	> 99.9	> 99.9	> 99.9	68.4
CP_24h_AE_COTTON	> 99.9	> 99.9	> 99.9	73.9

Figure 7 presents the (a) antioxidant capacity and (b) corresponding wash fastness of cotton fabrics pretreated with cellulase and subsequently finished with acorn shell extract, evaluated as a function of enzyme treatment duration. Cotton fabrics treated with acorn shell extract exhibited a high level of antioxidant activity, demonstrating over 92% DPPH radical scavenging efficiency, regardless of cellulase pretreatment. This strong antioxidant performance is attributed to the presence of polyphenolic compounds with electron-donating, radical-scavenging activity. These compounds neutralized free radicals by donating hydrogen atoms or electrons, thereby contributing to the antioxidant functionality of the finished cotton fabrics (Valencia-Avilés et al. 2018; Gonzalez-Iglesias et al. 2025).

Accordingly, finishing with acorn shell extract imparted significant antioxidant functionality to cotton fabrics. However, antioxidant activity decreased markedly, by up to 53%, after three laundering cycles. This reduction occurred independently of cellulase pretreatment,

suggesting that the wash durability of antioxidant compounds from the extract was inherently limited under the tested laundering conditions.

Two mechanisms likely contributed to the loss of functional durability during laundering. First, polyphenolic compounds, including flavonoids and phenolic acids, typically bind to cotton cellulose surfaces through hydrogen bonding, van der Waals forces, and other weak noncovalent interactions; after deposition and oxidation, additional π - π interactions may also contribute within polyphenol-rich surface layers (Sarkar et al. 2014; Phan et al. 2015; Zhou et al. 2020). These interactions are inherently weak and reversible. During laundering, mechanical agitation, combined with water and detergent action, promoted the desorption and leaching of these compounds. Highly water-soluble antioxidants were particularly vulnerable to such losses, resulting in diminished functional performance after repeated washing.

Second, polyphenols are susceptible to oxidation and, for some subclasses, hydrolysis or isomerization under alkaline and thermal conditions. Because laundry detergents provide an alkaline wash environment, laundering at elevated temperatures can accelerate the degradation of phenolic structures, leading to a reduction in antioxidant or other bioactive performance (Narita and Inouye 2013; Honda et al. 2019; Pasquet et al. 2024). This degradation may have occurred both on the fabric surface and within the wash bath, thereby reducing the overall concentration of active compounds available to impart functional effects.

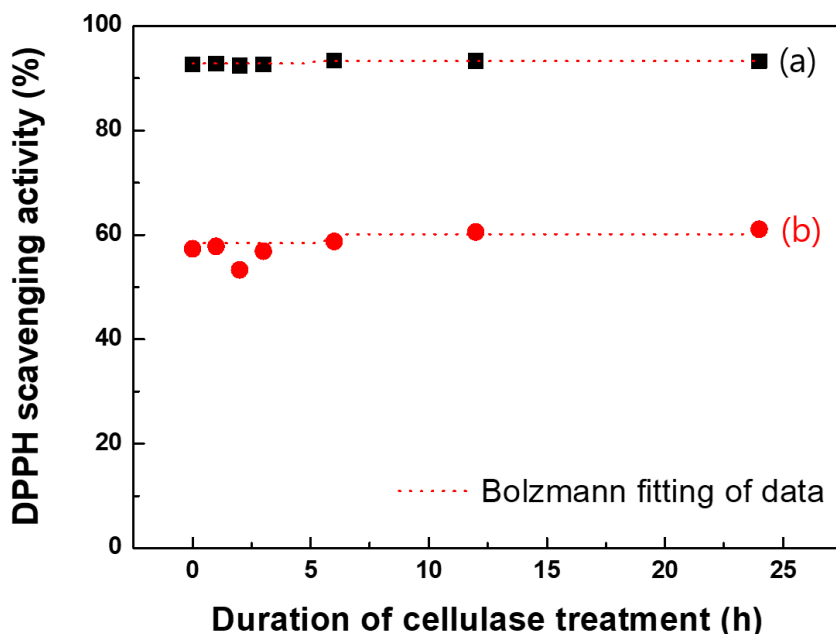


Fig. 7 Antioxidant capacity of cotton fabrics pretreated with cellulase and finished with acorn shell extract as a function of enzyme treatment duration: (a) before laundering, and (b) after three laundering cycles

