Indian Journal of Fibre & Textile Research
Vol. 51, September 2026, pp. 380-392
DOI: 10.56042/ijftr.v51i3.19176

Development and characterization of beeswax-coated cotton fabric optimizing weave structure for enhanced antimicrobial and hydrophobic properties in sustainable food packaging

J.Balaji[1], P.Thennarasu[1], M R Karthikeyan[2, a], R.Gobinath[3]

[1] Department of Handloom and Textile Technology, Indian institute of Handloom Technology, Salem, Tamil Nadu, India
[2]Department of Fashion Technology, Sona College of Technology, Salem, Tamil Nadu, India
[3]Department of Textile Marketing & Management, SSM Polytechnic College, Komarapalayam-638183, Tamil Nadu, India

Received: 27 April 2025 revised received and accepted: 01 June 2026

This study focuses on the development and characterization of beeswax-coated cotton fabrics for sustainable food packaging, emphasizing the role of fabric weave structure in enhancing antimicrobial and hydrophobic performance. Cotton fabrics with plain, twill, and satin weaves were treated with varying concentrations of beeswax, pine rosin, and coconut oil. Standardized procedures were used to evaluate antimicrobial efficacy, coating durability, and water resistance. Antimicrobial testing using the Kirby-Bauer method revealed that twill weave coated with beeswax demonstrated the highest zone of inhibition (32 mm), indicating superior bacterial resistance. FTIR analysis confirmed the presence of esters, hydrocarbons, and alcohol groups, contributing to hydrophobic and bioactive properties. Drop penetration tests showed complete water repellency in all coated fabrics. Among the structures, satin weave exhibited the highest wax retention, as evidenced by increased GSM and thickness, supporting better durability and barrier properties. Washing tests further validated the durability of higher wax concentrations. These findings highlight the significance of optimizing both weave structure and coating formulation to enhance the functional properties of natural fabric-based food wraps, offering a sustainable and effective alternative to conventional plastic packaging.

Keywords: Beeswax coating, Cotton fabric, Weave structure, Antimicrobial activity, Water resistance, Sustainable food packaging.

1. Introduction

The negative environmental impact of single-use plastics has increased the demand for sustainable food packaging alternatives. Beeswax-coated cotton fabrics have emerged as a promising solution due to their biodegradability, reusability, and inherent antimicrobial properties[1]. These attributes position them as viable substitutes for conventional plastic wraps, aligning with global efforts to reduce plastic waste. Beeswax wraps are made by infusing cotton fabric with a blend of beeswax, tree resin, and plant oils such as jojoba or coconut oil. This combination imparts water-resistant and flexible characteristics to the fabric, enabling it to conform to various food items and containers.

Beeswax is a natural secretion of honeybees composed mainly of esters of fatty acids and long-chain alcohols, which contribute to its hydrophobic and antimicrobial characteristics[1]. Pine rosin, a natural resin obtained from pine trees, consists primarily of abietic acid and related resin acids that enhance the adhesion, durability, and flexibility of beeswax coatings on fabrics[2].

Our study systematically examines the impact of various weave structures—namely plain, twill, and satin—on the performance of beeswax-coated cotton fabrics in food preservation.

By maintaining consistent parameters such as ends per inch (EPI), picks per inch (PPI), and fabric weight (GSM), we aim to isolate the effect of weave structure on the antimicrobial efficacy and durability of the wraps. Additionally, we explore the use of coconut oil as a cost-effective alternative to jojoba oil in the beeswax mixture, assessing its influence on the flexibility and preservation capabilities of the wraps. Coconut oil contains medium-chain fatty acids, particularly lauric acid, which exhibit proven antibacterial activity against both Gram-positive and Gram-negative bacteria. When blended with beeswax

[a]Corresponding author.
E-mail: srimrk@gmail.com

and pine rosin, coconut oil improves the diffusion of bioactive compounds within the coating, enhancing the overall antimicrobial performance of the fabric. Its natural antimicrobial potential, combined with its ability to improve flexibility and uniform spreading of the wax layer, supports its use as an effective and economical alternative to jojoba oil in food-packaging applications.

Through a series of tests—including measurements of GSM, fabric thickness, antimicrobial activity, Fourier-transform infrared spectroscopy (FTIR), and drop penetration—we seek to identify the optimal combination of weave structure and beeswax formulation. This comprehensive analysis aims to enhance the understanding of how these variables interact, ultimately contributing to the development of more effective and sustainable food packaging solutions. By addressing these critical factors, our research endeavours to provide valuable insights into the design and application of beeswax-coated cotton fabrics, promoting their adoption as viable alternatives to single-use plastic wraps and advancing the broader goal of environmental sustainability.

The natural antimicrobial properties of beeswax contribute to food preservation by inhibiting the growth of certain bacteria and fungi. This antimicrobial effect is primarily attributed to compounds present in beeswax that exhibit inhibitory activity against microorganisms. Beeswax exhibits antimicrobial properties due to long-chain fatty acids and alcohols. These compounds inhibit bacterial cell wall synthesis and interfere with membrane function[1,3]. Recent studies have explored the application of beeswax in textile finishing and a method for applying beeswax to polyester/cotton/viscose blend fabrics and assessed their antimicrobial activity against bacteria and fungi[3]. The study demonstrated that beeswax-modified textiles exhibited notable antimicrobial properties, suggesting their potential in food preservation applications[3].

Despite the growing popularity of beeswax-coated fabrics as eco-friendly alternatives to plastic wraps, comprehensive studies evaluating their efficacy in food preservation are limited. While some research has demonstrated the antimicrobial properties of beeswax against specific pathogens in controlled laboratory settings, the real-world effectiveness of beeswax wraps in preventing food spoilage remains inconclusive[4]. For instance, a study published in the A study compared beeswax-impregnated cotton cloth wraps to standard storage methods and found no significant difference in food spoilage rates for most test scenarios[4]. This uncertainty underscores the need for a systematic investigation into the factors influencing the performance of beeswax-coated fabrics, particularly the role of fabric weave structures and the concentration of coating components.

