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Eco-friendly Functionalization of Bamboo-based Union Fabrics with *Ficus religiosa* Bark Extract: Antimicrobial, Antifungal, and UV-Protective Performance

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ABSTRACT

This study investigates the use of *Ficus religiosa* (sacred fig) bark extract as a sustainable finishing agent for bamboo–linen and bamboo–cotton union fabrics. Extracts prepared with aqueous, methanolic, and acetone solvents were evaluated for antimicrobial, antifungal, and ultraviolet (UV) protective properties, along with wash durability. The aqueous extract at 5% concentration showed the most consistent antibacterial activity against *Escherichia coli* and *Bacillus subtilis* and provided complete resistance to *Aspergillus niger*. Treated fabrics exhibited enhanced UV protection, achieving "excellent" ultraviolet protection factor (UPF) ratings compared to untreated controls. While antibacterial effects diminished after repeated laundering, antifungal resistance and UV protection were largely retained. Phytochemical analysis revealed high levels of flavonoids and phenolics, supporting the observed bioactivity. The treatment preserved fabric structure and improved crease recovery and insulation. These findings demonstrate the potential of *F. religiosa* bark extract as an eco-friendly alternative to synthetic finishes for multifunctional protective textiles.

1. Introduction

Union fabrics, created by interlacing two different fibers in warp and weft directions, allow the combined advantages of each component to be harnessed within a single textile. Bamboo is recognized for its ecological sustainability, softness, air permeability, and inherent antibacterial as well as UV-protective features [1]. Flax (linen) contributes mechanical strength together with natural UV shielding [1], whereas cotton remains a dominant choice in apparel and household textiles because of its comfort, moisture regulation, and durability [2]. When blended in union structures, these fibers provide opportunities to engineer multifunctional fabrics with improved performance and environmental benefits [1].

Growing consumer awareness has shifted demand toward sustainable and health-oriented textiles. The conventional chemical finishing agents used to provide antimicrobial or UV protection often raise concerns regarding toxicity, skin irritation, and environmental persistence. This has stimulated research into alternatives that are safer, biodegradable, and compatible with eco-friendly processing [3,4]. In this context, plant-derived extracts are attractive because they are rich in secondary metabolites such as phenolics, flavonoids, tannins, and saponins, which display broad biological activity [4,5].

Among such plants, *Ficus religiosa* (sacred fig or Peepal) holds considerable medicinal importance in South Asia. Traditionally, its bark has been employed to manage inflammation, microbial infections, and oxidative stress-related ailments [6]. Phytochemical studies confirm that the bark is abundant in flavonoids, tannins, and phenolic compounds, including gallic acid, catechin, epicatechin, epigallocatechin gallate, and ellagic acid, which are strongly associated with antioxidant activity [5]. Earlier research has emphasized pharmacological aspects such as wound healing, antioxidant, anti-inflammatory, and analgesic properties [6].

The application of *F. religiosa* extracts in textile finishing, however, has not been widely investigated. Utilizing the bark extract for functionalization of union fabrics could provide a sustainable alternative to conventional chemical finishes by merging the natural qualities of fibers with bio-based activity. Beyond antimicrobial protection, the phenolic and flavonoid components may also contribute to UV resistance and improved wash durability, suggesting applications in healthcare, sportswear, and protective clothing [7]. The present work therefore examines the potential of *F. religiosa* bark extract in bamboo-based union fabrics, focusing on its phytochemical profile [5], antimicrobial efficacy [4,7] UV-protective properties [7] and durability after repeated laundering [7]. By linking traditional plant knowledge with modern textile science, this study highlights a promising route toward eco-friendly, multifunctional textiles.

2. Experimental Methods

2.1 Fabric Construction

Two union fabrics were produced on a manual frame loom at the Karnati Murali Handloom Unit, Sathenapalle [8,9]. For the bamboo/linen fabric, 2/20s bamboo yarn was doubled on a traditional charkha to obtain 2/40s yarn, while 40 Lea linen yarn was prepared in the same way. Bamboo served as the warp and linen as the weft. Weaving was carried out on a 54-inch loom using a 40-count reed, yielding fabric 42 inches wide and 20 m long. For the bamboo/cotton fabric, 2/40s bamboo yarn (warp) was combined with 2/20s cotton yarn (weft) and woven with a 50-count reed, producing a 45-inch-wide fabric of the same length. Each fabric type was completed within approximately 10 days of weaving.

2.2 Laboratory Setup

The experimental work was conducted across four facilities: the Department of Apparel and Textiles (PJTSAU), the Centre for Nanoscience and Technology (JNTUH), the Department of Biotechnology (IST-JNTUH), and the Department of Veterinary Microbiology (PVNRTVU).

