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DEVELOPMENT, CHARACTERIZATION AND APPLICATION OF POLYLACTIC ACID COATED BANANA PSEUDOSTEM PAPER FOR FOOD PACKAGING

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Abstract

The increasing demand for natural andbiodegradable food packaging has driven research into alternatives to conventional plastic materials.Among the various natural sources investigated, banana pseudostem exhibits considerable potential; however, its utilization remains largely unexplored. The present study investigated the feasibility of utilizing banana pseudostem (BS) fibres for the production of eco-friendly packaging material. Paper sheets were developed from both short and long-stranded fibres, with and without polylactic acid (PLA) coating. The study also focused on the application of the BS paper in substituting conventional popcorn box. Tray drying of BS (65.5±5°C/16 h) yielded optimal results with 94.5% reduction in moisture content. Delignification improved cellulose content before paper sheet preparation. PLA coating provided a shiny surface and significantly improved the strength and flexibility of the paper. Thickness and grammage of the paper increased with PLA coating, with double-sided coating resulting in the highest values (0.68±0.1mm and 294.5±2.1g/m²) respectively. PLA coating effectively reduced the paper's water absorbency (from 567.07 g/m² to 41.4 g/m²), offering better water resistance. Bursting strength was higher for long-strand compared to short-strand paper; and double-sided PLA coating provided the best resistance in both cases (8.25±0.4kg/m²). Similar trends were observed for tearing and tensile strength. Soil burial test confirmed thatuncoated paper was most biodegradable. Further popcorn boxes were successfully developed using PLA-coated BS paper, exhibiting no significant difference in popcorn quality and excellent oil resistance. PLA-coated BS paper has good potential as a biodegradable packaging material with good oil resistance.

Keywords Banana pseudostem fibres · Long and short strand · PLA coating · Popcorn-box

1 Introduction

Food packaging is one of the most vital element in the modern food processing industry. Paper, produced from the fibre of soft wood trees is widely used in food packaging. The papyrus plant, from which the name "paper" originated, was utilized by the Egyptians to create the first rough writing material ever. Kraft paper, greaseproof paper, glassine paper, paper board, wrapping tissue paper and waxed paper are some of the major types of paper used in food industries [1].Around 90% of paper produced worldwide has historically been made from wood, relying heavily on forest resources. However, the increased demand for wood fibre has resulted in a rise in deforestation [2]. In India, only 25–27% of wastepaper was reutilized compared to global recovery rate of 58% [3]. Many companies are looking for sustainable packaging options as environmental issues become more relevant. Several investigations are in progress, one of which involves using natural fibres in various ways by extracting it from the surrounding environment to create a biodegradable substance that does not harm the environment. Biopolymers have become leading food packaging materials with the advantages of biodegradability, processability, combinability and no food contamination. Some biopolymers would even act as compost and soil improvers [4]. Agricultural by-products, such as banana pseudostem can serve as the raw material for such biopolymers.

Bananas are one of the most important crops in the world, behind rice, wheat, and corn [5]. Pseudostem obtained from banana is the section of the plantain plant that is made up of tightly overlapping leaf sheaths and a fragile core in the middle. Plantains are grown primarily for their fruits, while other elements

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such as leaves, inflorescence, pseudostem, peels, and rhizomes are practically considered as waste [6]. Approximately 4 tonnes of biomass wastes, comprising rotten fruit, leaf, pseudostem, rhizome, and fruit bunch stems, are produced for each tonne of banana fruit collected [7]. A fully matured banana pseudostem has 20–25 layers of flesh sheaths. Banana pseudostem was effective in paper making due to its high cellulose content, low lignin content, and desirable pulp yield and papermaking properties. After harvesting, the pseudostems are generally discarded as waste or burnt after drying, thus causing substantial pollution. In a few places, it was used as a biofertilizer. The pulp produced from banana pseudostem has a high tensile index, tearing index, smoothness, and porosity, indicating high mechanical strength and good surface properties [8].

Though fibres are a good base material for the manufacture of biopolymers, they lack barrier properties against water vapour and gases. Thus they usually utilized in combination with bioplastics such as polylactic acid (PLA), which enhance their barrier properties. PLA is obtained from lactic acid monomers by catalytic ring-opening polymerization or by condensation polymerization of the lactides. These monomers are synthesized by fermenting corn, beet sugar, cane sugar, among others [9]. PLA offers superior properties over other widely used biodegradable polymers, including transparency and excellent thermal and mechanical properties [10].

The present study investigated the feasibility of utilizing banana pseudostem (BS) fibres to produce eco-friendly packaging material and examined their physical, mechanical and structural properties. The study evaluated the feasibility of using banana pseudostem paper boxes as a replacement for commercial popcorn boxes.

2 Materials and methods

Pseudostems of *Njalipoovan*, a banana of local variety, were collected after harvest, from a local farmin Ernakulam district, Kerala, India. Poly-lactic acid (PLA) was purchased from NATURTECH Chennai, India. All chemicals used, including sodium hydroxide, hydrogen chloride, ethanol, chloroform were of analytical grade.

2.1. Sample preparation

The collected banana pseudostems were washed to remove adhering soil and dirt. Further, the external strip layer was removed and the remaining portion was cut into small pieces (approximately 4-5 cm). The chopped banana pseudostem was then dried until a constant weight was attained.