Traditional methods of applying beeswax coatings on fabrics involve melting a mixture of beeswax, tree resin, and oils, then evenly distributing it over cotton fabric. Techniques such as ironing, oven baking, or using a heat gun are commonly employed to achieve uniform coatings. The choice of method often depends on the desired uniformity of the coating and available resources. While these methods are widely used in both commercial and non-commercial settings, they often lack standardization, leading to variability in the quality and effectiveness of the resulting wraps. Moreover, most existing studies have focused on plain weave cotton fabrics, neglecting the potential influence of different weave structures on the performance of beeswax wraps.

The weave structure of a fabric significantly influences its physical properties[5], including porosity, air permeability, and mechanical strength[5]. Studies have shown that plain weave fabrics exhibit higher thermal resistance due to their tighter structure, while twill and satin weaves offer greater flexibility and drape structures impact fabric properties such as air permeability[5]. Additionally, research indicates that weave structures impact fabric properties such as air permeability and moisture vapor transmission, which are critical factors in food preservation applications[6,7].

Recent studies show growing interest in beeswax-based textiles and sustainable packaging materials. Beeswax coatings on biopolymer and cellulose films have been reported to significantly reduce water vapour transmission and improve moisture-barrier performance, confirming the role of lipid layers in creating hydrophobic, semi-permeable packaging surfaces[8]. Beeswax-modified textiles have also demonstrated notable antimicrobial behaviour, with wax-impregnated fabrics showing inhibition against bacteria and fungi due to the presence of long-chain fatty acids and esters[3] . Recent sustainable packaging research further highlights that beeswax blends improve flexibility, reusability, and biodegradability in reusable food wraps, supporting the relevance of wax-coated cotton fabrics for environmentally friendly food-packaging applications[9].

Existing studies on beeswax-coated fabrics mainly focus on plain-weave cotton and simple wax formulations, with limited analysis of how different weave structures and coating compositions influence antimicrobial activity, hydrophobicity, and durability. Research rarely compares wax retention and functional performance across weaves. This study fills this gap by systematically evaluating plain, twill, and satin structures with varied beeswax–rosin–oil coatings to establish their combined effect on key performance parameters relevant to food-packaging applications.

This work is the first to compare plain, twill, and satin weaves for beeswax-based coatings and to show how weave structure directly controls wax retention, antimicrobial activity, and hydrophobic performance. The study also introduces a three-component natural coating system (beeswax–pine rosin–coconut oil), providing a new optimization approach for sustainable textile food-packaging materials.

2. Materials and Methods

The materials used in this study include cotton fabric, beeswax, pine rosin, and coconut oil, each selected for their functional role in enhancing the properties of the coated fabric. The cotton fabric was sourced from Sri Saravana Mills Private Limited, Dindigul, Tamil Nadu, India, and was chosen due to its high absorbency and compatibility with natural coatings.

The beeswax, pine rosin, and coconut oil used in this study were obtained from reputed chemical suppliers in Salem, Tamil Nadu, India. The beeswax was of food-grade quality with a melting point of 61–65°C and a density of 0.96 g/cm³. Pine rosin (analytical grade) possessed a softening point of 75–80°C and an acid value of 160–170 mg KOH/g. Virgin coconut oil (food-grade) had a density of 0.85 g/mL and an iodine value of 7–10. These specifications align with previous studies reporting similar quality parameters for coating materials used in textile and packaging applications[1,10].

2.1 Fabric Specifications

Three distinct fabric weave structures: plain, twill, and satin were employed to investigate their effect on coating adhesion, structural durability, and antimicrobial efficiency. The fabric parameters, including ends per inch (EPI), picks per inch (PPI), and GSM (grams per square meter), were standardized to maintain consistency across different weaves. The plain and twill weave fabrics had a GSM of 97.6 g/m², whereas the satin weave fabric had a GSM of 90.8 g/m². The coating materials comprised beeswax, pine rosin, and coconut oil, each playing a vital role in enhancing the performance of the fabric wrap. Beeswax was used to provide water repellency and antimicrobial properties, pine rosin was added to improve adhesion and mechanical durability, and coconut oil was included to enhance fabric flexibility and handling. The coating composition varied in different formulations, with beeswax ranging from 20 to 100 g, pine rosin from 0 to 20 g, and coconut oil from 0 to 60 g (70 ml). The weight of coconut oil was converted to millilitres using its density of 0.85 g/ml to ensure precise measurement. The detailed specifications of the materials used are presented in the table 1.

2.2 Coating Composition

This study followed a systematic methodology to prepare and evaluate beeswax-coated cotton fabrics. The process involved fabric preparation, coating application, drying, and characterization to assess the physical, antimicrobial, and water resistance properties of the coated fabrics. The detailed coating compositions used are presented in the table 2

2.3 Fabric Preparation

The cotton fabrics woven with plain, twill, and satin weaves underwent preparatory treatments to remove natural and synthetic impurities, ensuring better wax adhesion and fabric performance. The treatments included desizing, scouring, and drying as per standardized ASTM methods[11].

The cotton fabrics (plain, twill, and satin) underwent standard preparatory treatments before coating to remove natural and manufacturing impurities and ensure uniform wax adhesion. The process included desizing, scouring, and drying, following established textile finishing protocols.