2.3 Selection of Plant Source

Ficus religiosa (sacred fig/Peepal) was selected as the plant source owing to its well-established medicinal significance in South Asia. Traditionally, different parts of the tree, particularly the bark, have been used to manage inflammation, microbial infections, skin disorders, ulcers, and oxidative stress–related conditions [10]. Phytochemical investigations have confirmed that the bark contains flavonoids, tannins, phenolics, saponins, and other bioactive constituents such as terpenoids and steroids [5]. These metabolites are strongly associated with antimicrobial, antioxidant, and anti-inflammatory effects [5,10]. More recently, the bark extract has also been employed in textiles as a natural dye and finishing agent, imparting antibacterial and UV-protective

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properties to fabrics [11]. The combination of traditional therapeutic relevance, phytochemical richness, and demonstrated textile applicability makes *F. religiosa* bark a sustainable and promising candidate for developing bio-functional textile finishes.

2.4 Preparation of Bark Powder

Ficus religiosa bark was collected from the local market. The dried bark was first broken into small fragments using a stone grinder and then ground to a fine powder with an electric mixer grinder. To obtain uniform particle size, the powder was sieved repeatedly until a smooth consistency was achieved. The prepared bark powder was stored in airtight containers at room temperature to preserve its quality.

Ficus religiosa Bark Bark Powder

Fig. 1 Plant source

2.5 Preparation of Ficus religiosa Bark Extract

Bark extracts of *Ficus religiosa* were prepared using maceration with organic solvents and hot aqueous extraction. Methanol, acetone, and sterilized distilled water were selected as solvents, as they are widely used for recovering phenolics and flavonoids from plant materials [12].

For methanol and acetone extraction, bark powder samples (5, 10, and 20 g) were weighed into 100 mL of solvent in sealed conical flasks. The mixtures were stirred at 550 rpm for 24 h, then left undisturbed for another 24 h to promote sedimentation. Supernatants were separated by filtration through Whatman No. 1 paper and stored in borosilicate glass containers.

For aqueous extraction, the same quantities of bark powder were mixed with 100 mL of sterilized distilled water and heated to ~99 °C under continuous stirring for 30 min. After cooling to room temperature, the solutions were filtered (Whatman No. 1), and the filtrates were collected in borosilicate containers and refrigerated until further use [13]. The details of different solvents and concentrations used for preparing bark extracts is given in Table 1.

Table 1 Preparation of *F. religiosa* extracts

Name of the Source	Solvent	Concentrations
Ficus religiosa bark	Methanol	5%, 10%, 20%
	Acetone	5%, 10%, 20%
	Distilled water	5%, 10%, 20%

2.6 Application of F. religiosa Aqueous Extract on Union Fabrics

2.6.1 Pre-Treatment with Cross-Linking Agent

Citric acid was employed as an eco-friendly cross-linking agent to improve the binding of *Ficus religiosa* bark extract onto the union fabrics. A 9% (w/v) citric acid solution was applied by soaking the fabrics for 90 minutes, followed by a pad–dry–cure sequence. During padding, the fabric was passed through the mangle at 15 m/min under a pressure of 15 kg/cm^2, ensuring 100% wet pick-up. The samples were kept wrinkle-free during passage, then dried in shade prior to further finishing.

The use of citric acid as a non-formaldehyde cross-linker for cellulose is well established. Its action is based on esterification between carboxyl groups of citric acid and hydroxyl groups of cellulosic fibers, enabling durable finishes [14]. Applications of citric acid in textile finishing through pad–dry–cure treatments to impart durable press and antimicrobial effects have been demonstrated in cotton fabrics [15].

Bamboo-based union fabric samples, pretreated with citric acid, were finished with *Ficus religiosa* bark extracts prepared in different solvents and concentrations. Application was carried out using a material-to-liquor ratio (MLR) of 1:40, calculated on the basis of fabric weight. The fabrics were immersed in the extract solution for 60 minutes to enable adequate absorption, followed by a conventional pad–dry–cure process to fix the bioactive compounds onto the fibers. This approach is consistent with earlier reports on the application of natural plant extracts to textiles through exhaust and pad–dry–cure methods [16].

2.6.2 Assessment of Antibacterial Activity

The antibacterial efficacy of the finished fabrics was evaluated against *Escherichia coli* (Gram-negative) and *Bacillus subtilis* (Gram-positive) using the AATCC 147-2004 parallel streak method, while antifungal activity was tested against *Aspergillus niger* according to the AATCC 30-2004 (Part III) protocol [17,18].