2.2 Drying of banana pseudostems

The drying characteristics of the banana pseudostems were studied under solar and tray drying (65±5°C) conditions as per the method described by Chakraverty [11]. Weights of the samples were taken after constant time intervals until constant weight was obtained. After the drying period, drying rate (R) in g of water removed per minute per 100 g of bone-dry material was calculated as follows

$$R = \frac{Amount\ of\ moisture\ removed}{Time\ taken(min) * Total\ bone\ dry\ weight\ of\ sample} \times 100$$

2.3 Preparation of banana-pseudostem-based packaging material from short and long strand fibres

The flow chart for the preparation of banana pseudostem-based packaging material is shown in Fig. 1. Paper was prepared from short-stranded fibres obtained from powdered dried banana pseudostem. Long stranded fibre was prepared by minimal processing to retain fibre length. Shredding by hand or using a low-power beater, reduced the chance of fibre breakage.

2.6 Moisture content of banana pseudostem

The moisture content in powdered raw material was determined using the oven dry method [12]. The moisture content was calculated using the following equation.

$$Moisture\ \% = \frac{W_3 - W_1}{W_2 - W_1} \times 100$$

where W_1 -weight of empty dish
W_2 -weight of dish + sample
W_3 -weight of dish + sample after drying

2.7Analysis of ash

The ash content of sample was determined according to AOAC method [13].

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

$$Ash\% = \frac{Weight\ of\ ash}{\text{weight of sample}}$$

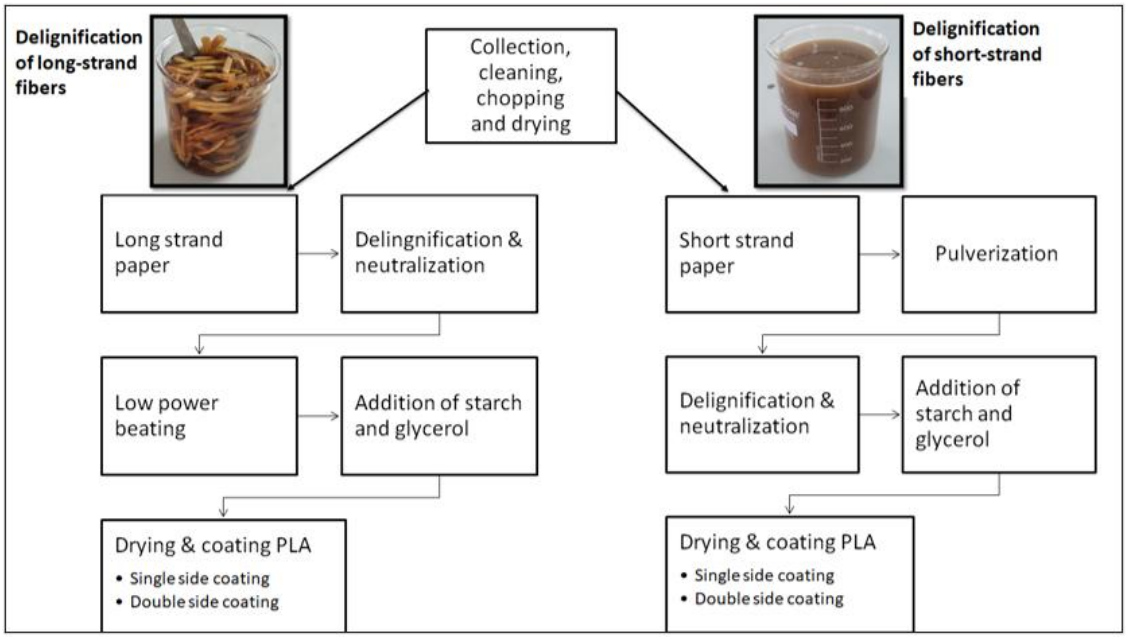


Fig.1 Preparation of BS Paper

2.8 Colour analysis of BS paper

The colour of the obtained paper was analysed using Hunterlab colorimeter (Miniscan EZ) in terms of L* (brightness/darkness), b* (yellowness/blueness), a*(redness/greenness). The instrument was standardized and the L*,a*,b* values were measured [14].

The hue (h*) and chroma (c*) were calculated using the formulas: -

$$h* = tan - 1\left(\frac{b^*}{a^*}\right)$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

2.9 Thickness of the BS paper

The thickness was measured at five separate points using a handheld micrometer (Yusuki China) and the average thickness was calculated with a precision of 0.001mm [15].

2.10 Grammage of BS paper

A substance tester, also known as a paper GSM tester, was used to measure the grammage of paper. The tester directly displayed the grammage (g/m²) of the paper sample.

2.11 Moisture content of BS paper

The moisture content of paper was determined by drying the weighed paper using a hot air oven (110°C for 24 h). The mean weight of five samples were taken and the results were expressed in percentage [12].

$$Moisture\ \% = \frac{W_3 - W_1}{W_2 - W_1} \times 100$$

where W_1 -weight of empty dish

W_2 -weight of dish + sample

W_3 -weight of dish + sample after drying

2.12 Solubility of BS paper

All the films were previously dried in oven at 50°C and BS paper (4cm x 4cm) was accurately weighed to determine the initial dry weight (W_1). Then each film was placed in a 50 mL beaker containing 30 mL distilled water and kept at room temperature (25°C) for 24 h with occasional agitation. After 24 h, the swollen papers were taken out and water on the surface was blotted with tissue paper. Subsequently, the swollen paper samples were dried at 50°C for 24 h and weight noted (W_2). The percentage of dissolved dry matter in water was calculated using the formula.

$$Solubility\ (\%) = \frac{Initial\ dry\ weight(W_1) - Final\ dry\ weight(W_2)}{Initial\ dry\ weight(W_1)}$$

2.13 Water absorptiveness of BS paper (Cobb value)

Cobb test is a standard method to measure the water absorbency of paper and paperboard, determining their resistance to liquid

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

penetration. It involves placing a specific area of paper or paperboard in a specific volume of water for a set time; then measuring the weight of absorbed liquid to calculate the Cobb value as described in ISO 535 [16].