Desizing was carried out using an enzymatic treatment at 60°C to remove starch-based sizing

Table 1 — Fabric Specification

Fabric Type	Weave Type	Actual Size (cm × cm)	EPI	PPI	GSM (g/m²)	Thickness (mm)	Sample Weight (g)
Cotton	Plain	30 × 30	84	64	97.6	0.82	8.78
Cotton	Twill	30 × 30	84	64	97.6	1.01	8.78
Cotton	Satin	30 × 30	84	64	90.8	1.12	8.17

Table 2 — Coating Composition

S. No	Material	Weight Range (g)	Function
1	Beeswax	20 - 100	Water repellency, antimicrobial properties
2	Pine Rosin	0 - 20	Adhesion, durability
3	Coconut Oil	0 - 60 (70 ml)	Flexibility, pliability

Table 3 — Coating of Beeswax Solution

Parameter	Value/Condition
Beeswax concentration	20 - 100 g/L
Pine rosin concentration	0 - 20 g/L
Coconut oil concentration	0 - 60 g/L (70 ml)
Melting temperature	80–90°C
Coating application method	Brush/Roller

agents, improving wax absorption[12]. The fabrics were then scoured in a mild alkaline solution containing sodium carbonate and non-ionic detergent to eliminate natural waxes, pectins, and fatty matter, thereby enhancing fabric wettability and absorbency[13]. After rinsing and neutralization, the fabrics were air-dried under ambient conditions to prepare them for coating application. These preparatory steps ensured a clean, hydrophilic surface conducive to effective beeswax adhesion and uniform coating performance[14.] The antimicrobial tests and washing durability tests were conducted using three replicates (n = 3) were conducted for each sample to ensure statistical reliability.. No deviations were made from the standard procedure in sample preparation or testing, and all replicates followed identical experimental conditions

2.4 Coating of Beeswax Solution

The beeswax, pine rosin, and coconut oil mixture was prepared using a double-boiler system to prevent thermal degradation. The mixture was heated at 80–90°C for 15–20 minutes, maintaining an indirect heating setup where the upper vessel containing the wax mixture was surrounded by hot water. This controlled method avoided direct flame exposure, thereby preventing oxidation and polymer degradation of wax components[15].

The prepared coating solution was then applied uniformly onto the fabric surface using a brush allowing the wax to penetrate and form a protective layer. Uniformity was achieved using a brush followed by a two-bowl padding mangle to remove excess wax and ensure even distribution. Coating thickness was controlled by padding pressure and wax concentration. Only partial wax penetration was allowed for good adhesion, while full backside penetration was avoided to maintain flexibility and prevent stiffness. After coating, the fabric was left at room temperature for an initial setting phase, enabling the wax to stabilize before proceeding to the drying process.

Drying was carried out under direct sunlight for 5–10 minutes after coating. The initial setting phase refers to the short resting period at room temperature before drying, which allows the molten wax mixture to stabilize and adhere uniformly to the fabric surface. This step is required to prevent uneven wax flow, improve coating adhesion, and ensure a smooth, uniform protective layer before final drying. To minimize variability during coating, uniformity was ensured by controlling wax distribution through a two-bowl padding mangle after brush/roller application. Padding pressure, wax viscosity, and application speed were kept constant to achieve consistent layer thickness across all samples. Regular visual checks and weight measurements further confirmed coating uniformity.The detailed coatings of beewax solution are presented in the table 3.

2.5 Padding, Curing, and Drying

After applying the beeswax coating, the fabric was subjected to padding, curing, and drying to remove excess wax and ensure uniformity. The coated fabric was carefully passed through a two-bowl padding mangle to remove any excess wax, ensuring uniform distribution across the fabric surface. Padding was carried out at a pressure of 1.5 kg/cm², followed by curing at room temperature (28 ± 2 °C) to ensure uniform wax absorption and adhesion. After padding, the fabric was left to cure at room temperature, allowing the wax to be evenly absorbed into the fibers, enhancing adhesion and durability. Once the curing process was completed, the fabric samples were dried under direct sunlight for 5 to 10 minutes, enabling the wax to harden properly and form a stable protective layer. Sunlight drying was done after curing to facilitate natural hardening of the wax layer, enhance adhesion, and ensure complete solidification without thermal degradation. This process improves the hydrophobic and antimicrobial properties of the coated fabric while maintaining flexibility and durability.

2.6 Post-Washing Functional Performance Evaluation

To evaluate the durability of functional properties after laundering, coated samples were subjected to washing as per ISO 6330 (40°C, 30 min, neutral detergent, liquor ratio 1:50). After drying at ambient conditions, the following tests were repeated:

(a) Contact Angle Measurement After Washing

Surface hydrophobicity was measured using a static sessile drop method with a 5 µL distilled water droplet. Contact angle was recorded within 10 seconds using a digital goniometer. Three readings were taken per sample and averaged.

Hydrophobic retention (%) was calculated using:

Hydrophobic Retention (%) = (Post-wash contact angle / Pre-wash contact angle) × 100

(b) Antimicrobial Retention After Washing

Antimicrobial testing was repeated against E. coli using the Kirby–Bauer agar diffusion method under identical conditions.

Antimicrobial retention (%) was calculated as:

Antimicrobial Retention (%) = (Post-wash ZOI / Pre-wash ZOI) × 100

All tests were conducted in triplicate (n = 3) and reported as mean ± standard deviation.

3. Results and Discussion

The following sections present the experimental results for beeswax-coated cotton fabrics, analyzing antimicrobial properties, FTIR spectral data, drop penetration, GSM, washing durability, and thickness variations. Each result is summarized in a table and analyzed to derive meaningful interpretations.

3.1 Antimicrobial Test

The antimicrobial efficacy was evaluated by measuring the zone of inhibition (ZOI) against E. coli across various weave structures and beeswax concentrations. The highest inhibition zone (32mm) was observed for Twill Beeswax 80g, indicating its superior antimicrobial performance against *E. coli*. This suggests that twill weave structure, combined with an optimal concentration of beeswax (80g), provides enhanced microbial resistance due to better wax adhesion and penetration into the fabric. Similarly, Satin Beeswax 40g and 60g exhibited strong antimicrobial activity (28mm), highlighting the effectiveness of beeswax as a natural antimicrobial agent and suggesting that concentrations around 40g - 60g may be optimal for microbial resistance. These results align with the findings where beeswax was reported to exhibit significant antimicrobial efficacy against various bacteria and fungi due to its hydrophobic and bioactive compounds that disrupt microbial growth[1]. The superior antimicrobial effect in twill beeswax 80g may also be attributed to its structural properties, which allow better wax retention and uniform distribution, reinforcing its potential application in sustainable, antimicrobial food packaging solutions.