Conclusion

This study demonstrated that acorn shell extract, a polyphenol-rich natural byproduct of *Quercus variabilis*, functioned as an effective biofinishing agent for cotton fabrics. Cellulase pretreatment enhanced the interaction between the extract and the cotton substrate, as reflected by changes in color characteristics, FTIR band intensities, and improved wash retention of antibacterial activity against *K. pneumoniae*.

As a result, the treated fabrics exhibited superior antioxidant and antibacterial properties, with > 92% DPPH radical scavenging activity and > 99.9% bacterial reduction. Notably, cellulase-pretreated fabrics exhibited increased FTIR peak intensities associated with phenolic compounds and improved wash durability of antibacterial activity, particularly against *K. pneumoniae*, whereas antioxidant durability remained limited.

Despite the decline in antioxidant activity after laundering, enzyme-assisted finishing contributed to improved retention of antibacterial functionality. The limited wash fastness is attributed to the noncovalent binding of phenolic compounds and their partial leaching under aqueous detergent conditions.

Future work should focus on developing fixation strategies, such as mordanting or biopolymer entrapment, to further improve laundering durability. Overall, these findings support the valorization of acorn shell waste as a sustainable, multifunctional finishing material for eco-conscious textile applications.

445 **Statements & Declarations**

446 **Ethical Approval:** Not applicable

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450 **Availability of data and materials:** The datasets used and/or analyzed during the current study are available
451 from the corresponding author upon reasonable request.

452 **Author contributions:** Kyung Hwa Hong conceived the study, prepared and analyzed all materials, and wrote
453 the original draft of the manuscript.

