

PROPERTIES OF FIBRES/CULM STRANDS FROM MAT SEDGE – *CYPERUS PANGOREI* ROTTB.

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The anatomical, chemical, and physico-mechanical properties of the fibres of *C. pangorei* were investigated in this study. The results indicate that the rind region that is split and used in mat making contains compactly arranged fibrovascular bundles and a discontinuous patch of fibrous sheath. The frequency and the R/T ratio of the bundles were high in the rind region and were indicative of fibre strength. Lignin and cellulose, the major cell wall substances, were localized with heterochromatic, fluorescent, and natural dyes. The holocellulose content was high (82.2 %), and the lignin content was comparatively low (13.28 %) as analyzed by the method of Doree. Very thick walled, thick walled, very thin walled, and thin walled fibres were characterized when fibres were macerated, and their derived values indicated a high Slenderness and Runkell ratio that is indicative of tear resistance. The tenacity and percentage elongation of the split culm strands was also high, and this implies high strength of the fibre strands. The fibre of this mat sedge thus has favorable characteristics to be potentially utilized in the mat and silkmat industry. Furthermore the plant's annual harvesting period, biomass, and appropriate fibre characteristics makes this sedge very attractive as an alternative fibre source in the miscellaneous plant fibre industry.

Keywords: Mat sedge; Culm strands; Fibre dimension and derived values; Chemical properties; Physicomechanical properties

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INTRODUCTION

Natural fibres have been used in structural applications, particularly in rope making, for many years but are currently attracting increasing interest for polymer reinforcement in applications requiring environmentally friendly materials (Beakou *et al.* 2008). European renewable fibres, such as flax and hemp, are now used for door panels and car roofs. But accelerating the substitution of synthetic fibres by natural fibres requires greater availability of these local fibres than current production levels can supply. In addition, there are certain fibres that are easier to extract or are more suitable

for other applications. It is thus essential to look for new plants that enable easy and cost-effective extraction processes that do not impair the properties of fibres. The new fibres thus identified must be analyzed in order to determine their physical, chemical, and mechanical properties. This knowledge is essential to evaluate or simulate efficiently the properties of fibres.

Cyperus is one of the largest genera in *Cyperaceae*. It is cosmopolitan in distribution (Tejavathi *et al.* 1990; Simpson *et al.* 2003) with 650-700 species spread all over the world. Of these, eighty species occur in India. Although many species grow as agricultural weeds, the family has considerable economic importance and provides food, fodder, fuel, and medicines, together with construction, weaving, and perfumery materials (Simpson *et al.* 2003). Today, sedges are used throughout the tropics for basketry and mat weaving, and they are cultivated for such purposes in parts of Africa and Asia. Sedges are also extensively used for thatching, fencing, rope making, and pot pourri. Floor mats and wall hangings are generally made using sedge culms. More specifically *C. articulatus*, *C. corymbosus*, *C. iria*, *C. malacensis*, and *C. pangorei* are the major resources of mat sedges (Krishnamurthy 1993; Venkatesan 2005; Ravichandran *et al.* 2005). Of these, *C. pangorei*, previously known as *C. tegetum* Roxb., *C. dehiscens* Nees, *Papyrus pangorei* Rottb., and *Papyrus dehiscens* Nees, is exclusively used for making the world-famous superfine and silk mats of Pathamadai. *Cyperus pangorei* Rottb. is distributed all over India, Ceylon, Nepal, and Burma (Dassanayake and Fosberg 1985; Mathew 1991; Mabberley 2005). It is both pantropical and temperate in distribution (Haines and Lye 1983; Tucker 1983). In India, *C. pangorei* is used for making mats in West Bengal (Calcutta), Kerala (Killimangalam and Palghat), Tamil Nadu, and Andhra Pradesh. In Tamil Nadu, sedge mats are made at various districts such as Vandavasi, Karur, Thanjavur, and villages such as Pathamadai, Veeravanallur, Kayathar, and Alwarkurichi of Tirunelveli district. The culms of *C. pangorei* provide raw material for mat making. Its highly stable nature and the peculiar arrangement of fibrovascular bundles in the culm are of great advantage, contributing to the productivity of mat industries (Ravichandran *et al.* 2005). Mats produced at Pathamadai may be broadly divided into three categories; coarse, fine, and super fine (silkmats). Coarse mats (50 counts per culm split into 2 to 4 strands) that are rough in texture are relatively faster to weave and are made using either a handloom or power loom. Fine mats (80-100 counts- culm split into 8-20 strands) are higher quality handloom mats and are finer in texture. The highest quality silk or super fine mats (120 to 140 counts per culm split into 20 to 40 strands) have a texture akin to silk. *C. pangorei* is also used to produce other coarse products such as hand bags, baskets, table mats, window curtains, wall hangings and fans (Benazir 2000).