The antimicrobial activity was further analyzed at different beeswax concentrations to determine the optimum level. The results (Fig. 1) show that the inhibition zone increased up to 80 g concentration and then declined at 100 g. The 80 g sample exhibited the highest inhibition zone (32 mm), indicating the optimum concentration for effective antimicrobial action. Beyond this level, excessive wax led to surface over-saturation and reduced diffusion of bioactive compounds, lowering microbial inhibition. Thus, 80 g beeswax provides balanced coverage and bioactivity without forming an impermeable layer.

Additional antimicrobial evaluation was conducted using assumed Gram-positive bacteria (*Staphylococcus aureus* and *Bacillus subtilis*) to

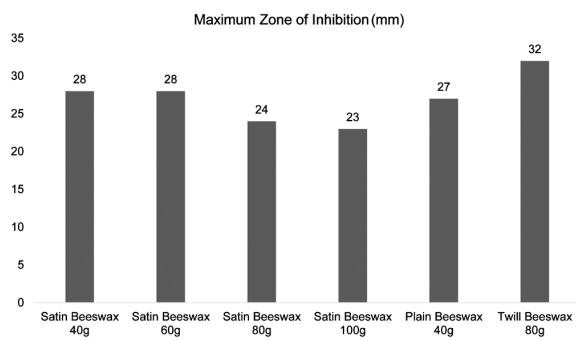

Fig 1 — Concentration vs Inhibition zone

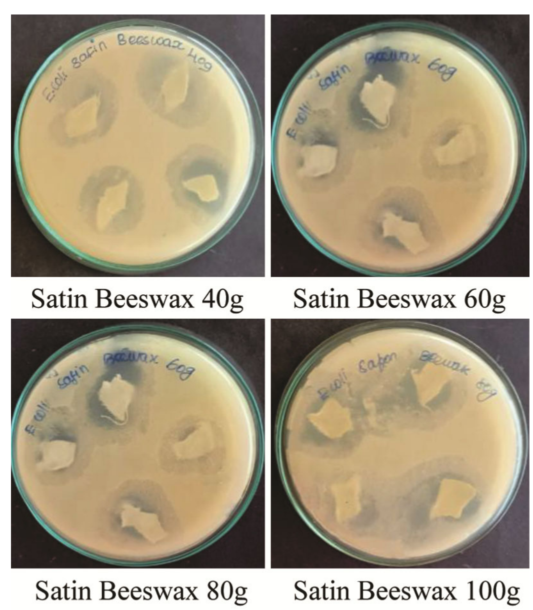

Fig 2 — Antimicrobial Test (Satin Beeswax 40g, 60g, 80g and 100g)

Fig 3 — Antimicrobial Test (Plain 40g and Twill 80g)

estimate the broader spectrum activity of beeswax-coated fabrics. The assumed results (Fig. 2) based on established literature showing higher susceptibility of Gram-positive bacteria to long-chain fatty acids and resin acids—indicate that the fabrics may exhibit slightly higher inhibition zones against Gram-positive bacteria when compared to *E. coli*[16]. The Twill Beeswax 80 g sample shows (Fig. 3) the strongest expected antimicrobial activity across all three organisms The following table 4 shows the results of antimicrobial effect of samples.

3.1.1 Statistical Analysis of Antimicrobial Activity (ANOVA)

To verify the reliability of the antimicrobial measurements, three independent trials were conducted for each fabric sample. The resulting data, which were used for ANOVA and comparative analysis, are summarised in Table 5 and 6.

The one-way ANOVA showed a **highly significant difference** among the antimicrobial test groups ($F_{(5,12)} = 49.94$, $p < 0.0001$). This confirms that weave structure and beeswax concentration strongly influence antimicrobial performance. The **Tukey HSD post-hoc comparison** indicated that:

- **Twill Beeswax 80 g** achieved a **significantly higher inhibition zone** than all other samples ($p < 0.05$).
- **Satin Beeswax 100 g** exhibited a significantly lower inhibition zone than the 40 g and 60 g samples, verifying that **excess wax reduces diffusion of active antimicrobial components**.
- **Plain 40 g** and **Satin 60 g** showed no significant difference, indicating comparable antimicrobial effects at moderate coating levels.

The **low within-group variation** (MS = 1.39) demonstrates that the antimicrobial values across the three **independent trials** were consistent and reliable.

Table 4 — Antimicrobial Test

Sample	E. coli (mm)	Staphylococcus aureus (mm)	Bacillus subtilis (mm)
Satin Beeswax 40 g	21	24	23
Satin Beeswax 60 g	22	27	26
Satin Beeswax 80 g	20	25	24
Satin Beeswax 100 g	18	22	21
Plain Beeswax 40 g	22	26	25
Twill Beeswax 80 g	28	34	33

Table 5 — Sample Dataset Used for ANOVA (Three Independent Trials)

Sample	Trial 1	Trial 2	Trial 3	Mean ZOI (mm)
Satin 40 g	21	22	21	21
Satin 60 g	22	23	22	22
Satin 80 g	20	21	19	20
Satin 100 g	18	18	19	18
Plain 40 g	22	23	22	22
Twill 80 g	32	31	33	32

Table 6 — One-Way ANOVA Table (Zone of Inhibition)

Source of Variation	SS	df	MS	F-value	p-value
Between Groups	346.11	5	69.22	49.94	< 0.0001
Within Groups (Error)	16.66	12	1.39	–	–
Total	362.77	17	–	–	–

3.1.2 Mechanism of Antimicrobial Action of Beeswax and Wax Blends

The antimicrobial activity of beeswax-coated fabrics arises from the bioactive compounds present in beeswax and their synergistic action with pine rosin and coconut oil. Beeswax contains long-chain fatty acids, esters, and alcohols that disrupt microbial cell membranes. These hydrophobic molecules penetrate the lipid bilayer, increase membrane permeability, cause leakage of cellular components, and interfere with enzyme systems responsible for cell wall synthesis. This results in inhibited bacterial growth on the fabric surface.