References

- Alasalvar C, Huang G, Bolling BW, Jantip PA, Pegg RB, Wong XK, Chang SK, Pelvan E, de Camargo AC, Mandalari G, Hossain A, Shahidi F (2025) Upcycling commercial nut byproducts for food, nutraceutical, and pharmaceutical applications: A comprehensive review. *Food Chem* 467:142222. <https://doi.org/10.1016/j.foodchem.2024.142222>
- Altıntig E, Altundag H, Tuzen M, Sari A, Sari A (2017) Effective removal of methylene blue from aqueous solutions using magnetic loaded activated carbon as novel adsorbent. *Chem Eng Res Des* 122:151–163. <https://doi.org/10.1016/j.cherd.2017.03.035>
- Brudzyńska P, Sionkowska A, Grisel M (2023) Cotton textile dyeing by plant-derived colorants in the presence of natural additives. *Fibers Polym* 24(10):3641–3655. <https://doi.org/10.1007/s12221-023-00332-3>
- Buschle-Diller G, Zeronian SH, Pan N, Yoon MY (1994) Enzymatic hydrolysis of cotton, linen, ramie, and viscose rayon fabrics. *Text Res J* 64(5):270–279. <https://doi.org/10.1177/004051759406400504>
- Gomez del Pulgar EMG, Saadeddin A (2014) The cellulolytic system of *Thermobifida fusca*. *Crit Rev Microbiol* 40(3):236–247. <https://doi.org/10.3109/1040841X.2013.776512>
- Gonzalez-Iglesias D, Rubio L, Martinez-Vazquez F, Castillo A, Celeiro M, Garcia-Jares C, Lores M (2025) Phytochemical and antioxidant comparison of *Quercus ilex* and *Quercus robur* acorn extracts obtained by matrix solid-phase dispersion. *RSC Adv* 15(16):12538–12546. <https://doi.org/10.1039/D4RA08675A>
- Grifoni D, Bacci L, Zipoli G, Albanese L, Sabatini F (2011) The role of natural dyes in the UV protection of fabrics made of vegetable fibres. *Dyes Pigments* 91(3):279–285. <https://doi.org/10.1016/j.dyepig.2011.04.006>
- Haji A, Naebe M (2020) Cleaner dyeing of textiles using plasma treatment and natural dyes: A review. *J Clean Prod* 265:121866. <https://doi.org/10.1016/j.jclepro.2020.121866>
- Hao L, Wang R, Liu J, Liu R (2012) The adsorptive and hydrolytic performance of cellulase on cationised cotton. *Carbohydr Polym* 89(1):171–176. <https://doi.org/10.1016/j.carbpol.2012.02.067>
- Harsito C, Prabowo AR, Prasetyo SD, Arifin Z (2021) Enhancement stability and color fastness of natural dye: A review. *Open Eng* 11(1):548–555. <https://doi.org/10.1515/eng-2021-0055>
- Honda S, Ishida R, Hidaka K, Masuda T (2019) Stability of Polyphenols under Alkaline Conditions and the Formation of a Xanthine Oxidase Inhibitor from Gallic Acid in a Solution at pH 7.4. *Food Sci Tech Res* 25:123–129. <https://doi.org/10.3136/fstr.25.123>
- Hong KH (2021) Sustainable functional finishing for cotton fabrics using chestnut shell extract. *Cellulose* 28(18):11729–11743. <https://doi.org/10.1007/s10570-021-04273-z>
- Hong KH (2024) Effect of UV irradiation on color and functionality of wool and cotton fabrics finished with spent coffee extract. *Cellulose* 31(9):5931–5946. <https://doi.org/10.1007/s10570-024-05948-z>
- Hoshino E, Shiroishi M, Amano Y, Nomura M, Kanda T (1997) Synergistic actions of exo-type cellulases in the hydrolysis of cellulose with different crystallinities. *J Ferment Bioeng* 84(4):300–306. [https://doi.org/10.1016/S0922-338X\(97\)89248-3](https://doi.org/10.1016/S0922-338X(97)89248-3)
- Huang J, Wang Y, Li C, Wang X, He X (2016) Anti-inflammatory oleanolic triterpenes from Chinese Acorns. *Molecules* 21(5):669. <https://doi.org/10.3390/molecules21050669>