For antibacterial assays, sterilized fabric swatches (25 mm × 50 mm) were placed on nutrient agar plates inoculated with *E. coli* along five parallel streaks. Following incubation at 37 ± 2 °C for 18–24 h, bacterial growth inhibition beneath and around the specimens was recorded. The inhibition width (W) was determined using:

$$W=T-D^2W = (T - D)*W/2 =2T-D$$

where *W* is the inhibition zone (mm), *T* the total diameter of the clear zone including the specimen, and *D* the specimen dimension. Antibacterial performance was expressed as the mean inhibition width across all streaks. This modified parallel streak technique is widely employed in textile research to assess antibacterial finishes derived from natural extracts and other functional treatments [17,18].

2.6.3 Assessment of Antifungal Activity

The antifungal performance of control and treated fabric samples was assessed against *Aspergillus niger* following AATCC Test Method 30 (Part III, 2004) [20]. Circular fabric specimens (10 mm diameter) were placed on agar plates inoculated with *A. niger* spores and incubated at ambient temperature for seven days. After incubation, fungal colonization of the specimen surfaces was evaluated visually and graded on a five-point scale, where 0 corresponded to >90% colonization, scores 1–3 indicated progressively lower levels of fungal coverage, and 4 denoted complete absence of visible fungal growth. This procedure is widely applied in studies investigating antifungal finishes on cellulosic fabrics, particularly those based on natural bioactive agents.

2.6.4 Determination of Ultraviolet Protection Factor (UPF)

The ultraviolet protection factor (UPF), which expresses the ability of a fabric to attenuate ultraviolet (UV) radiation, was determined using UV–Vis diffuse reflectance spectroscopy (DRS). Measurements were carried out on a Perkin Elmer Lambda 750 spectrophotometer fitted with an integrating sphere, using barium sulfate ($BaSO_4$) as the reflectance standard. Spectra were recorded in the range of 250–800 nm.

For each fabric sample, transmittance was measured at multiple points to minimize variability. Both untreated controls and treated fabrics were tested in triplicate. UPF values were calculated according to the Australia/New Zealand Standard AS/NZS 4399, which is internationally recognized for assessing UV protective textiles [19]. The computation was based on the total spectral transmittance of the fabric, using the following expression:

$$UPF = \frac{\sum_{\lambda=290}^{400} E_\lambda S_\lambda \Delta_\lambda}{\sum_{\lambda=290}^{400} E_\lambda S_\lambda T_\lambda \Delta_\lambda}$$

where:

E_λ = relative erythemal spectral effectiveness (unitless),
S_λ = solar UVR spectral irradiance (W·m^{-2}·nm^{-1}),
T_λ = spectral transmittance of the fabric,
Δ_λ = wavelength interval (nm), λ = wavelength (nm).

The resulting UPF values were interpreted according to AS/NZS 4399 classification, where UPF 15–24 corresponds to "good," 25–39 to "very good," and ≥40 to "excellent" protection [20,21].

2.7 Phytochemical Characterization of F. religiosa Bark Extract

Phytochemical screening was conducted to identify the principal bioactive constituents in the *Ficus religiosa* bark extract that demonstrated the highest antimicrobial activity (FAQ5%). Specific emphasis was placed on flavonoids, tannins, and phenolic compounds, which are recognized for their antimicrobial, antioxidant, and crosslinking properties in natural product applications [10].

Standard qualitative protocols, including colorimetric assays and spectroscopic techniques, were employed to detect and confirm the presence of these phytochemical groups.

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2.7.1 Qualitative (FTIR) Phytochemical Analysis

Fourier-transform infrared (FTIR) spectroscopy was carried out to identify the functional groups present in the *Ficus religiosa* bark extract that may contribute to its bioactivity. The analysis was performed using an FTIR spectrophotometer equipped with an attenuated total reflectance (ATR) accessory. Dried extract was placed directly in the sample holder, and spectra were recorded in the mid-infrared region (4000–400 cm^{-1}). Characteristic absorption peaks corresponding to O–H stretching (phenolics), C=O stretching (tannins), and C–O–C vibrations (flavonoids) were assigned with reference to published spectral libraries. These functional groups are consistent with earlier FTIR studies of *F. religiosa* bark, confirming the presence of polyphenolic and flavonoid compounds associated with antimicrobial activity [22,23].

2.7.2 Quantitative Phytochemical Analysis

The *Ficus religiosa* bark extract was analyzed for major phytochemicals associated with antimicrobial and antioxidant activity, including saponins, tannins, phenols, flavonoids, and total antioxidant capacity. Saponins were quantified using a modified vanillin–sulfuric acid method, where 50 µL of extract was reacted with vanillin reagent and 72% sulfuric acid. The mixture was heated at 60 °C for 10 min, cooled, and absorbance recorded at 544 nm. Results were expressed as mg diosgenin equivalents per gram extract (mg DE/g).