The Cobb value can be obtained by using the following equation: -

$$Cobb\ value\ = \frac{(W_2 - W_1)}{S}$$

where W_1 and W_2 are the weights of paper before and after water absorption, respectively, and S was the surface area of the paperboard sample (96cm^2)

2.14 Water vapour transmission rate (WVTR) of BS paper

Water vapor transmission rate (WVTR) is a measure of water vapor passing through a packaging material under test conditions. The WVTR of BS paper was measured using the method described in ASTM E96-66 [17] and calculated using the following equation.

$WVTR = \frac{Q \times 24 \times 90}{At}(H_1 - H_2)$ g/m^2/24h at 90 ± 2% RH & 37°C

where Q = quantity of water vapour passing through the test material of area Am^2 for t h when the relative humidity on either side was maintained at H_1 and H_2

2.15 Bursting strength of BS paper

Bursting strength of the paper was evaluated using a bursting strength tester (Ubique Enterprises, Pune) in accordance with ISO 2758:2014. This test method determines the paper's capacity to withstand pressure, with results expressed in kg/cm^2 [18].

2.16 Tearing strength of BS paper

Tearing strength was tested using a tearing strength tester (Ubique systems, Pune). Tearing strength was determined in gram force based on the reading in the scale (ASTM D689) [19].

2.17 Tensile strength and elongation at break of BS paper

Mechanical properties of the particle board were analysed by the Universal Testing Machine (Shimadzu EZLX) of 5 kN loading capacity. Tensile strength and elongation at break of each paper sample were evaluated in accordance with the American Society for Testing and Materials [20].

2.18 Scanning electron microscopy (SEM) of BS paper

The morphological analysis was carried out using SEM (JEOL JSM-6390LV, Japan) to observe the film morphology. All the images were taken at 2500 magnification with an accelerating voltage of 20 kV and a resolution of 10 µm.

2.19 Fourier-transform infrared spectroscopy (FT-IR) of BS paper

Infrared Spectroscopy (Vibrational spectroscopy) deals with the interaction of matter with electromagnetic radiation. It is widely used as an analytical method for the determination of functional groups in a molecule. The FT-IR patterns of the synthesized samples were recorded in the range of 650-4000 cm^{-1} on IR spectrophotometer (Perkin Elmer, Model; SPECTRUM 400)

2.20 Soil burial test of BS paper

Soil burial test was carried out to examine the biodegradability of the samples in a laboratory scale. Specimens of definite sizes 2×2 cm were cut from each of the samples. Moist soil (13% moisture) was placed into plastic containers with tiny holes perforated at the bottom and on the body of the container to increase air and water circulation. Samples of each uncoated and coated of both short- and long-strand paper were buried in a depth of 5 cm and retrieved every seven days from the soil and changes were observed up to 30 days. Further, the weight of the sample was monitored. Commercial kraft paper was taken as the control for comparison.

2.21 Evaluation BS paper as an alternative for popcorn box

The selected PLA coated long-strand BS paper was moulded into a popcorn box and evaluated as a potential alternative to traditional paperboard boxes. A market available paperboard popcorn box was used for comparison. Both boxes were filled with equal quantity of pop-corn.

To assess oil resistance, two prevalent methods of Tappi (Technical Association of the Pulp and Paper Industry) test methods were employed as described below:-

2.21.1 Kit test (ASTM D722 / TAPPI T 559:2009 The Kit Test)

To conduct an oil repellence test, circular samples were cut from the packaging material and conditioned for 24 h (23°C and 50% RH). The sample was placed in a petridish and a drop of oil was applied to the centre of the sample. The petridish was then closed with the

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Vol 2/Issue1/ January--June/2026

lid. Thereafter, the dish was positioned under a light source for 30 seconds and the spreading behaviour of the oil drop was observed. Changes in translucency due to oil absorption and time taken for complete oil absorption was noted [21].

2.21.2 Gravimetric oil absorption test (ASTM D726 / TAPPI T460)

To conduct this test, squares (2 x 2 cm) were cut from the packaging material and weighed accurately, Samples were dried in an oven at 105°C for an hourand then cooledin a desiccator. Each sample was placed in a separate beaker or weighing dish; one drop of test oil was added and soaked for 30 min. After soaking, excess oil was removedand the samples were dried at 105°C for 1 h [22]. Percentage of oil absorbed for each sample was calculated using the formula: -

$$Oil\ absorption(\%) = \frac{W_3 - W_1}{W_2} \times 100$$

where W_1= initial weight of the sample. W_2= weight of sample after drying. W_3= weight of the sample after soaking in oil and drying.

3 Results and discussion

The study was undertaken to prepare an ecofriendly packaging material from BS fibres and to evaluate its physical, mechanical and structural properties. Feasibility of using BS paper boxes as a replacement for commercial popcorn boxes was also evaluated. The results are compiled in the subsequent sections.

3.1 Drying of BS fibres

Sun drying is a traditional and cost-effective method for drying banana pseudostem, offering simplicity, affordability, and widespread applicability. In the present experiment, both sun drying and tray drying of the BS fibres were carried out. For sun drying, temperature varied from 35 to 40°C at peak daytime and humidity (77% RH). On the other hand, tray drying was carried out at constant temperature of 45°C. Tray drying has been reported to be the optimum method for drying, according to previous studies [23]. After tray drying, the overall yield of the dried BS was found to be approximately 4.9±0.92%.

