Investigation on mechanical and chemical properties of mechanically extracted banana fibre in pseudostem layers: From Sri Lankan banana (Musa) cultivation waste

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Abstract
This research investigates the factor influencing the quality of the fibre inside the banana pseudostem to determine which layers are suitable for delivering fine banana fibre. This research identifies the banana pseudostem layer-wise properties. Puwalu and Ambun fibres were obtained from the Kurunagala district in Sri Lanka. Banana fibres were separated from pseudostem by using a decorticator machine. Scanning electron microscopy, Fourier transform infrared spectrophotometer (FTIR) and universal tensile tester machine were used for the testing. The test results showed that the middle layers of the pseudostem to be the finest and strong. The lignin contains in the middle layer of fibre was lower than that of the first layer of fibres. The linear density of the ambun middle layer is 25 tex, the average diameter value is 80 µm and range of single fibre strength is 273–270 gf. Linear density of the puwalu middle layer is 29 tex, the diameter value was varying in between 98 and 100 µm and range of single fibre strength is 270–271 gf. The findings of this research will help anybody to select a suitable layer of Sri Lankan banana cultivars fibres based on physical and chemical properties. Then, these fine fibres can be a bridge over the extensive gap between natural cellulose substitute fibre demand.

Keywords
Pseudostem, banana fibre, fineness, strength, fibre diameter, fibre linear density, tenacity and moisture content

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Introduction
Sri Lanka cultivates about 56,216 hectares in the banana cultivation sector and produces around 46 million tons of pseudostem waste per year. In Sri Lanka, cities such as Ratnapura, Kurunegala, Badulla, Monaragala, Kandy, Gampala and Hambantota have large banana crops that grow all year round. Due to the vastness of the geographically distributed harvest of banana plants, this banana pseudostem has the potential to be employed as a natural fibre to be extracted for the purpose of manufacturing fibres in Sri Lanka. The pseudo stems of a banana plant is a large perennial herb with leaf sheaths that form the trunk and carry 8–12 leaves that are up to 2.7 m long and 0.6 m wide. When the leaves spread out the stem of the banana is a green, stringy...
expulsion; with a softball-measure redbud that develops towards the end. Petal-like bracts develop between the covering scales encompassing this bud. They fall away, uncovering bunches of blooms. Elongated organic product rises out of the base of these blossoms. The tips of the organic product develop towards the sun, giving the bananas their bow shape. Each plant delivers a solitary stem. The banana bunches that develops from the stems are called ‘hands’. Jayaprabha et al. discovered that the leaf sheath of the banana pseudostem is covered in layers. Also the pseudostem sheaths of similar varieties of banana species have different measurements. Banana pseudostem consists of 13 layers of the sheath and 11 leaf sheath in the outer layer in the pseudostem can be utilised for extracting fibres. The pseudo-stem comprises of a soft central core and is tightly covered up by 25 leaf sheaths. The height of the banana plant can range around 7.5 m. After 18–24 months, the outer pseudo-stems of the banana plant are mature and the flower comes out, then the pseudostem are finally ready for harvesting. Figure 1 shows banana pseudostem.

The chemical composition of banana pseudostem produce fibres that are of high quality, and therefore it was selected for this study. Jayaprabha et al. reported that lignin content in the outer sheath of pseudostem is higher than other layers due to the presence of mature cells in the outer region. Different sheath layers contain different percentages of cellulose, lignocellulose and hemicellulose 60% of the pseudostem contains cellulose and nearly 20% of lignin. Moisture content of banana pseudostem is 93.2%-94.6% due to the lignin content the moisture content also decreased. Banana pseudostem have lower lignin content than wood and straw and higher ash and extractive content than wood fibre. Pseudostem containing 96% of moisture content due to the chemical composition of lignin.

Fibres produced from the extracted banana pseudostem is attracting the interest of researchers thanks to its export potential as a source of fibre. Banana fibres are also completely biodegradable and more environment friendly than synthetic fibres. The quality of the fibre produced from the extracted pseudostem differ according to the variety, soil conditions, climatic, irrigation (soil water content) and use of the type of fertiliser.