Tannins were estimated via the vanillin–HCl method. About 0.2 g of sample was extracted in 1% HCl–methanol, and the supernatant was treated with vanillin–HCl reagent. After incubation at 30 °C for 20 min, absorbance was measured at 500 nm, and tannic acid was used as standard. Phenolic content was determined by the Folin–Ciocalteu assay. Twenty micrograms of extract was treated with diluted Folin–Ciocalteu reagent followed by 20% sodium carbonate. After incubation in the dark for 40 min, absorbance was measured at 725 nm. Results were expressed as mg gallic acid equivalents per gram extract (mg GAE/g) [24].

Flavonoids were quantified using the aluminum chloride colorimetric assay. The extract was sequentially mixed with sodium nitrite, aluminum chloride, and sodium hydroxide solutions. Absorbance was taken at 510 nm after 15 min, with concentrations calculated against a rutin standard curve (mg RE/g). Total antioxidant capacity was assessed by the phospho-molybdenum method. Extract solution was combined with reagent (sulfuric acid, sodium phosphate, ammonium molybdate) and incubated at 95 °C for 90 min. Absorbance was measured at 695 nm, and results were expressed as mg ascorbic acid equivalents [25].

2.8 Assessment of Durability of Multi-functional Textile Finish

Wash fastness of the treated fabrics was evaluated according to the Bureau of Indian Standards (IS 687-1979) method using a Launder-O-meter at the NDTQL Laboratory, Department of Apparel and Textiles, PJTSAU. Durability of the antimicrobial finish was assessed after 1, 5, 10, and 15 wash cycles. At each stage, antibacterial activity against *Escherichia coli* and *Bacillus subtilis* was measured using the parallel streak method, while antifungal efficacy was examined against *Aspergillus niger*.

The treated fabric samples (FUF1 and FUF2) were tested up to 15 wash cycles. Antimicrobial performance was determined at each wash interval, and the retention of UV protective properties was assessed in parallel following the Australian/New Zealand Standard AS/NZS 4399 protocols. This combined approach has been used in earlier studies evaluating the durability of antimicrobial and UV protective finishes on cotton and blended fabrics [26].

2.8.1 Assessment of Textile Properties

The physical and mechanical properties of the fabrics were evaluated before and after treatment with *Ficus religiosa* bark extract, following national and international standard test methods (Table 2).

Table 2 Standard methods for testing textile properties [27]

Textile property	Test method Standard
Fabric weight	BIS NO. 1964-1970.
Yarn count	IS NO. 1315-1977
Fabric thickness	ISI 1963-1969
Fabric stiffness	BIS 6490-1971
Crase recovery	IS 4681-1968
Drapability	BIS 8357 –1957
Air permeability	ASTM 737-1975 & BIS 11056-1984.
Thermal conductivity	ASTM D-1518-64
Water repellency	ISI 390-1975
Tear strength	IS 6489- 1971
Pilling resistance	ISO 12945-2:2002

2.8.2 Statistical Analysis

Experimental data for untreated control samples and fabrics treated with *Ficus religiosa* bark extracts (FUF1 and FUF2) were tabulated and analysed statistically. Results were expressed as mean ± standard deviation (SD). Significance of differences between control and treated samples was evaluated using Welch's *t*-test, a robust variation of Student's *t*-test that does not assume equal variances [28].

3. Results and Discussion

3.1 Antimicrobial Assessment

Optimization of Concentration of Ficus religiosa Bark Extract Based on Antimicrobial Test Results

Bark extracts of *Ficus religiosa* (methanolic, acetone, and aqueous; FME, FAE, and FAQE) at concentrations of 5%, 10%, and 20% were applied to fabric samples (UF1 and UF2) and evaluated against *Escherichia coli* and *Bacillus subtilis*. The results are furnished in Table 3.

The untreated controls (CUF1 and CUF2) showed no inhibition zones, confirming the absence of inherent antibacterial activity. Among the methanol extracts, the 5% concentration produced moderate inhibition, with maximum activity against *E. coli* (3.75 mm in CUF1) and *B. subtilis* (2.83 mm in CUF1). Higher concentrations (10% and 20%) did not improve activity consistently, suggesting a saturation effect beyond which efficacy does not increase. Acetone extracts gave variable responses, with the 10% concentration showing relatively better activity, especially against *E. coli* (3.30 mm in CUF2) and *B. subtilis* (2.50 mm in CUF2).