3.2 Moisture and ash of dried BS

Moisture content of the dried BS sample was found to be 13.40±0.76%. The banana pseudostem contains 13.5% ash, which specifies rich mineral content. The study on different banana pseudostems varieties by Khan et al. [24] also found the highest ash content up to 13.4±0.78%.

3.3 Preparation of BS/ PLA paper

Banana pseudostem based packaging material was prepared from both long-strand and short-strand fibre and were further coated with biodegradable PLA film.

Short-stranded BS paper resembled thin carboard sheets (Fig. 2a) making it a good alternative for the preparation box containers. It had a bright yellowish-white appearance. The texture of the paper which was in contact with the silicon tray had a very smooth texture; while upper side was rough. PLA coated BS paper (Fig.2b) exhibited increased strength and flexibility as compared to its uncoated counterpart in physical examination.

Long-stranded BS paper was very flexible and can be rolled or folded. Physical examination also showed that the strength of long-stranded BS paper was higher than paper made from short-stranded fibre. Thus, it can be used for making pouches and paper bags. It had a yellowish appearance on the bottom side (Fig. 2c) and slight brownish appearance on the upper side (Fig. 2d). It had an overall smooth texture on both sides. PLA coating increased the smoothness, rigidity and impart whitish colour to the paper (Fig. 2e & f).

3.4 Colour analysis of BS paper

Colour analysis in terms of L* (brightness/darkness), b* (yellowness/blueness), a* (redness/ greenness) of banana pseudostem paper are shown in Table 1.

Short strand paper (both uncoated and PLA coated) appeared to be marginally lighter than long strand paper samples. Short strand paper had the highest L* value of 55.84±0.03. The effect PLA coating had a minimal influence on the colour properties of short strand paper, with a slight decrease in L* value. In contrast. PLA coating on long stranded

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

paper resulted in slightly brighter colour (higher L*), reduction in redness (lower a*), decrease in yellowness (lower b*) and slight reduction in colour intensity (c*). Gregor-Sveta & Sumrada et al. [25] also reported similar findings that PLA coating resulted decrease in brightness of less than 2% and a slight decrease in opacity.

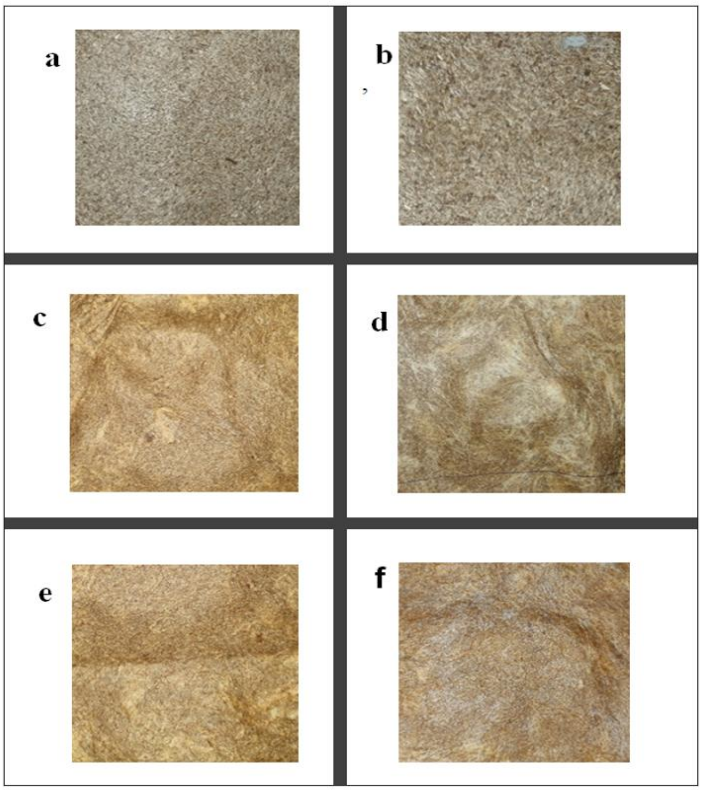


Fig. 2 Paper made from BS fibres, (a) Uncoated short-strand BS fibre paper, (b) PLA coated short-strand BS fibre paper, (c) Upper-side of uncoated long-strand BS fibre paper, (d) Lower side of uncoated long-strand BS fibre paper, (e) Upper-side of PLA coated long-strand BS fibre paper, (f) Lower side of PLA coated long-strand BS fibre paper

Table 1 Color analysis of BS paper

BS paper sample	L*	a*	b*	c*
Short strand	55.84±0.03^{a}	6.27±0.01^{d}	17.96±0.3^{c}	19.02±0.03^{d}
PLA coated short strand	53.52±0.5^{b}	6.34±0.1^{d}	17.96±0.1^{c}	19.04±0.1^{d}
Long strand: lower side	44.5±0.5^{d}	12.14±0.3^{a}	24.48±0.3^{b}	27.32±0.3^{a}
Long strand: upper side	53.81±1.6^{b}	7.42±0.4^{c}	21.78±0.5^{ab}	23.01±0.4^{c}
PLA coated long strand: lower side	46.59±0.9^{c}	11.16±0.4^{b}	22.48±1,8^{ab}	25.09±0.6^{b}
PLA coated long strand: upper side	52.59±1.8^{b}	7.54±0.3^{c}	22.23±1.2^{a}	23.47±0.06^{c}

Values in the same column with the same superscript letter are not statistically significant from each other ($p>0.05$)

3.5 Thickness of the BS paper

The average thickness obtained for short- and long-strand uncoated BS paper were 0.507±0.06 mm and 0.504±0.12 mm, respectively (Table 2). PLA coated on one side of paper, showed increased thickness due to

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

the direct addition of the PLA layer. Coating both sidesresulted uniform increase in thickness and doubles the potential for filling fibre gaps, while providing extra layer of protection. Short-stranded BS paper PLA coated on both side (0.855±0.09 mm) showed increase in thickness compared to long stranded paper (0.68±0.16 mm). Similar results were obtained in the study conducted by Rhim et al. [26] on coating of PLA to paperboards.