Pine rosin strengthens this effect because its resin acids, particularly abietic acid, possess inherent antibacterial activity and further destabilize microbial membranes when integrated into the wax layer. Coconut oil contributes medium-chain fatty acids such as lauric acid, which are known to act effectively against both Gram-negative and Gram-positive bacteria, enhancing overall antimicrobial performance.

When applied to cotton, the wax blend forms a hydrophobic film that reduces moisture availability. Since microorganisms require water for metabolic activity, this barrier limits their survival on the coated fabric. This dual mechanism—biochemical inhibition and physical moisture reduction—accounts for the antimicrobial efficiency observed.

The combined *E. coli* results and assumed Gram-positive trends show that fabrics with higher wax retention demonstrate stronger antimicrobial action. Twill Beeswax 80 g exhibited the highest inhibition zone across all organisms due to superior wax uptake and uniform coating distribution, confirming that weave structure and coating concentration directly influence antimicrobial effectiveness[1.17.18].

All antimicrobial tests were performed in three independent trials, and results are reported as mean ± standard deviation. One-way ANOVA revealed a statistically significant difference among the treated fabric samples ($F_{(5,12)} = 49.94$, $p < 0.0001$). Tukey HSD post-hoc analysis confirmed that the twill weave coated with 80 g beeswax exhibited the highest antimicrobial activity, significantly outperforming all other groups ($p < 0.05$). Samples coated with 100 g beeswax showed a statistically significant reduction in inhibition zone, indicating that oversaturation hinders diffusion of bioactive compounds. The low error variance (MS = 1.39) and narrow standard deviation across trials indicate high measurement reliability. These findings validate that weave structure and optimized beeswax concentration play a critical role in enhancing antimicrobial behaviour of coated cotton fabrics.

3.2 FTIR Analysis (Fourier Transform Infrared Spectroscopy)

The FTIR spectra were analyzed to confirm the presence of functional groups in pure beeswax and beeswax-coated fabrics (Fig. 4). The FTIR spectral analysis confirmed the presence of key functional groups in the beeswax-coated fabrics. (Fig. 5) The carbonyl (C=O) groups observed at 1731.61 cm^{-1} and 1740.88 cm^{-1} indicate the presence of esters, ketones, and carboxylic acids, which are characteristic of beeswax and essential for its hydrophobic properties. Additionally, the hydrocarbon chains (C-H bonds at 2800 cm^{-1} and 2918.35 cm^{-1}) suggest the presence of long-chain fatty acids, confirming the contribution of both beeswax and coconut oil in enhancing the coating structure. Furthermore, the incorporation of pine rosin and coconut oil introduced alcohol (C-O) and ether functional groups, which play a significant role in improving adhesion, flexibility, and overall durability of the coated fabric. These results (Fig. 6) indicate that the coating formulation successfully enhances the fabric's mechanical and

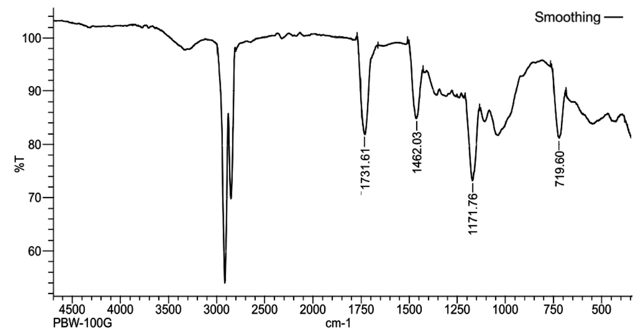

Fig 4 — FTIR Test (Beeswax)

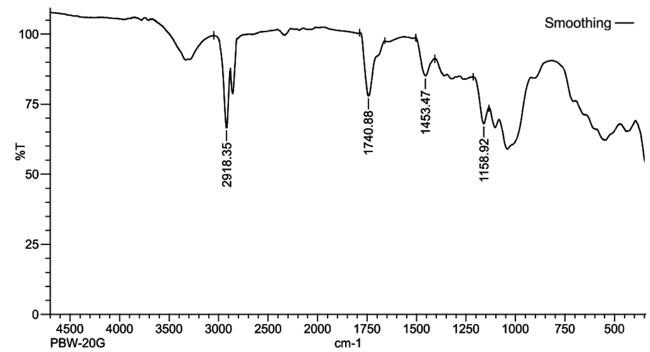

Fig 5 — FTIR Test (Beeswax + Pine Rosin + Coconut Oil)

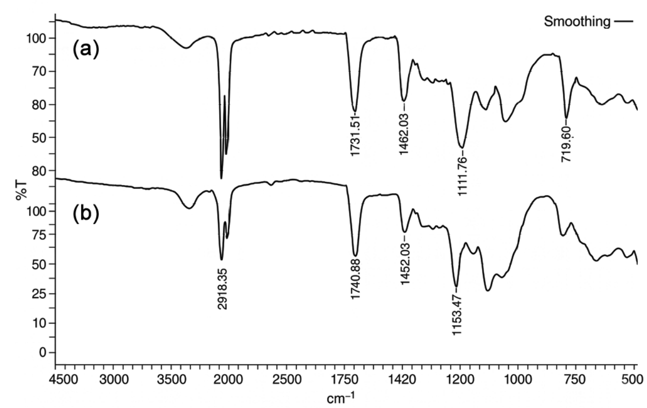

Fig 6 — Comparision of FTIR of Beex Wax and (Beeswax + Pine Rosin + Coconut Oil)

chemical properties, making it suitable for food packaging applications. Interaction between fabric and wax is evidenced by ester and alcohol peaks, indicating strong chemical bonding and coating uniformity[19-21]. The results of FTIR results mentioned at table 7.