The aqueous extracts exhibited the most effective and consistent results, particularly at 5% concentration, where *E. coli* inhibition reached 6.30 mm (CUF2) and *B. subtilis* inhibition 3.42 mm (CUF2). Antimicrobial activity decreased at higher concentrations (20%), possibly due to reduced absorption or deposition of active molecules on the fiber surface.

Taken together, these results indicate that aqueous bark extracts at 5% concentration provide superior antibacterial performance compared to methanol or acetone extracts. Therefore, FAQE 5% was chosen as the optimized concentration for subsequent experiments [10,29].

Table 3 Antibacterial activity of bark extracts at different concentrations (Average ZOI in mm of 5 readings)

Bark Extract	*E. coli* (CUF1)	*E. coli* (CUF2)	*B. subtilis* (CUF1)	*B. subtilis* (CUF2)
Control (CUF)	0.00	0.00	0.00	0.00
FME 5%	3.75	1.53	2.83	2.76
FME 10%	0.92	1.90	1.25	1.90
FME 20%	3.08	1.53	0.80	3.20
FAE 5%	1.53	0.90	1.90	0.90
FAE 10%	2.81	3.30	1.50	2.50
FAE 20%	2.67	1.80	1.23	1.28
FAQE 5%	3.03	6.30	3.33	3.42
FAQE 10%	1.90	3.73	1.40	2.50
FAQE 20%	0.90	0.10	3.30	1.30

Descriptive statistics were applied to evaluate antibacterial test results, with mean values and standard deviations (SD) calculated (Table 4). The untreated fabrics showed no inhibition zones, confirming the absence of inherent antibacterial activity. Treated samples displayed slightly higher average inhibition against *E. coli* (2.06–2.11 mm) compared to *B. subtilis* (1.75–1.98 mm), indicating greater sensitivity of the Gram-negative strain. The higher SD observed in *E. coli* CUF2 (1.90) reflects variability among solvent–concentration treatments, particularly the pronounced effect of the aqueous 5% extract. In contrast, inhibition of *B. subtilis* was more uniform, though generally lower in magnitude. These results suggest that solvent choice and concentration significantly influence the antibacterial response of *Ficus religiosa* bark on union fabrics [20].

Table 4 Descriptive Statistics of Antibacterial Activity

Group	Mean ZOI (mm)	SD (mm)
E. coli (CUF1)	2.06	1.20
E. coli (CUF2)	2.11	1.90
B. subtilis (CUF1)	1.75	1.09
B. subtilis (CUF2)	1.98	1.09

3.2 Antifungal Test results

The antifungal performance of treated and control fabrics was evaluated against *Aspergillus niger* using a 0–4 rating scale, where 0 indicates poor resistance (>90% surface colonization) and 4 represents excellent resistance (no visible growth). The results are shown in Table 5.

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Table 5 Antifungal activity of bark extract-treated fabrics

Bark Extract	Sample	Rating	Sample	Rating
Control (CUF) (No extract treatment)	CUF1	0	CUF2	0
FAQE 5%	CUF1	4	CUF2	4

The untreated controls (CUF1 and CUF2) were completely colonized by the fungus, whereas fabrics finished with 5% aqueous *F. religiosa* bark extract (FAQE) achieved the maximum rating (4), indicating full resistance to *A. niger* growth [18].

3.3 UV Protective Property Assessment

The ultraviolet protection factor (UPF) of untreated and treated union fabrics was assessed following the Australia–New Zealand standard AS/NZS 4399:1996. Spectral measurements were obtained using a Shimadzu UV3101 PC UV–VIS–NIR spectrophotometer across 300–900 nm. UPF values were calculated from the spectral transmittance data, solar UV irradiance, and transmission bandwidth. Percentage transmittance of UV-A and UV-B was also recorded, and fabrics were classified according to the standard UPF rating system. The results are given in Table 6.

Table 6 UV protective properties of bark extract-treated fabrics

Extract	Sample	% Transmittance (UVA)	% Transmittance (UVB)	UPF Value	UPF Range	UPF Rating
Control	CUF1	25.20	24.60	23	<25	Good
Control	CUF2	25.60	27.71	25	<25	Good
FAQE	FUF1	53.82	40.44	46.75	40–50+	Excellent
	FUF2	52.00	27.06	68.59	50+	Excellent

The untreated control fabrics (CUF1 and CUF2) showed relatively high UV-A and UV-B transmittance (25–28%), corresponding to UPF values of 23–25. According to AS/NZS 4399:1996, these fall within the "good" category, which is inadequate for high-protection applications.