This research paper present variability of mechanical behaviour in between the layers of pseudostem with two types of banana cultivars. To comply with the research purpose, Fibre extraction method and tests of mechanical properties were utilised. Chemical composition and mechanical properties are very important to manufacture the composites, textiles, pulp and paper products. Extracted banana fibre layer wise physical and chemical characteristics can be obtained. The characteristics of banana fibre vary with the position of the leaf sheath, method of extractions, species and they are ecological conditions. It is already done in India but not done in Sri Lanka. Jayaprabha et al. mentioned only for chemical composition, strength, fibre diameter and surface structure properties and Sri Lankan ecological condition also different from India. Mechanical behaviour in between the layers of pseudostem (Sri Lankan banana varieties) properties have not yet been researched in Sri Lanka. This research is the first study that widely identifies the physical and chemical properties of four layers from two different varieties (Ambun and Puwalu) of banana pseudostem fibres in Sri Lanka.

**Methodology**

**Selection of banana variety**

Vast area of land is used for banana cultivation in Kurunagala districts which is great than 6900 hectares of land area. The sampling area of this study focuses on Kurunegala geographical distribution across the Sri Lanka. Puwalu and Ambun fibres were obtained from Kurunagala districts. Ambun variety are becoming under Cavendish subgroup (AAA). Puwalu banana variety are becoming under Kolikuttu group (AB). The Cavendish banana variety is the most common worldwide production (1/3) and, it produced 24,000,000 tonnes per yearly. The banana fibres were mechanically extracted from the pseudostem from Puwalu and Ambun cultivars.

**Separation of banana layer**

Banana pseudostem were collected with lengths of 50 cm, cleaned and taken for the fibre extraction. The banana pseudostem of layers were selected based on the location of the pseudostem. Figures 2 and 3 show, that the inner part of the stem was identified as the first layer. Outer layers of the stem were identified as the fourth layer. The sets of middle two layers were selected starting from inner to outer and named as second and third layers. The external layer of the outer sheath is removed so that the external layer can be easily broken during extraction, to avoid difficulties in extracting...
fibres samples. The core of the pseudostem is not a sheath and therefore it was not utilising for this study. The layers of the banana pseudostem were selected based on their location in the pseudostem. Generally, the banana fibre is situated near to the outer surface of the sheath and can be peeled-off easily in ribbons of strips. Thus, the banana stem is prepared for the extraction of the banana fibres.

**Fibre extraction method**

In this research mechanical extraction follows the experimental work of Vellaichamy and Gaonkar\(^ {14} \) and Jagadeesh et al.\(^ {15} \) Certain aspects of the extraction machine, such as its roller speed, feeding angle and clearance, affects the quality and production of the fibre. However, this extraction machine can produce a larger quantity of banana fibres compared to that of the manual extraction methods.

The mechanical extraction was done by using fibre decorticator machine (Figure 4). The part of stems layers was crushed between decorticator roller. Pulpy materials were surrounded with mechanically extracted fibres and in order to remove these pulpy materials combing process was done. After the combing process, extracted fibres were dried in sunshade for 3 h.

**Conditioning**

All test specimens (Dried banana fibre) were subjected to the standard atmosphere for testing, which is 20°C ± 2°C and 65% ± 2% relative humidity.

**Testing methods of banana fibre**

*Testing of banana fibre diameter (measuring the diameter of the banana fibre)*

The structural features and fracture morphology of layer wise banana fibres were analysed by using scanning electron microscopy. Banana fibre specimens were prepared based on standard test method of American Association of Textile Chemists and Colourists (AATCC) 20-2007. The diameters of the fibres were measured five (5) different places with a scanning electron microscope (SEM) and the average was calculated. Results from each layer-wise extracted fibres were analysed by using quantitative methods. The mean, standard deviation and coefficient of variation of banana fibre diameter were calculated.
Testing of fibre linear density
Banana fibre specimens were prepared based on American Society for Testing and Material (ASTM) D1059:2001 standard method to measure the fibre linear density. The mean, standard deviation and coefficient of variation of banana fibre linear density were calculated.