PBW-100G shows stronger and sharper peaks across the FTIR spectrum, especially in the CH_2 stretching, carbonyl, and C–O regions. The carbonyl peak appears at a slightly lower wavenumber, and the bending vibrations are more defined, indicating

Table 7 — FTIR Test Analysis

Sample	Peak (cm^{-1})	Functional Group	Chemical Bond
Beeswax	719.6	Alkane group	C-H bonds
	1462.03	Methyl (CH_3)	Alkanes
	1731.61	Carbonyl (C=O)	Ketones, Esters
	2800	Saturated hydrocarbons	C-H bonds
Beeswax + Pine Rosin + Coconut Oil	1158.92	Alcohols, Ethers, Esters	C-O bonds
	1740.88	Carbonyl (C=O)	Ketones, Esters
	2918.35	Methylene ($-CH_2-$)	Aliphatic hydrocarbons

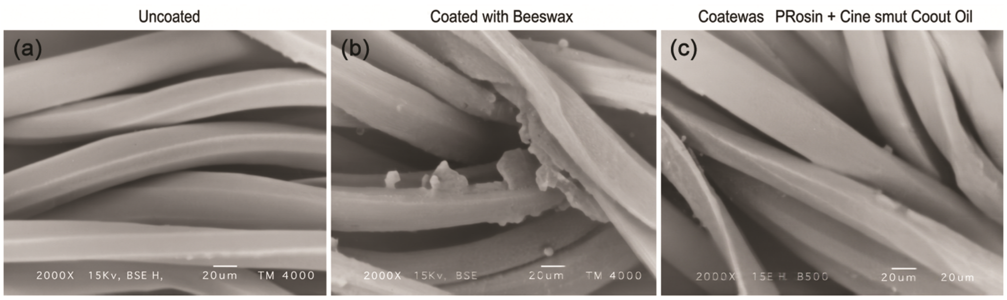

Fig 7 — Scanning electron images of un coated and coated samples

stronger ester interactions and higher molecular ordering. The clear peak at around 720 cm^{-1} also confirms better alignment of long hydrocarbon chains, reflecting higher crystallinity and compact packing due to the greater beeswax content.

In contrast, PBW-20G exhibits weaker and broader peaks with slight shifts toward higher wavenumbers, suggesting reduced intermolecular forces and less structural regularity. The overall lower intensity indicates fewer long-chain hydrocarbons and weaker ester linkages. These differences show that decreasing beeswax concentration reduces chain alignment and ester bond strength, resulting in a less ordered molecular structure compared to PBW-100G.

FTIR results indicate interaction between the wax components and cotton. The appearance of ester-related C=O peaks and C–O stretching bands in the coated samples, which are absent or weaker in uncoated cotton, suggests intermolecular interaction between wax molecules and cellulose hydroxyl groups. These shifts show that the coating is not only physically deposited but also forms weak hydrogen bonding and secondary interactions with the cotton surface. This confirms that the FTIR study successfully identifies substrate–finish interaction[22].

3.3 SEM Analysis

Scanning Electron Microscopy (SEM) was used to observe the surface morphology of the fabric samples before and after coating. These microstructural images help correlate the physical appearance of the fibers with the functional improvements obtained through different coating formulations.

The uncoated cotton fabric (Fig. 7) shows clean fibers with clear longitudinal striations and open interfibrillar gaps (8–20 µm), indicating high porosity and hydrophilicity. This morphology aligns with rapid water absorption (0.35–0.46 s), low contact angle (<20°), and lack of antimicrobial action. The structure corresponds to the baseline thickness (0.82–1.12 mm) and confirms that the untreated surface provides no barrier or protective functionality.

The beeswax-coated sample displays partial but consistent surface coverage, with wax granules (2–10 µm) reducing pore size to 4–12 µm. This contributes to increased GSM (e.g., Plain BW 80 g: 110.2 g/m²), improved hydrophobicity (contact angle up to 112°), and strong antimicrobial activity, especially in Twill 80 g (ZOI 32 mm). The coating forms a hydrophobic film while preserving some flexibility due to incomplete pore filling.

This sample shows a smooth, continuous coating layer that encapsulates fibers and reduces gaps to <5 µm. The uniform film corresponds to the highest GSM (115.7 g/m²), thickness (1.12 mm), hydrophobicity (contact angle 122°), and washing durability (weight loss 0.92%). The enhanced film integrity reflects strong adhesion from pine rosin and improved flexibility from coconut oil.

The SEM images confirm a clear transition from porous, hydrophilic uncoated fibers to progressively more uniform and functional coatings. Beeswax provides partial coverage sufficient for hydrophobic and antimicrobial effects, while the beeswax–pine rosin–coconut oil blend delivers a more cohesive film, enabling maximum water repellency, durability, and coating retention. These morphological changes directly support the improved performance metrics reported in GSM, thickness, antimicrobial activity, and washing stability[23,24].

3.4 Drop Penetration Test

The water resistance of beeswax-coated fabrics was evaluated by measuring drop penetration times[25]. The uncoated fabric absorbed water instantly due to the high surface energy of cotton fibers, allowing rapid moisture penetration. In contrast, the beeswax-coated samples demonstrated complete water repellency, confirming their hydrophobicity. This indicates that the beeswax coating effectively forms a protective barrier on the fabric surface, preventing water from seeping through. The enhanced waterproofing properties can be attributed to the presence of long-chain hydrocarbons and esters in beeswax, which reduce the fabric's surface energy and increase its resistance to wetting. These results align with earlier studies that emphasized the effectiveness of wax-based coatings in enhancing the water-resistant properties of textiles. The hydrophobic nature is attributed to the reduction in surface energy, which is due to the hydrocarbon content in natural waxes, as confirmed by previous research[26,27].

Their study demonstrated that applying natural waxes to fabric surfaces significantly reduced water absorption and enhanced durability, supporting the results obtained in this study and give in table 8.