In contrast, fabrics treated with the aqueous bark extract (FAQE) displayed a substantial improvement in UV shielding. FUF1 recorded a UPF of 46.75 ("40–50+" category), while FUF2 achieved a UPF of 68.59 ("50+" category). Both values are classified as "excellent" protection.

The enhanced UV resistance can be attributed to phenolic and flavonoid compounds in *F. religiosa* bark, which effectively absorb and scatter UV radiation. These results demonstrate that aqueous bark extract treatment can upgrade union fabrics from moderate to excellent UV-protective materials, making them suitable for protective and outdoor textiles. Welch's *t*-test was used to compare the UV protection of control and treated fabrics (Table 7).

Table 7 Statistical comparison of Control vs. FAQE-treated fabrics

Parameter	Control Mean	FAQE Mean	*t*-statistic	*p*-value
UVA Transmittance	25.40	52.91	−29.53	0.016*
UVB Transmittance	26.16	33.75	−1.11	0.454
UPF Value	24.00	57.67	−3.07	0.197

*Significant at $p < 0.05$

The analysis revealed a significant reduction in UVA transmittance ($p < 0.05$) for treated fabrics, confirming the strong UVA-blocking effect of *Ficus religiosa* bark extract. No significant differences were observed for UVB or overall UPF values. These findings suggest that the extract contributes mainly to UVA absorption, thereby improving fabric protection.

3.4 Phytochemical Analysis

The FTIR spectrum of *Ficus religiosa* bark extract showed (Fig. 2 and Table 8) characteristic absorption bands at 503.7 cm^{-1} (metal–oxygen bond vibrations), 1012.35 cm^{-1} (C–O stretching of alcohols, ethers, esters, or carboxylic acids), 1112.91 cm^{-1} (C–O–C stretching of ethers/cyclic ethers), 1461.01 cm^{-1} (CH_2/CH_3 bending of alkanes), 1662.11 cm^{-1} (C=C stretching of alkenes or aromatic groups), 2365.06 cm^{-1} (CO_2), 2835.94 cm^{-1} (C–H stretching of alkanes), and 3315.53 cm^{-1} (O–H stretching of alcohols, phenols, or carboxylic acids). These signals confirm the presence of phenolic, alcoholic, and aromatic compounds, which are consistent with earlier FTIR characterizations of *F. religiosa* bark [29].

The aqueous bark extract of *Ficus religiosa* contained a notably high flavonoid concentration (6130 mg QE/100 g), consistent with its strong antimicrobial potential, as flavonoids are effective against bacteria, fungi, and viruses. Phenolic compounds were also abundant (219.42 mg GAE/100 g), contributing bactericidal and fungicidal effects that likely act synergistically with flavonoids. Saponins (6.72%) and tannins (3.65 mg TAE/100 g) were present in lower amounts but are known to enhance antimicrobial efficacy through membrane disruption, protein precipitation, and enzyme inhibition. The extract also showed moderate antioxidant capacity (320.69 µg/mL GAE/100 g), which may further support microbial inhibition by reducing oxidative stress. Together, these metabolites explain the strong antibacterial and antifungal activity observed in treated union fabrics, with flavonoids and phenols as the primary contributors [29].

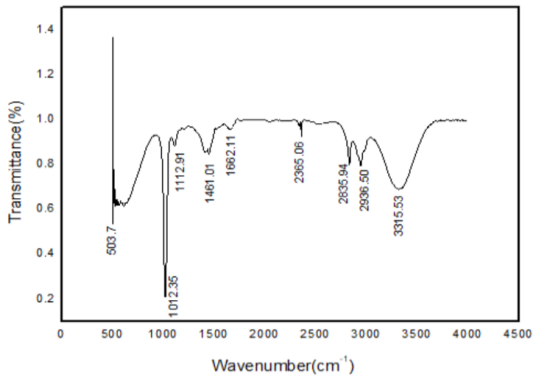

Fig. 2 FTIR Analysis of *Ficus religiosa* Bark Extract

Table 8 FTIR Characterization of FAQE5%

Peaks, cm^{-1}	Functional Groups	Bioactive Compounds
503.7	metal oxygen bonds bending	Presence of aromatic compounds
1012.35	C-O stretching	alcohols, ethers, esters, and carboxylic acids
1112.91	C-O-C stretching	Ethers or cyclic ethers
1461.01	CH_2 or CH_3 groups	Alkanes, alkyl groups
1662.11	C=C stretching	Alkenes or aromatic compounds
2365.06	presence of CO_2, other atmospheric gases	Presence of overtones and combinations bands
2835.94	C-H stretching	Alkenes
3315.53	O-H stretching	Alcohols, phenols, arboxylic acids