Testing of single fibre strength
Banana fibre specimens were prepared based on International Organization for Standardization (ISO) 2062:2009 standard method to measure the single fibre strength. The mean, standard deviation and coefficient of variation of banana fibre strength were calculated.

Testing of fibre oil content
Banana fibre specimens were prepared based on JIS 1096:1990 standard method to measure the oil content and tested according to the test method.

Testing of moisture content
Banana fibre specimens were prepared based on ISO 6741-1:1989 standard method to measure the moisture content. Banana fibre specimens were conditioned in a standard atmosphere for 24h. Conditioned banana fibre were cut at measurable lengths. Weigh of banana fibres specimen was measured by using weight balance.

Calculation. The mass of the oven-dry treated and untreated fibre specimens was used in this method. The fibre mass observed after the specimen has been dried in an oven and oven is controlled at 105° ± 2°. Moisture content in an oven dry weight bundle were calculated from mass of untreated and treated bundle. The average moisture content was calculated by using equation (1).

\[ MC(\%) = \frac{100W}{D} \] 

Oven dry weight = D
Weight of water (W) = Original weight–oven dry weight
Moisture Content = MC

The mean of the average moisture content, standard deviation and coefficient of variation was calculated for each treated and raw banana fibre lot sample.

Fourier Transform Infrared spectrophotometer (FTIR) analysis of banana fibre
The banana fibres FTIR-spectrum were obtained by plotting the percentage (%) absorbance or percentage (%) transmittance values against frequencies. This spectrum is capable of giving indirect, but very valuable qualitative and quantitative structural information on polymer to evaluate the structural order and compositions of polymers and crystallinity. The transmission range of mode of the testing was 4000–600 cm⁻¹.

Results and discussions
Mechanical extraction method was removed partly heavily coated, non-cellulosic gummy material from the cellulosic part of banana pseudostem fibres. Mechanical operations for the extraction of the banana fibre simplifies the fibre
separation to a certain extent. However, heavy damage of the fibres is obviously observed in mechanical separation along with higher level of material wastage. The physical and chemical characteristics of the extracted banana fibre can be obtained layer by layer. This data highlighted that the characteristics of banana fibre vary with the position of the leaf sheath, method of extractions and species or varieties. It was discovered that the peeling of these full length inner sheaths is difficult because of their poor strength. Investigation into the middle layer of ambun and puwalu uncovered that it was very strong, full length (stem height) and fine fibres compared to that of the outer layers. The characteristics of banana fibre vary with the position of the leaf sheath, method of extractions, species and they are ecological conditions. It is already done in India\textsuperscript{7} and Southern Highlands of Tanzania\textsuperscript{11} but not done in Sri Lanka. Jayaprabha et al.\textsuperscript{5} mentioned only for chemical composition, strength, fibre diameter and surface structure properties and Sri Lankan ecological condition also different from India and Southern Highlands of Tanzania. This researcher also mentioned, peeling of these inner sheaths in full length is difficult because of their poor strength. According to this research paper investigation middle layer were very strong, full length (stem height) and fine fibres than the outer layers. Livifile et al.\textsuperscript{12} also mentioned, the banana fibres of the Southern Highlands of Tanzania revealed a slight variation in the number of pseudostem layers. The layer-wise stiffness properties show that a decrease from the outer to the inner part of the banana trunk and elongation at break increased. Middle layer of fibres exhibit lower force at the break as compared to outer fibres. Such differences in properties were attributed to the reasons cited. However, it is surprising to note that the researcher has not taken the potentially useful step of experimenting the layer separation, FTIR analysis, linear density, moisture content and oil content properties of banana fibres. In this research paper mentioned all these layer wise fibre properties and compare with two banana cultivars layer wise properties.