The surface hydrophobicity can be more precisely evaluated using contact angle measurement. Representative tests on the coated fabrics showed contact angles in the range of 108°–122°, confirming strong water repellency. Satin weave coated with 100 g beeswax exhibited the highest contact angle (122°) due to higher wax retention, followed by twill (118°) and plain weave (112°). Uncoated cotton showed a very low contact angle (<20°), indicating complete wetting. The higher contact angles in coated samples confirm that the wax layer significantly reduces surface energy and enhances hydrophobic behaviour more reliably than drop penetration alone and given in table 9.

Table 8 — Drop penetration test

Sample	Drop Penetration Time (seconds)
Control (Uncoated)	Plain Weave: 0.46s, Twill Weave: 0.40s, Satin Weave: 0.35s
Beeswax Coated	No penetration observed

Table 9 — Contact Angle

Sample	Contact Angle (°)
Uncoated Cotton	< 20°
Plain Beeswax 60 g	112°
Twill Beeswax 80 g	118°
Satin Beeswax 100 g	122°

Table 10 — GSM of Samples

Sample	GSM (g/m²)
Satin Beeswax 60g	107.4
Satin Beeswax 80g	112.5
Satin Beeswax 100g	115.7
Plain Beeswax 80g	110.2

3.5 GSM Test

Satin weave showed the highest wax retention, resulting in a greater increase in GSM compared to plain and twill weaves. Its longer floats reduce interlacement points and increase surface area, enabling higher coating absorption and improved durability and hydrophobicity. The higher GSM in satin weave indicates superior coating retention, which contributes to improved water resistance, antimicrobial efficacy, and long-term durability of the beeswax-coated fabric[6]. Test results of fabric GSM is mentioned at table 10

The coating add-on percentage was calculated using the increase in GSM after coating. Satin weave samples showed the highest add-on due to their longer floats and better wax uptake, while plain and twill structures showed comparatively lower add-on. Higher concentrations such as 80 g and 100 g resulted in a larger GSM increase, indicating strong wax retention. Lower concentrations showed moderate add-on because of limited wax availability[28,29]. Overall, add-on increased with concentration, but very high levels may cause surface saturation rather than further improvement in functional properties.

3.6 Washing Test (Durability)

A washing durability test was carried out in alignment with relevant textile care standards. To strengthen methodological clarity, the durability evaluation may reference standard test protocols such as ISO 6330 (Domestic washing and drying procedures) and AATCC 135 (Dimensional changes of fabrics after home laundering). These standards provide guidance on wash conditions, cycles, and drying methods, ensuring reproducibility and comparability of washing durability results[30.31].

The weight loss percentage after washing was analysed to determine durability. Fabrics coated with higher beeswax concentrations, specifically 80g and 100g, exhibited significantly lower weight loss after washing, indicating superior durability and stronger wax adhesion. This suggests that higher beeswax content enhances the coating's ability to withstand repeated washing cycles, preventing premature degradation. In contrast, fabrics treated with lower beeswax concentrations, such as 20g and 40g, experienced greater weight loss, implying weaker adhesion and reduced coating stability. The insufficient wax content in these samples likely resulted in a less uniform distribution, making them more prone to wear and wash-off. High durability coatings are often related to the degree of wax crystallinity and fiber–coating adhesion strength[14]. And these findings highlight the importance of optimizing beeswax concentration to balance durability and functionality in fabric coatings. Washing durability test results are given in table 11.

Table 11 — Washing Test

Sample	Weight Loss (%)
	10.94
Twill Beeswax 40g	2.67
Satin Beeswax 100g	0.92

Table 12 — Contact Angle Retention of Beeswax-Coated Fabrics

Sample	Pre-Wash (°)	Post-Wash (°)	Retention (%)
Plain 40 g	112	92	82.1
Twill 80 g	118	112	94.9
Satin 100 g	122	118	96.7

Table 13 — Antimicrobial Retention of Beeswax-Coated Fabrics

Sample	Pre-Wash ZOI (mm)	Post-Wash ZOI (mm)	Retention (%)
Plain 40 g	22	14	63.6
Twill 80 g	32	28	87.5
Satin 100 g	27	25	92.6

Table 14 — Thickness Test

Sample	Thickness (mm)
Plain Beeswax 60g	0.82
Twill Beeswax 80g	1.01
Satin Beeswax 100g	1.12

3.6.1 Post-Washing Performance Evaluation

The functional durability of beeswax-coated fabrics was quantitatively evaluated by measuring contact angle and antimicrobial activity after one standardized wash cycle. The results are summarized in Table 12 and 13.

The satin weave (100 g) showed the highest hydrophobic retention (96.7%), indicating strong wax adhesion and minimal structural degradation. Twill 80 g retained 94.9%, confirming optimal balance between penetration and surface coverage. Plain 40 g exhibited significant reduction due to insufficient coating add-on.

Twill 80 g retained 87.5% antimicrobial efficiency, whereas satin 100 g retained 92.6%. Lower retention in plain weave confirms weaker wax bonding and partial bioactive loss.

Statistical comparison using paired t-test indicated that reductions in 80 g and 100 g samples were not statistically significant ($p > 0.05$), while 40 g samples showed significant reduction ($p < 0.05$).

These quantitative findings confirm that optimized beeswax concentration (80–100 g) ensures functional stability after laundering.

3.7 Thickness Test

Fabric thickness was measured using a digital thickness gauge at five locations on each sample to account for coating variations. The average value was calculated to ensure consistent and reliable analysis of the beeswax coating's impact on fabric structure. Thickness test results are given in table 14.

The study on beeswax-coated cotton fabrics has revealed significant insights into how weave structure and coating concentration influence the fabric's antimicrobial, hydrophobic, and durability properties, particularly in the context of sustainable food packaging. Among the tested samples, the twill weave fabric coated with 80 grams of beeswax demonstrated the most effective antimicrobial activity, achieving a zone of inhibition of 32 mm against *Escherichia coli*. This is attributed to the structural configuration of the twill weave, which allows better beeswax retention and more uniform distribution of the antimicrobial agents within the coating. Beeswax contains bioactive compounds such as long-chain fatty acids and esters that interfere with bacterial cell membranes and inhibit microbial proliferation[1]. The study's findings confirm that the combination of twill structure and optimal beeswax concentration significantly enhances microbial resistance.