Table 2 Physical characteristics of BS paper

Paper Characteristics	Short-strand paper	Long-strand paper	Single-side PLA coated		Double-side PLA coated	
			Short-strand paper	Long-strand paper	Short-strand paper	Long-strand paper
Thickness (mm)	0.507±0.06	0.504±0.11	0.804±0.08	0.559±0.11	0.855±0.09	0.68±0.16
Grammage (g/m^2)	225±1.4	239±1.4	215±1.4	243.5±1.4	284±2.8	294.5±2.1
Moisture content (%)	13.62±0.03	10.03±0.1	9.8±0.11	8.43±0.26	8.45±0.14	5.53±0.16
Paper solubility (%)	21.8±0.23	21.78±0.28	17.47±0.46	13.14±0.08	6.18±0.31	5.56±0.54
Water absorptiveness of paper (g/m^2) (Cobb Test)	603.74±39.5	296.89±38.0	82.72±16.5	567.06±7.7	95.24±2.4	41.40±1.9
Bursting strength (kg/cm^2)	4.72±0.3	7.17±0.4	4.55±0.07	5.77±0.3	6.17±0.4	8.25±0.4
Tearing strength (Gram force)	11±1.4	35±0.5	17±0.7	33±1.4	27±1.4	37±1.4
Tensile strength and (kg/cm^2)	33.66±0.09	216.88±4.21	25.25±1.39	171.67±0.26	36.9±0.76	226.19±2,9
Elongation at break (%)	5.13±0.01	26.05±0.5	6,09±0.3	15.88±0.2	9.46±0.1	24.76±0.6

Note: All values are average of three trials (mean ± SD)

3.6 Grammage of BS paper

Polymer coating increases the GSM (grams per square meter) of paper. Single-sided PLA coated samples showed slight increase in grammage: 239±1.4 g/m^2 (short-strand BS paper) and 286±2.8 g/m^2 (long stranded paper) is shown in Table 2. Further increase in grammage was seen in samples coated with PLA on both sides. The values obtained were 245±1.4 g/m^2 and 294.5±2.1 g/m^2 for short- and long-stranded BS paper, respectively. Increased thickness corresponds to increased GSM. Therefore, it was a suitable material for making rigid food boxes. A similar trend in the increase of thickness and paper weight was seen in the study conducted by Sundar et al. [27] on kraft paper coated with PLA.

3.7 Moisture Content of BS paper

The moisture content of the both short-strand and long-strand paper is shown in Table 2. The average moisture content of the uncoated BS papers was found to be 13.62±0.03% (short strand BS paper) and 10.03±0.1% (long stranded BS paper). Single sided PLA coated papers showed a slight decrease in moisture level: 9.8±0.1% (short strand BS paper) and 8.43±0.2% (long strand BS paper). Double side PLA coated paper exhibited maximum protection with lowest moisture content of 8.45±0.1% (short strand BS paper) and 5.53±0.1% (long strand BS paper). BS paper naturally possesses a certain degree of

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

porosity, allowing for moisture movement through capillary action. The addition of less porous PLA coating decreased the paper's overall porosity by filling the voids and subsequently reducing the moisture content. Interestingly, similar results were reported by Sundhar et al. [27]. Moisture content of uncoated kraft paper was found to be 6.32%. PLA coating decreased moisture content to 5.46%.

3.8 Solubility of BS paper

The paper solubility of coated and uncoated short-and long-strand papers is shown in Table 2. Coated paper had lower solubility in water than the uncoated counterparts due to the water-repellent properties of PLA, thus giving extra protection. Long-stranded fibres create a stronger, less porous paper structure due to better fibre entanglement and interlinking, hindering water penetration and resulting in lower solubility. Short-stranded paper showed slightly higher solubility due to its inherent porosity, creating more voids within the paper matrix. However, the difference observed between short- and long-strand coated papers was less significant compared to uncoated paper.

3.9 Water absorptiveness of BS paper (Cobb value)

The hydrophobic nature of PLA coating significantly reduced the cobb value, while the uncoated side retains water absorption properties. Double-sided PLA coated paper had the lowest cobb value due to water repellent property of PLA, leading to a drastic reduction in the cobb value: 82.72 g/m² (short-strand paper) and 41.4 g/m² (long-strand paper) (Table 2). Similarly, cobb value of the paperboards decreased from 21.38 g/m² for the uncoated paper board to 0.20 g/m² for 3% PLA-coated paperboard [28]. Similar results were obtained on PLA coated kraft paper Rhim et al. [26], where the water absorptiveness of the paperboards decreased 12–18 times by coating with PLA. However, the reversed phenomena was observed in paper coated with hydrophilic biopolymers such as whey-protein, alginate and soya-protein [29, 30]