Table 9 Quantitative phytochemical composition of FAQE 5%

Sample	Parameter	Quantity
FAQE5%	Total antioxidant activity	320.69 µg/mL GAE/100 g
	Saponins	6.72 %
	Flavonoids	6130.00 mg QE/100 g
	Phenols	219.42 mg GAE/100 g
	Tannins	3.65 mg TAE/100 g

3.5 Durability Assessment of Multi-functional Textile Finish
Wash Durability of Antimicrobial and Antifungal Activity

The durability of the antimicrobial finish developed using 5% FAQE was assessed against *Escherichia coli*, *Bacillus subtilis*, and *Aspergillus niger* after repeated wash cycles (1, 5, 10, and 15 washes). Antibacterial activity expressed as zone of inhibition (ZOI, mm), antifungal resistance was recorded on a standard 0–4 rating scale. Results are given in Table 10.

Table 10 Durability of FAQE (5%) antimicrobial finish on treated fabrics

No. of wash	*E. coli* (ZOI in mm)				*Bacillus subtilis* (ZOI in mm)				*A. niger* (Rating)			
	CUF1	PUF1	CUF2	PUF2	CUF1	PUF1	CUF2	PUF2	CUF1	PUF1	CUF2	PUF2
1	0.00	0.56	0.00	0.40	0.00	0.25	0.00	0.30	0	4	0	4
5	0.00	0.15	0.00	0.38	0.00	0.21	0.00	0.41	0	4	0	4
10	0.00	0.55	0.00	0.86	0.00	0.18	0.00	0.15	0	3	0	4
15	0.00	0.17	0.00	0.12	0.00	0.11	0.00	0.15	0	3	0	2

The antibacterial effect of FAQE-treated fabrics declined with repeated laundering. In FUF1, inhibition against *E. coli* fell from 0.56 mm after the first wash to 0.17 mm after 15 washes, while activity against *B. subtilis* decreased from 0.25 mm to 0.11 mm. FUF2 showed fluctuating responses, with inhibition against *E. coli* peaking at 0.86 mm after 10 washes before declining to 0.12 mm at 15 washes; for *B. subtilis*, activity reached 0.41 mm after 5 washes but dropped to 0.15 mm by 15 washes. After 15 cycles, both fabrics retained only minimal antibacterial activity, indicating moderate wash fastness. Antifungal resistance was more durable. FUF1 retained the maximum rating (4) against *A. niger* through 5 washes, decreasing to 3 after 10–15 washes. FUF2 sustained a rating of 4 up to 10 washes and 3 after 15 washes. These findings show that although antibacterial activity diminished rapidly, antifungal performance remained comparatively more stable across laundering cycles [16].

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3.6 Wash Durability of UV Protective Property

The ultraviolet protection factor (UPF) of untreated and FAQE5%-treated fabrics was evaluated after 1, 5, 10, and 15 wash cycles. Results are expressed in terms of % transmittance (UVA and UVB), UPF value, and corresponding UPF rating (Table 11).

The untreated controls (CUF1 and CUF2) showed low UPF values (23–25), corresponding to a "good" protection rating. In contrast, FAQE 5%–treated fabrics exhibited durable UV resistance. For FUF1, UPF decreased from 294.12 after the first wash to 54.14 after 15 washes, yet the protective rating consistently remained "excellent." FUF2 declined from 77.93 to 43.13 across the same washing sequence, with its rating shifting from "excellent" to "very good." The variation between fabrics is likely due to structural factors such as fabric thickness, which strongly influences UV transmittance. Overall, the results indicate that the FAQE finish imparts wash-resistant UV protection, maintaining functional performance even after 15 laundering cycles (Table 12)

Table 11 Durability assessment results of UV protective finish for FAQE 5%

sample	% transmittance (UFA)	% transmittance (UFB)	UPF Value	UPF Range	UPF Rating
CUF1	25.20	24.60	23	< 25	good
CUF2	25.60	27.71	25	< 25	good
FUF1 1W	40.60	29.71	294.12	50+	Excellent
FUF2 1W	41.36	0.94	77.93	50+	Excellent
FUF1 5W	28.09	23.12	50.65	50+	Excellent
FUF2 5W	23.27	38.43	35.69	25-39	Very Good
FUF1 10W	62.45	51.95	50.20	50+	Excellent
PUF2 10W	54.13	35.67	70.47	50+	Excellent
FUF1 15W	39.23	26.58	54.14	50+	Excellent
FUF2 15W	44.27	33.15	43.13	25-39	Very Good

3.7 Assessment of Textile Properties

Treatment with *Ficus religiosa* bark extract altered several structural and comfort-related characteristics of the fabrics. Fabric weight increased in treated samples (251–268.5 GSM) compared to controls (209.5–238 GSM), reflecting deposition of bioactive compounds. Air permeability improved in FUF1 (33.0 $cm^3/cm^2/s$), indicating higher porosity, while other treated samples showed values similar to controls. Water repellence remained unaffected, with all fabrics recording zero ratings. Thermal conductivity differed between samples, with FUF1 exhibiting lower values (1.38 CLO), suggesting improved insulation, and FUF2 showing higher conductivity (2.14 CLO).