- Ibrahim NA, El-Badry K, Eid BM, Hassan TM (2011) A new approach for biofinishing of cellulose-containing fabrics using acid cellulases. *Carbohydr Polym* 83(1):116–121.
<https://doi.org/10.1016/j.carbpol.2010.07.025>
- Ibrahim NA, Fahmy HM, Hassan TM, Mohamed ZE (2005) Effect of cellulase treatment on the extent of post-finishing and dyeing of cotton fabrics. *J Mater Process Technol* 160(1):99–106.
<https://doi.org/10.1016/j.jmatprotec.2004.04.370>
- Jabasingh SA, Sahu P, Yimam A (2016) Enviro-friendly biofinishing of cotton fibers using *Aspergillus nidulans* AJSU04 cellulases for enhanced uptake of Myrobalan dye from *Terminalia chebula*. *Dyes Pigments* 129:129–140. <https://doi.org/10.1016/j.dyepig.2016.02.019>
- Jajpura L, Rangi A, Khandual A (2020) Natural finishes, technologies and recent developments. In: Nayak R (ed.), *Sustainable technologies for fashion and textiles*, Woodhead Publishing Series in Textiles, Sustainable Technologies for Fashion and Textiles. Elsevier, Amsterdam, p 209–229.
<https://doi.org/10.1016/B978-0-08-102867-4.00010-4>
- Koh E, Hong KH (2014) Gallnut extract-treated wool and cotton for developing green functional textiles. *Dyes Pigments* 103:222–227. <https://doi.org/10.1016/j.dyepig.2013.09.015>
- Koh E, Hong KH (2017) Preparation and properties of cotton fabrics finished with spent coffee extract. *Cellulose* 24(11):5225–5232. <https://doi.org/10.1007/s10570-017-1466-8>
- Kuhad RC, Gupta R, Singh A (2011) Microbial cellulases and their industrial applications. *Enzyme Res* 2011:280696. <https://doi.org/10.4061/2011/280696>
- Leal Filho WL, Perry P, Heim H, Dinis MAP, Moda H, Ebhuoma E, Paço A (2022) An overview of the contribution of the textiles sector to climate change. *Front Environ Sci* 10:973102.
<https://doi.org/10.3389/fenvs.2022.973102>
- Martins RB, Gouvêas I, Nunes MC, Ferreira LM, Peres JA, Raymundo A, Barros AIRNA (2022) Acorn flour from holm oak (*Quercus rotundifolia*): Assessment of nutritional, phenolic, and technological profile. *Curr Res Food Sci* 5:2211–2218. <https://doi.org/10.1016/j.crfs.2022.11.003>
- Mateus C, Alonso-Esteban JI, Finimundy TC, Mandim F, Oliveira I, Babo P, Canadas RF, Ferreira ICFR, Barros L (2025) Exploring acorn shells: Phenolic composition and bioactive potential for sustainable valorization. *Ind Crops Prod* 226:120686. <https://doi.org/10.1016/j.indcrop.2025.120686>
- Narita Y, Inouye K (2013) Degradation kinetics of chlorogenic acid at various pH values and effects of ascorbic acid and epigallocatechin gallate on its stability under alkaline conditions. *J Agric Food Chem* 61:966–972.
<https://doi.org/10.1021/jf304105w>
- Pasquet PL, Julien-David D, Zhao M, Villain-Gambier M, Trébouet D (2024) Stability and preservation of phenolic compounds and related antioxidant capacity from agro-food matrix: Effect of pH and atmosphere. *Food Biosci* 57:103586. <https://doi.org/10.1016/j.fbio.2024.103586>
- Phan ADT, Netzel D, Wang D, Flanagan BM, D’Arcy BR, Gidley MJ (2015) Binding of dietary polyphenols to cellulose: Structural and nutritional aspects. *Food Chem* 171: 388–396.
<https://doi.org/10.1016/j.foodchem.2014.08.118>
- Rahman MM, Koh J, Hong KH (2022) Coloration and multi-functionalization of cotton fabrics using different combinations of aqueous natural plant extracts of onion peel, turmeric root, and pomegranate rind. *Ind Crops Prod* 188:115562. <https://doi.org/10.1016/j.indcrop.2022.115562>