3.10 Water vapor transmission rate of BS paper (WVTR)

The average WVTR of the uncoated long strand paper (40 g/m²) was significantly ($p < 0.05$) lower compared to the uncoated short strand paper (52 g/m²) as shown in Table 3. Long fibres create a more tortuous path for water vapor diffusion, leading to a higher resistance and lower WVTR. The PLA coating significantly reduced the average WVTR for both long strand (14 g/m²) and short strand papers (16 g/m²) compared to their respective uncoated counterparts. These results showed that hydrophobic nature of PLA creates a barrier that hinders water vapor permeation. The difference in WVTR between coated long and short fibre paper might be minimal or even insignificant depending on the PLA coating efficiency. Similarly, the WVTR of PLA film (thickness: approximately 90 µm) prepared by solution casting method was 4.66±0.25 g/m² though water vapor barrier properties of the paperboard improved greatly by coating with PLA. However, the results are still lower than those of PE-coated paperboard, where WVTR at RH 99.92 ± 0.03% was 8.71 ± 0.29 g/m² [30].

Table 3 WVTR of BS paper

BS paper samples	WVTR
Short strand	52±0.5 g/m²
Double-side PLA coated short-strand	16±0.7 g/m²
Long-strand	40±0.8 g/m²
Double-side PLA coated long-strand	14±0.4 g/m²

3.11 Bursting Strength of BS paper

The bursting strength of uncoated BS paper in case of shortstrand paper was found to be low, 4.72±0.3 kg/m² compared to values of long stranded paper: 7.17±0.3 kg/m² (Table 2). This correlates the fact that long fibres tend to produce stronger paper than short fibres. Long fibres can interlock more effectively, leading to improved resistance to pressure. PLA coating given only on one side reduced the bursting strength of the both short and long-strand paper. This suggests that single-sided PLA coating might have a minor negative impact on the paper strength. Long-stranded BS paper coated with PLA on both sides showed highest bursting strength (8.25±0.4 kg/m²). Short-strand paper showed slight increase (6.17±0.4 kg/m²) compared to single-

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Vol 2/Issue1/ January--June/2026

coated and uncoated samples. Thus, PLA coating on both sides acts as a reinforcing shell to distribute the force evenly across the paper. Similarly, when carboxymethyl cellulose and sodium alginate were applied on BS greaseproof paper, bursting strength was increased [31]

3.12 Tearing strength of BS paper

Tearing strength of both short- and long-strand BS papers are shown in Table 2. Long strand paper constantly exhibited higher tearing strength of 35±0.5 gf compared to short strand paper (11±1.4 gf). Long fibres offer better resistance to tearing forces by bridging gaps and redistributing stress across a larger area. When PLA was applied on one side, it could not effectively distribute the tearing force across the entire material thickness, therefore, a reduced value compared to uncoated paper was recorded. Slight increase of tearing strength was observed for short strand-paper because of the leaching of PLA into fibre voids. PLA coating on both sides appears to provide a greater improvement in tearing strength compared to one-sided coating for both short- and long-strand paper. This suggests that a complete encapsulation by PLA offers a more uniform distribution of tearing force and better protection against tear initiation from any direction. Similar results were obtained by Razak et al. [32] on coating PLA to pineapple leaf pulp.

3.13 Tensile strength and elongation at break of BS paper

Long-stranded paper exhibited higher tensile index of 216.88±4.2 kg/cm^2 compared to short-stranded paper (33.66±4.2 kg/cm^2) (Table 2). The addition of PLA to short-strand paper resulted in slight increase in elongation at break compared to pure BS paper (6.09±0.3%). This is due to the inherent flexibility of PLA compared to the paper fibres. Tensile strength of long-strand paper dropped to 15.88±0.2%. Similarly, for short-strand coated on both sides, the value again increased to 9.46±0.1%. For long-strand paper, PLA on both sides acts like a stiff layer. The value decreased to 24.7±0.6%. The results obtained in different studies does not follow a consistent trend as both tensile strength and elongation at break increased significantly as a result of PLA coating on paper board [33].

3.14 Scanning electron microscopy of BS paper

The SEM images of long stranded BS paper is shown in Fig 3. It indicated the porous fibrous structure covered and filled with PLA coating. The coating materials acted like fillers such as clay, to provide a smooth surface. Higher magnification on the surface of PLA coated paper revealed internal dimple-like patterns as a result of solvent evaporation [34]. A paper coated with whey protein isolate [29] and a Kraft paper coated with PLA [26] also produced a more homogeneous and smooth coating surface than their uncoated counterpart.