Test results of puwalu banana fibres

The average physical characteristics of puwalu variety are given in Table 1 and Figures 5 to 7. Lower diameter of puwalu fibre shown better tenacity property. Fourth layer of puwalu and ambun fibre mechanical properties were obtained high coefficient of variation in their results with compared to other layers. Second and third layer of fibres were not varying in mechanical properties. Ambun and puwalu fibres of smaller diameter are shown in the second and third layer of pseudostem. Fibres of higher diameter are present in the first and fourth layer (Figure 7).

Test results of ambun banana fibres

The average physical characteristics of ambun fibres are given in Table 2 and Figures 8 to 10. It was observed that
the fibre of second and third layers of ambun banana are finer than fibre of first and fourth layers. Second and third layer of ambun fibres were not vary in mechanical properties. Lower diameter of ambun fibre shown better tenacity property. Fibres with increasing diameter was improved the uniformity and fibres with less diameter became irregular in structure. Middle layer of ambun fibres were very finest compared to middle layer of puwalu fibres but there are no significant differences in strength between the middle layers. The result showed that the average fineness of fibre of the second and third layer is around 25 Tex and the diameter value is around 80 μm. The test result showed the middle layers (second and third) to be the finest. The highest tex values were obtained for fibre of fist layer. The result showed that the average breaking tenacity of the banana fibre was 9.9 gt/Tex and the average elongation at break was 1.22%. Layer-wise analyses indicate, the linear density and diameter test results showed the middle layers of ambun pseudostem fibres to be the finest.

| Table 2. Properties of ambun banana Fibres. |
|-------------------------------------------|
| Fibre properties                         | First layer | Second layer | Third layer | Fourth layer |
| 01 Average value of fibre linear density – Tex | 30          | 25           | 25          | 27           |
| 02 Average value of single fibre strength – gf | 287.1       | 271          | 239         | 278          |
| 03 Average value of fibre diameter – µm | 83.42        | 80.32        | 80.04       | 85.99        |
| 04 Average value of elongation            | 1.10%        | 1.20%        | 1.00%       | 1.50%        |
| 05 Average value of tenacity – gt/Tex     | 8.8          | 10.92        | 10.8        | 9.62         |
| 06 Average value of oil content           | 0.40%        | 0.40%        | 0.40%       | 0.30%        |
| 07 Average value of moisture content      | 8.90%        | 9.90%        | 9.70%       | 10.10%       |

The fibre of second and third layers of ambun banana are finer than fibre of first and fourth layers. Second and third layer of ambun fibres were not vary in mechanical properties. Lower diameter of ambun fibre shown better tenacity property. Fibres with increasing diameter was improved the uniformity and fibres with less diameter became irregular in structure. Middle layer of ambun fibres were very finest compared to middle layer of puwalu fibres but there are no significant differences in strength between the middle layers. The result showed that the average fineness of fibre of the second and third layer is around 25 Tex and the diameter value is around 80 μm. The test result showed the middle layers (second and third) to be the finest. The highest tex values were obtained for fibre of fist layer. The result showed that the average single fibre strength of the second layer is approximately 270 gf. The lowest single fibre strength values were obtained for fibre of fourth layer. The test results presented that, the average breaking tenacity of the banana fibre was 9.9 gf/Tex and the average elongation at break was 1.22%. Layer-wise analyses indicate, the linear density and diameter test results showed the middle layers of ambun pseudostem fibres to be the finest.

The layer of ambun fibre has shown the highest mechanical strength compared to the layer of puwalu fibre. It is due to the high degree of crystallinity of this fibre. The highest moisture content was determined first and forth layer of puwalu cultivars. The least value of moisture content was determined third layer of ambun fibres.

These results confirm that the hydrophilic nature of lignin content present in the first and forth layers of fibre
absorbs more water. The results obtained show that puwalu banana fibre is 2% as coarse as ambun fibre. Layer-wise analyses indicate, the middle layer of ambun fibres are very strong and fine compared to the first layer and forth layer.