- Rahman MM, Koh J, Hong KH (2024) Sustainable chitosan biomordant dyeing and functionalization of cotton fabrics using pomegranate rind and onion peel extracts. *J Nat Fibers* 21(1):2290856. <https://doi.org/10.1080/15440478.2023.2290856>
- Şahin Ö, Saka C (2013) Preparation and characterization of activated carbon from acorn shell by physical activation with H₂O–CO₂ in two-step pretreatment. *Bioresour Technol* 136:163–168. <https://doi.org/10.1016/j.biortech.2013.02.074>
- Sankarraj N, Nallathambi G (2018) Enzymatic biopolishing of cotton fabric with free/immobilized cellulase. *Carbohydr Polym* 191:95–102. <https://doi.org/10.1016/j.carbpol.2018.02.067>
- Sarkar D, Das S, Pramanik A (2014) A solution spectroscopy study of tea polyphenol and cellulose: effect of surfactants. *RSC Adv* 4:36196–36205. <https://doi.org/10.1039/c4ra04171b>
- Segal L, Creely JJ, Martin AE Jr, Conrad CM (1959) An empirical method for estimating the degree of crystallinity of native cellulose using the X-ray diffractometer. *Text Res J* 29(10):786–794. <https://doi.org/10.1177/004051755902901003>
- Seow YX, Tan YH, Mubarak NM, Kandedo J, Khalid M, Ibrahim ML, Ghasemi M (2022) A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications. *J Environ Chem Eng* 10(1):107017. <https://doi.org/10.1016/j.jece.2021.107017>
- Srivastava N, Srivastava M, Mishra PK, Gupta VK, Molina G, Rodriguez-Couto S, Manikanta A, Ramteke PW (2018) Applications of fungal cellulases in biofuel production: Advances and limitations. *Renew Sustain Energy Rev* 82:2379–2386. <https://doi.org/10.1016/j.rser.2017.08.074>
- Valencia-Avilés E, García-Pérez ME, Garnica-Romo MG, Figueroa-Cárdenas JD, Meléndez-Herrera E, Salgado-Garciglia R, Martínez-Flores HE (2018) Antioxidant properties of polyphenolic extracts from *Quercus laurina*, *Quercus crassifolia*, and *Quercus Scytophylla* bark. *Antioxidants (Basel)* 7(7):81. <https://doi.org/10.3390/antiox7070081>
- Vinha AF, Barreira JCM, Ferreira ICFR, Oliveira MBPP (2020) Therapeutic, phytochemistry, and pharmacology of acorns (*Quercus* Nuts): A review. *Bioactive compounds in underutilized fruits and nuts* Murthy HN, Bapat VA (eds). Springer, Cham, p 1–15. https://doi.org/10.1007/978-3-030-06120-3_46-1
- Vinha AF, Costa ASG, Barreira JCM, Pacheco R, Oliveira MBPP (2016) Chemical and antioxidant profiles of acorn tissues from *Quercus* spp.: Potential as new industrial raw materials. *Ind Crops Prod* 94:143–151. <https://doi.org/10.1016/j.indcrop.2016.08.027>
- Wongsa P, Phatikulrungsun P, Prathumthong S (2022) FT-IR characteristics, phenolic profiles and inhibitory potential against digestive enzymes of 25 herbal infusions. *Sci Rep* 12(1):6631. <https://doi.org/10.1038/s41598-022-10669-z>
- Yılmaz Keskin S, Avcı A, Fajriana Febda Kurnia H (2024) Analyses of phytochemical compounds in the flowers and leaves of *Spiraea japonica* var. *fortunei* using UV–vis, FTIR, and LC-MS techniques. *Heliyon* 10(3):e25496. <https://doi.org/10.1016/j.heliyon.2024.e25496>
- Yoo Y, Hong KH (2025) Effect of cellulase pre-treatment on finishing of cotton fabrics using spent coffee extract. *J Korean Soc Clothing Text* 49(4):805–815. <https://doi.org/10.5850/JKSCT.2025.49.4.805>
- Zhou J, Lin Z, Ju Y, Rahim MA, Richardson JJ, Caruso F (2020) Polyphenol-Mediated Assembly for Particle Engineering. *Acc Chem Res* 53:1269–1278. <https://doi.org/10.1021/acs.accounts.0c00150>

Figure legends

Fig. 1 SEM and azimuthal images of cotton fibers after cellulase treatment (R_q : root-mean-square roughness): (a) CP_0h_COTTON, (b) CP_1h_COTTON, (c) CP_6h_COTTON, and (d) CP_24h_COTTON

Fig. 2 XRD patterns of cotton fabrics after cellulase treatment: (a) pristine, (b) CP_1h_COTTON, (c) CP_2h_COTTON, (d) CP_3h_COTTON, (e) CP_6h_COTTON, (f) CP_12h_COTTON, and (g) CP_24h_COTTON

Fig. 3 XPS survey spectra of cotton fabrics (a) before and (b) after cellulase treatment for 24 h, illustrating changes in surface elemental composition