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

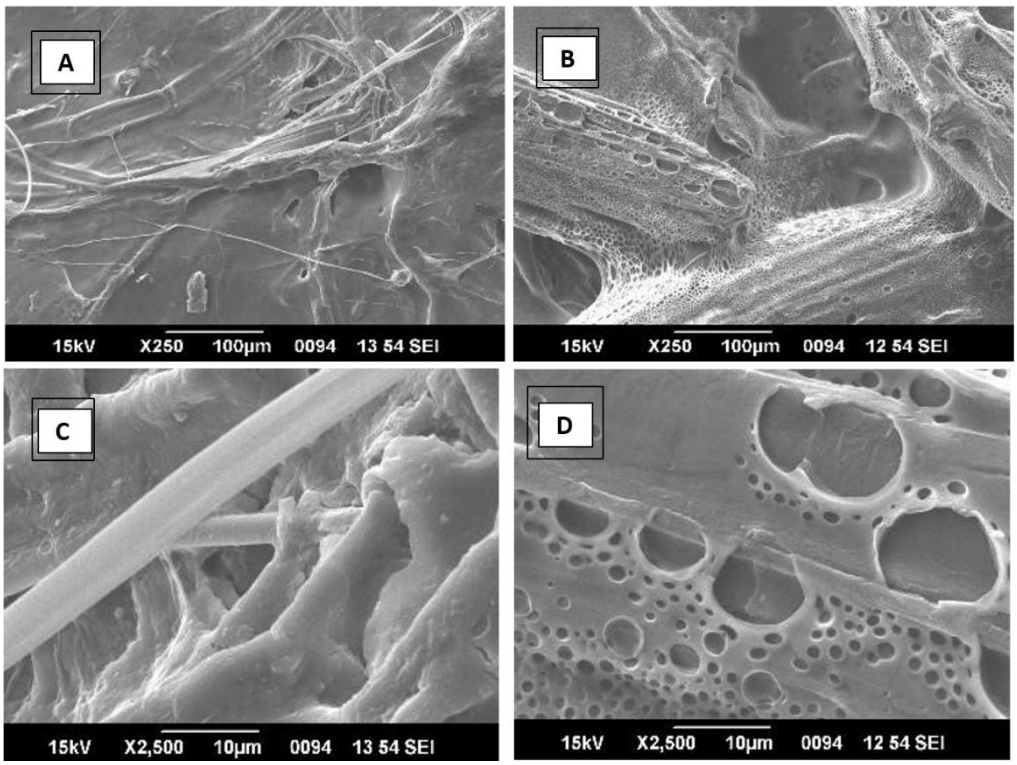


Fig. 3 SEM images of the uncoated and coated surface of long stranded BS paper, (A) uncoated paper at 250x, (B) coated paper at 250x, (C) uncoated paper at 2500x, (D) coated paper at 2500x

3.15 Fourier-transform infrared spectroscopy (FT-IR) of BS paper

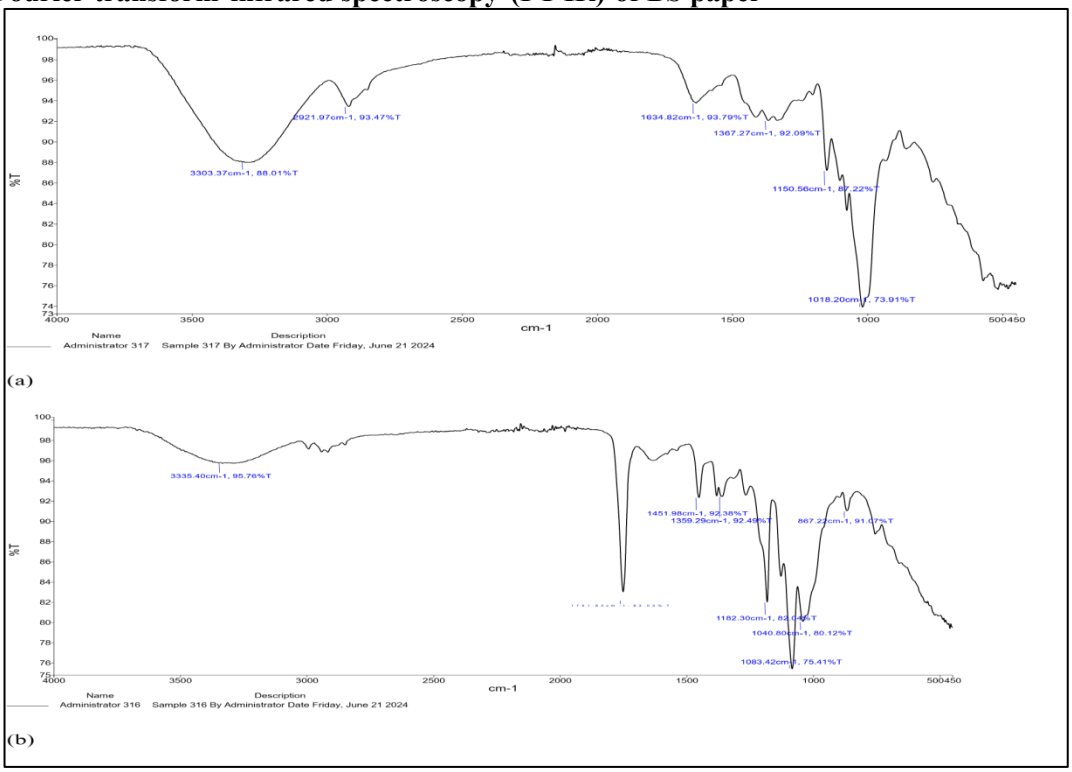


Fig. 4 FTIR spectrum of uncoated BS paper, (b) FTIR spectrum of coated BS paper

The FTIR spectrum of the control BS paper exhibited a band at 3300 cm^{-1}, which represented the intermolecular and intramolecular H bonds of free OH groups in cellulose (Fig 4a). It also displayed a C-H

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Vol 2/Issue1/ January--June/2026

stretching peak at 2900 cm^{-1}, as well as a peak at 1700 cm^{-1}, which represented the C=O stretching (acetyl group of hemicellulose and ester linkage of lignin). Characteristic peaks include C-O stretches around 1160 cm^{-1} and 1030 cm^{-1}. These IR vibrations are in agreement with the functional groups of lignocellulosic fibre [35]. Coating of 5% PLA (Fig 4. b) resulted in lower detection of the OH band compared with that of the control BS-paper. This was due to the PLA coating, since it limited exposed cellulose surfaces. The 1700 cm^{-1} peak (representing the acetyl groups of PLA) seemed to increase with the treatment, indicating that the BS-paper surfaces had been dominated by the hydrophobic functional group of the PLA, thus reducing the environmental moisture uptake. New peaks in the 1750-1700 cm^{-1} range were also introduced by addition of PLA, typically corresponds to C=O stretches in esters, a prominent functional group in PLA. Noticeably a new peak emerged at 1450 cm^{-1}, which represented the CH_3 band. This was due to the considerable amount of PLA present on BS paper. Furthermore, additional peaks exhibited between 1100-1250 cm^{-1}, potentially attributed to C-O stretches associated with PLA's ester groups or ether linkages. Interestingly, a comparative copy of the results was also obtained by Razak et al. [32] on coating PLA paper made from fibres obtained from pineapple. The FTIR spectrum of the control BS paper in Fig 4a exhibited a band at 3300 cm^{-1}, which represented the intermolecular and intramolecular H bonds of free OH in cellulose.