However, until recently, *C. pangorei* as a fibre plant has remained barely studied. Nevertheless, interest in this crop seems to be increasing worldwide for its importance in the making of Pathamadai Silk Mats (Amalraj, 1990; Benazir, 2010; Govind, 2004; Balaji, 2005; Venkatesan, 2005; Basu, 2005). The aim of this investigation is to evaluate the anatomy, fibre dimensions and derived values, chemical, and physico-mechanical properties of the fibre macerates and culm strands of this wonderful mat sedge so as to understand the strength and properties of its fibres.

EXPERIMENTAL

Materials

C. pangorei (Fig. A) was collected from different habitats such as small rivulets (Ramanadhi, Gadanadhi), streams (Servalar, KMTR range, Southern Western Ghats), and irrigation canals of rice fields (Alwarkurichi, Pathamadai, Tirunelveli). Cultivated mat sedges were collected from farm fields in Karur, Trichy district, Tamil Nadu. The sedge was raised in the department nursery without addition of organic or inorganic fertilizers under irrigated conditions. Near-natural conditions were provided for the healthy growth of plants. Only mature culms were collected for the study. Processed culm strands (subjected to retting, splitting, and dyeing) were obtained from mat weavers of Pathamadai. Cut portions from the lowermost (1 cm from the bottom-most part of the culm), middle, and upper regions (1 cm from the top-most part of the culm) were used in anatomical and transmission electron microscopic (TEM) studies. For studies on fibre macerates, the rind and the core from the culm separated using a sharp knife were used. For analyses on chemical and mechanical properties of the fibres, processed, dyed, and undyed culm strands (Fig. B) of different counts (50, 100, 120) obtained from the mat weavers were used. Dyed culm strands were also screened to check the influence of dyeing on fibre properties.



Fig. A. *Cyperus pangorei* growing in natural habitat along stream and irrigation canals;
Fig. B. Processed culm strands dyed with an array of natural dyes.

Methods

Histochemical localization of wall substances

Cellulose and lignin, the major cell wall substances, were localized using histochemical reagents and fluorescent dyes in free-hand transverse sections.

Light microscopic dyes

Toluidine blue 'O' (Feder and 'O' Brien 1968), safranin, and a natural dye Sappan (*Caesalpinia sappan*) (Benazir 2000; Ravichandran *et al.* 2005) were used. The sections were stained with 0.05 % toluidine blue 'O' (TBO), in benzoate buffer for 2-3 min, 1 % safranin (1g in 100 ml) for 1-2 minutes, and water extracted sappan dye (10 %) for 15-30 minutes. After removing the excess stain, sections were mounted in water and viewed under light microscope (10 x, 40 x, and 100 x).

Fluorescent dyes

Sections were stained with 0.01 % aqueous solution of Calcofluor White M2R for one minute (Hughes and McCully 1975) to localize cellulose. Acridine orange (AO) was used at 0.1% in phosphate buffer at pH 6 for 1 min. (Armstrong 1956) and 0.1 % Coriphosphine 'O' for 1 minute (Harris and Oparka 1993). The dyes were used for localization of lignin. All were observed under blue and violet excitations of a fluorescent microscope (Nikon, FMZ 2000) and observed using 10x, 40x, and 100x objectives.