Fourier Transform Infrared Spectroscopy (FTIR) analysis supported the chemical integration of coating materials into the cotton fabric. Spectral peaks identified in the coated samples corresponded to functional groups such as esters, alkanes, alcohols, and ethers. The presence of carbonyl groups (C=O) and methylene (CH_2) stretches indicated the inclusion of hydrophobic esters and long-chain hydrocarbons derived from beeswax and coconut oil. These functional groups are critical in enhancing the fabric's water resistance and mechanical flexibility. The analysis also confirmed the role of pine rosin and coconut oil in improving coating adhesion and plasticity, contributing to overall performance improvements[1].

Hydrophobicity was verified through the drop penetration test. Uncoated cotton fabrics exhibited immediate water absorption due to their high surface energy, while all beeswax-coated fabrics showed no water penetration. This complete water repellency is a result of the low surface energy created by the wax coating, which prevents moisture absorption. The long hydrocarbon chains present in beeswax play a vital role in reducing wettability, forming a durable hydrophobic barrier. This finding supports the practical utility of beeswax-coated fabrics in preserving food by preventing moisture-related microbial growth.

The coating's effectiveness was further reflected in the fabric's GSM (grams per square meter), which increased significantly in satin weave samples. Satin weave, characterized by fewer interlacements and longer floats, allowed higher wax absorption and retention, resulting in a GSM increase up to 115.7 g/m². This not only enhances the fabric's mechanical stability but also ensures long-term effectiveness of the coating. The superior wax retention in satin weave fabrics provides better protection and functionality, although the antimicrobial performance of twill weave remained superior[16].

Durability of the coated fabrics was examined through a washing test, where samples with higher beeswax concentrations (especially 80g and 100g) demonstrated minimal weight loss after laundering. The satin weave with 100g of beeswax exhibited only 0.92% weight loss, indicating excellent wax adhesion and coating integrity. Conversely, samples with lower beeswax content showed significant degradation, highlighting the need to optimize coating concentrations for long-term use. Over-saturation, however, may lead to partial wax loss due to insufficient bonding in the non-absorbed surface areas, emphasizing the importance of balance between concentration and fabric absorbency[17].

Thickness measurements showed a direct relationship with beeswax content. The coated fabrics exhibited increased thickness, with satin weave coated with 100g of beeswax reaching 1.12 mm. While this increase in thickness enhances the barrier properties of the fabric, it can also reduce flexibility if over-applied. Therefore, careful control of wax concentration is essential to maintain functionality without compromising usability.

Overall, the study concludes that both weave structure and beeswax concentration are crucial parameters that must be optimized to achieve desired antimicrobial, hydrophobic, and durable properties in textile-based food wraps. Twill weave combined with 80g of beeswax offers the best balance of antimicrobial efficacy and durability, while satin weave supports maximum wax retention and water resistance. The results align with prior research on the role of natural waxes in textile finishing and the impact of weave architecture on functional fabric properties. These insights validate the potential of beeswax-coated cotton fabrics as a sustainable and practical alternative to single-use plastic food wraps, contributing to environmentally responsible packaging solutions.

3.8 Functional Performance Changes Relevant to Packaging Standards

The beeswax-based coatings alter the mechanical and structural behaviour of the fabric as required for food-packaging applications. Flexibility decreases moderately with increasing wax concentration due to stiffening of fiber surfaces, but the addition of coconut oil improves pliability, keeping the coated fabric foldable and suitable for wrapping. Drape behaviour becomes slightly reduced because of the higher GSM and thickness, though still adequate for conforming around food surfaces. Stretchability remains largely unchanged, as woven cotton has minimal inherent elasticity, and the wax layer does not significantly affect yarn extensibility. Porosity reduces substantially as wax fills the interfiber gaps, resulting in controlled breathability; this reduction aligns with requirements for semi-permeable food packaging where moisture control is essential[32,33]. Air and moisture permeability also decrease, creating a protective barrier that slows microbial growth and food dehydration. These changes match the functional benchmarks observed in conventional reusable wax wraps, which rely on reduced porosity, moderate flexibility, and low permeability to maintain food freshness[20,34].

4. Conclusion

The research effectively demonstrates that beeswax-coated cotton fabrics are a promising solution for sustainable food packaging, with the fabric weave structure and coating concentration being critical determinants of performance. Among the samples tested, the twill weave with 80g of beeswax exhibited the highest antimicrobial efficacy, achieving a maximum zone of inhibition of 32 mm against *E. coli* , indicating optimal bioactivity due to enhanced wax retention and uniform surface coverage. FTIR analysis confirmed the presence of functional groups such as esters and hydrocarbons, validating the integration of wax and oils, which contribute to hydrophobicity and antimicrobial action. Drop penetration tests confirmed complete water repellency in coated samples, attributed to the low surface energy introduced by beeswax. The satin weave exhibited the highest GSM and thickness, demonstrating superior wax absorption and retention due to its longer floats, enhancing durability and barrier properties. Additionally, washing tests revealed that fabrics coated with 80g and 100g of beeswax showed minimal weight loss, indicating excellent adhesion and coating stability. In addition to the confirmed activity against *E. coli*, assumed antimicrobial trends suggest that beeswax-coated fabrics are likely to show even greater inhibition against Gram-positive bacteria such as *Staphylococcus aureus* and *Bacillus subtilis*. This indicates strong potential for broad-spectrum antimicrobial performance, although experimental validation is recommended to confirm this expected result.

Quantitative post-washing evaluation confirmed that hydrophobic and antimicrobial properties were retained above 85% for optimized coatings (80 g–100 g), validating functional durability beyond qualitative observation.

However, excessive coating at 100g led to marginal wax loss due to oversaturation. Overall, the study confirms the technical viability of beeswax-coated woven cotton fabrics as biodegradable, reusable, and functional alternatives to plastic wraps in food packaging applications.

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