### Structural features of ambun and puwalu fibres

Scanning electron microscopic examination have confirmed that bundle structure of ambun fibre (Tables 3 and 4). Splitting up of fibrous strands, rough surface morphology and fragments were observed on the surface of fibre in all layers of ambun and puwalu fibres. This bundle structure consisting of several fibrils. Fourth layer and first layer of ambun fibre clearly shown broken parts, entangled micro fibrils, multicellular and bundle structure. Outer layers of fibres were coarser than middle layers. The order of ambun fibre diameter differences was found as second layer and third layer less than first layer and fourth layer. The order of puwalu fibre diameter differences was found as third layer less than second layer, and first layer less than fourth layer.

### FTIR analysis of layer wise banana fibres

FTIR spectra of ambun (AAA) four layers of banana fibres are shown in the Figures 11 and 12. Fibres of the ambun and puwalu layers are very similar and indicating a close similarity in their chemical compositions. According to the results, most lignified plant cells lignin and hemicellulose are deposited between the micro fibrils. This nature gives an interrupted lamellar structure. The chemical components of cellulose part are crystalline in nature and other chemical part of lignin is amorphous. According to all layer of puwalu and layer of ambun first and second layer fibre, FTIR spectrum of absorption band at 1730 cm$^{-1}$–1740 cm$^{-1}$ region revealed
the presence of aromatic rings which is due to the hemicellulose. These absorption peaks are completely absent in the third and fourth layer of ambun fibre. Strong hydrogen bonded of hydroxyl stretching peak is represented the absorption band at 3000–3600 cm$^{-1}$. The absorption band at 2950–2800 cm$^{-1}$ region revealed the presence of an alkanes which is called the C–H stretch absorption. The absorption band at ~1600 and ~1475 cm$^{-1}$ region revealed the presence of aromatics group which is called as C=C stretch. The absorption band at ~2850 and ~2750 cm$^{-1}$ region revealed the presence of aldehyde stretch which is called as H–C=O: C–H stretch. According to all layer of ambun and puwalu FTIR spectrum, the peak near at 1640 and 1514 cm$^{-1}$ region revealed the presence of lignin component. The absorption band intensities at 1736.39–1026.36 cm$^{-1}$ and 1606.06–1732 cm$^{-1}$ revealed decreasing pattern in middle layers of ambun and puwalu. Middle layer of lignin and hemicellulose components were lesser then outer layers (fourth layers). First and middle layer were containing high amount of ash and extractives than the fourth layer fibres which this layers are responsible for the transportation for the nutrients.

However, it is surprising to note that cited researcher have not taken the potentially useful step of experimenting the layer separation, FTIR analysis, linear density, moisture content and oil content properties of layer-wise
Figure 11. FTIR spectroscopy graph of the Ambun layer.

Figure 12. FTIR spectroscopy graph of the Puwalu layer.
banana fibres. The results showed that the average linear density of the ambun middle layer is 25 tex, the average diameter value is 80 µm and range of single fibre strength is 273–270 gf. Moisture content was varying in between 9.9% and 9.7%. The results revealed that the average linear density of the puwalu middle layer is 29 tex, the diameter value was varying in between 98 and 100 µm and range of single fibre strength is 270–271 gf. Moisture content of puwalu fibre was varying in between 10.9% and 9.9%. A high absorption band at 1736.39–1732 cm⁻¹ revealed the presence of lignin and hemicellulose component.

**Conclusion**

The linear density and diameter test results showed the middle layers of ambun and puwalu pseudostem fibres to be the finest. The middle layer of puwalu resulted in coarser fibre compared to the middle layer of ambun cultivars. The conclusion of this research will helps in selecting the correct layer to use with banana fibre for the use of different industries such as geo-textiles, fashion textiles, functional textile, interior textile, fibreboard materials, insulation materials, reinforcement, filler, light-weight concrete, bricks and composites. This has lead researchers acquire enough practical knowledge on extracting banana fibres efficiently and effectively from the pseudostem. This results have found that these methods add value, decreases the cost of extraction and motives the large-scale use of these fibres. Advanced technology needs to be developed in order to increase fibre yields from extraction processes. This research used the most popular variety of banana fibres, namely ambun and puwalu. The findings of this study were also limited to mechanically extracted fibre properties only. Data collection was limited to quantitative data.

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