Fig. 4 TGA curves and reduction rates derived from derivative thermogravimetric (DTG) peak areas of cotton fabrics after cellulase treatment: (a) pristine, (b) CP_1h_COTTON, (c) CP_2h_COTTON, (d) CP_3h_COTTON, (e) CP_6h_COTTON, (f) CP_12h_COTTON, and (g) CP_24h_COTTON

Fig. 5 K/S values of cotton fabrics pretreated with cellulase and finished with acorn shell extract: (a) pristine, (b) CP_0h_AE_COTTON, (c) CP_1h_AE_COTTON, (d) CP_2h_AE_COTTON, (e) CP_3h_AE_COTTON, (f) CP_6h_AE_COTTON, (g) CP_12h_AE_COTTON, and (h) CP_24h_AE_COTTON

Fig. 6 FTIR spectra of acorn shell extract (right) and cotton fabrics pretreated with cellulase and finished with acorn shell extract (left): (a) pristine, (b) CP_1h_AE_COTTON, (c) CP_3h_AE_COTTON, (d) CP_6h_AE_COTTON, and (e) CP_24h_AE_COTTON

Fig. 7 Antioxidant capacity of cotton fabrics pretreated with cellulase and finished with acorn shell extract as a function of enzyme treatment duration: (a) before laundering, and (b) after three laundering cycles

Tables

Table 1 Maximum peak intensities obtained from XRD and crystallinity index of cotton fabrics after cellulase treatment

Fabric samples	I_{am}	I_{200}	CrI (%)
Pristine	15181	77817	80.49
CP_1h_COTTON	15506	70915	78.14
CP_2h_COTTON	16018	71695	77.66
CP_3h_COTTON	17086	69176	75.30
CP_6h_COTTON	16968	73090	76.78
CP_12h_COTTON	16561	72877	77.28
CP_24h_COTTON	15528	60904	74.50

Table 2 Colorimetric data of cotton fabrics after cellulase pretreatment and acorn shell extract finishing

Duration of cellulase treatment (h)	Cotton fabrics pretreated with cellulase				Cotton fabrics pretreated with cellulase and finished with acorn shell extract			
	L^*	a^*	b^*	ΔE^*_{ab}	L^*	a^*	b^*	ΔE^*_{ab}
0	91.55	0.13	1.20	-	66.89	7.08	24.56	34.67

1	91.49	0.12	1.58	0.38	64.74	7.68	24.80	36.51
2	91.50	0.11	1.56	0.36	66.15	7.46	24.97	35.55
3	91.26	0.13	1.53	0.44	64.99	7.59	25.11	36.51
6	91.32	0.10	1.56	0.43	65.10	7.12	24.74	36.09
12	91.52	0.11	1.42	0.22	64.44	7.69	25.27	37.03
24	91.55	0.12	1.32	0.12	63.34	7.85	25.73	38.17

$$\Delta E^*_{ab}(\text{total color difference value}) = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$$

Table 3 Antimicrobial efficacy and corresponding wash fastness of cotton fabrics.

Fabric samples	Bacteria reduction rate (%)			
	Before laundering		After three laundering cycles	
	<i>S. aureus</i>	<i>K. pneumoniae</i>	<i>S. aureus</i>	<i>K. pneumoniae</i>
CP_0h_AE_COTTON	> 99.9	> 99.9	99.7	26.8
CP_1h_AE_COTTON	> 99.9	> 99.9	> 99.9	38.5
CP_2h_AE_COTTON	> 99.9	> 99.9	> 99.9	43.3
CP_3h_AE_COTTON	> 99.9	> 99.9	> 99.9	54.6
CP_6h_AE_COTTON	> 99.9	> 99.9	> 99.9	68.3
CP_12h_AE_COTTON	> 99.9	> 99.9	> 99.9	68.4
CP_24h_AE_COTTON	> 99.9	> 99.9	> 99.9	73.9