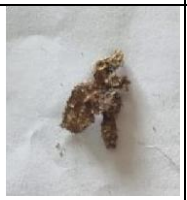
3.16 Soil burial test of BS paper

The pictorial representation of degradation shown by individual sample in each week is given in Table 4. PLA is generally considered to be biodegradable, but it can take longer time to breakdown than other organic materials [36]. BS paper, on the other hand, was expected to biodegrade relatively quickly. Uncoated BS paper showed 49% degradation for short-strand and 43% degradation for long-strand. This was observed within the first week itself. Uncoated short-strand BS paper showed the fastest degradation and it completely shredded and weighing was not possible in the second week. On the other hand, long strand paper showed more than three-quarter of degradation in second week. Single side coated PLA paper showed a gradual degradation with values near to 42% in the first week for short-stranded paper and 35% for long strand paper. Degradation in the second week rose to 65% for short-stranded paper and 60% in the case of long-strand paper. This was probably due to the degradation of BS fibres from the uncoated side; while the PLA coat was slowly degrading, protecting the other side. By third week, 75% degradation was complete for short strand paper and 73% for long-strand paper. Thereafter, degradation rate fell drastically and took four weeks to completely degrade. Double side coated paper showed the maximum resistance to degradation and took three weeks to achieve a degradation of 58% in case of short strand paper and 45% for long-strand paper.

PLA coating gives the BS fibres maximum protection from degradation and PLA also resisted degradation by itself. The study conducted by Sridach et al. [37] suggested similar results that uncoated paperboard samples broke down quickly when exposed to nutrient-rich soil. The coating layers were also biodegradable, but slower than the fibrous baseboard. The deterioration occurred locally, possibly at holes, grooves, or fissures in the coated layers. The board samples used in the study were not converted into packages, so the biodegradable coatings were likely to erode around the package's corners and creasing lines, allowing microorganisms easier access and increasing degradation. The biodegradable coatings have a tendency to break easily, making it possible that conversion processes will erode them, leading to further degradation [36].

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

Table 4 Pictorial representation of paper degradation

Sl. No.	Sample	Week 1	Week 2	Week 3	Week 4
1	Kraft paper				
2	Short-strand paper		Degraded	-	-
3	One-side PLA coated short-paper				Degraded
4	Both-side PLA coated short-strand paper				
5	Long-strand paper			Degraded	
6	One-side PLA coated long-paper				Degraded
7	Both-side PLA coated short-strand paper				

3.17 Application of PLA coated BS paper as popcorn boxes

The quality assessment based on the freshness of pop-corn packed in both control box and PLA coated BS paper-box was examined for a period of 30 min as shown in Fig. 5a. Similar changes in the freshness were observed and it was concluded that both control box and BS-paper box were not different from a sensory perspective. Kit test (TAPPI T559) with minor modifications was carried out for testing the penetration of oil into the BS paper coated with PLA. Samples were evaluated after 30 s for signs of penetration of oil into the sample

ISSN: 3139-0951 (Online)
Vol 2/Issue1/ January--June/2026

box. No stain or penetration of oil into the sample was observed, indicating higher resistance to oil. Thus, the double side PLA coated long strand paper was found to be a good container for carrying pop-corn.



Fig. 5 (a) Popcorn packed in both control box and PLA-coated BS paper box, (b) Oil absorption of popcorn packed in both control box and PLA coated BS paper box

On the other hand, the commercial popcorn box showed oil stains after conducting the test for 30 min (Fig 5.b). The oil absorption capacity of PLA-coated BS paper, measured using gravimetric method, was found to be significantly lower (17±0.8%) compared to kraft paper (48±0.5%). This indicated that the PLA coating effectively reduced the oil penetration into the BS paper. The lower oil absorption capacity of PLA-coated paper suggests its potential suitability for packaging applications requiring oil resistance, such as for greasy or oily food items (popcorn).

4 Conclusion

This study highlights the potential of BS fibres as a sustainable raw material for eco-friendly packaging applications. The ease of forming BS fibre sheets, as well as their economic value demonstrates high potential for large-scale production. The BS/PLA coated paper showed promise in packaging applications that require bio-derived resources and cost effectiveness. A significant advantage of this material is that the fibre source can be obtained from banana plant as a by-product. PLA coating enhances paper properties, including moisture resistance, strength, and flexibility. Double sided PLA coated long strand paper proved to be a promising sustainable food packaging material. Further research is recommended to optimize the production and coating process to explore different PLA ratios to create a fully marketable bio-based packaging material.

Author contribution ASN carried out the experiment and organized the data. VPR prepared the draft of the manuscript. MR and JAJ conceptualized and supervised the work, read and edited the manuscript. All authors read and accepted the manuscript.

Competing interests The authors declare no competing interests.

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