Mechanical testing revealed a modest increase in crease recovery (116° in FUF1 vs. 98° in CUF1), indicating enhanced wrinkle resistance. Tear strength declined in treated fabrics, particularly in the weft direction (e.g., 2.94 kgf in FUF2 vs. 6.14 kgf in CUF1), suggesting reduced flexibility. Stiffness and flexural rigidity varied but remained within acceptable limits for apparel use. Yarn and fabric counts were largely unchanged, confirming that the structural integrity of the fabrics was preserved. These effects are consistent with earlier findings on natural extract–based finishes influencing both functional and mechanical textile properties [16]. The results are given in Table 12 and Annexure Table A1.

Table 12 Primary and comfort-related textile properties of untreated and treated fabrics

Sample	Fabric Weight (GSM)	Fabric Thickness (mm)	Air Permeability ($cm^3/cm^2/s$)	Water Repellency (rating)	Thermal Conductivity (CLO)	Pilling Resistance (rating)	Drape Coefficient
CUF1	209.5	46	10.4	0	1.63	5.00	0.33
CUF2	238.0	55	11.9	0	1.92	5.00	0.33
FUF1	251.0	40	33.0	0	1.38	5.00	0.33
FUF2	268.5	47	12.2	0	2.14	5.00	0.33

3.8 Discussion

The findings demonstrate that *Ficus religiosa* bark extract can be successfully applied to bamboo-based union fabrics to impart durable bio-functional properties. The high flavonoid and phenolic content of the extract correlate with its strong antimicrobial efficacy, particularly at lower aqueous concentrations (5%), which outperformed methanol and acetone extracts. These results are consistent with the established role of polyphenolic compounds in inhibiting microbial growth and providing UV absorption capacity [5].

Wash durability tests revealed a gradual decline in antibacterial activity, whereas antifungal resistance and UV protection were retained to a greater extent. This suggests that the phytochemicals in F. religiosa may interact more strongly with fungal cell structures and ultraviolet wavelengths than with bacterial targets. Although a reduction in tear strength was noted, other structural and comfort-related properties, such as crease recovery, thermal conductivity, and air permeability, remained within acceptable limits, indicating that the finish did not compromise overall fabric performance.

Overall, the study confirms the potential of *F. religiosa* bark as a sustainable alternative to synthetic chemical finishes. Its bioactivity, combined with reasonable wash durability, supports its application in protective textiles, healthcare fabrics, and eco-friendly apparel.

4. Conclusion

This present study established that *Ficus religiosa* bark extract can be effectively used to functionalize bamboo union fabrics, providing antimicrobial, antifungal, and UV-protective properties. Among the tested extracts, the aqueous preparation at 5% concentration offered the most effective and durable results. Treated fabrics consistently achieved "excellent" UPF ratings and maintained antifungal resistance through multiple wash cycles, although antibacterial efficacy diminished with laundering. Importantly, the treatment did not adversely affect basic structural integrity, while modest improvements in crease recovery and insulation were observed. The results highlight *F. religiosa* as a promising bio-based finishing agent for sustainable textile development. Further studies on process optimization and large-scale application may enable its commercial adoption in protective and health-oriented fabrics.

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Table A1 Mechanical properties and structural characteristics of untreated and treated fabrics

Sample	Crease Recovery Angle (°)	Tear Strength (kgf) Warp	Tear Strength (kgf) Weft	Bending Length (cm) Warp	Bending Length (cm) Weft	Flexural Rigidity (cm^3) Warp	Flexural Rigidity (cm^3) Weft	Yarn Count (warp × weft)	Fabric Count (warp × weft)
CUF1	98 × 64	5.69	6.14	0.95	10.4	0.02	0.14	11 × 15	57 × 26
CUF2	106 × 96	5.95	3.78	1.10	11.9	0.03	0.05	10 × 10	47 × 51
FUF1	116 × 63	4.28	5.31	0.85	33.0	0.02	0.20	8 × 12	52 × 46
FUF2	101 × 94	4.80	2.94	1.40	12.2	0.07	0.13	8 × 9	50 × 46

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