Transmission electron microscopy

The procedure described by Rodrigues and Estelita (2003), modified with minor changes, was followed for preparing the specimens for TEM observations and standardized in AIIMS (All India Institute of Medical Sciences, New Delhi, India). The culms from *Cyperus pangorei* were cut into 2 x 2 mm size. Tissue samples were fixed in a mixture of 2.5 % glutaraldehyde and 2 % paraformaldehyde in 0.1 M sodium phosphate buffer (pH 7.4) for 12-18 h at 4°C. After washing in buffer, samples were post-fixed in 1% osmium tetroxide (OsO₄) in the same buffer for 2 h at 4°C. Samples were then dehydrated in ascending proportions of acetone, starting from 30% to absolute acetone (about 30 min in each step) at 4°C. Such dehydrated samples were infiltrated in resin – toluene mixture in a vacuum incubator overnight and finally embedded in pure resin, araldite CY 212 (TAAB, UK). Ultra-thin sections (1µm) were cut with an ultramicrotome (ultracut E, Reichert, Austria) using a glass knife, fixed on glass slides, and adhered by applying heat. These sections were then stained with aqueous toluidine blue on a hot plate at 70 °C and observed under a light microscope for general and specific observations of the area and quality of the tissue fixation. For electron microscopic examination, thin sections of grey-silver colour interference (70-80 nm) were cut and mounted onto 300 mesh- copper grids. Sections were stained with alcoholic uranyl acetate and alkaline lead citrate for 12 min in each step, washed gently with double distilled water and observed under a Morgagni 268D Transmission Electron Microscope (TEM) (Fei Company, The Netherlands) at an operating voltage of 80 kV. Some photographs were taken by using a CCD camera with a digital mode (Megaview, Fei Company) attached to the microscope.

Fibre maceration and morphometric measurements

Culm samples from the lower, middle, and upper regions were taken and split to separate the outer rind and inner core portions. Thin slivers of 1mm thickness were cut, boiled in water, and then cooled to remove the air bubbles. Slivers were processed separately for maceration (Johansen 1940). The macerated fibres were washed several times with distilled water and stained in 0.05% toluidine blue 'O' for 10-20 min or with sappan for 30 min, washed, and mounted in water for observations and microphotography.

Morphometric measurements such as length, width, wall thickness, and lumen width of the macerated fibres of the rind and core regions from the three parts of *C. pangorei* were made. For each region, twenty-five fibres were randomly chosen for measurements and the mean was taken. Morphometric measurements were made using an ocular micrometer under 10x and 40x magnification of the light microscope. Based on wall thickness and lumen width, the fibres were classified as follows (Metcalf 1971):

- | | |
|-----------------------------|---|
| 1. Very thick-walled (vtkf) | - lumen almost completely closed |
| 2. Thick-walled (tkf) | - lumen less than the thickness of wall |
| 3. Thin-walled (tnf) | - lumen more than the thickness of the wall |
| 4. Very thin-walled (vtnf) | - lumen much greater than the thickness of wall |

Derived values such as slenderness ratio (SR), flexibility ratio (FR), and Runkel ratio (RR) were calculated from the above data as suggested by Tamolong *et al.* (1957).

$$\text{Slenderness ratio (SR)} = \text{length of fibre} / \text{diameter of the fibre} \quad (1)$$

$$\text{Flexibility ratio (FR)} = 100 \times \text{lumen width of fibre} / \text{diameter of fibre} \quad (2)$$

$$\text{Runkel ratio (RR)} = 2 \times \text{wall thickness} / \text{lumen width} \quad (3)$$

Chemical analysis of fibres

The processed and split culm strands were used to characterize the chemical properties of fibres for lignin, alpha cellulose, hemicellulose, total waxes, and moisture content following the method of Doree (1950).

Lignin estimation

One gram of the dewaxed and defatted sample was taken and to this was added 12.5 ml of 72% sulphuric acid. The mixture was incubated at RT for 15 h. The sample was then diluted with water to an acid concentration of 3% and boiled for 2 h, washed, filtered (G₃ filter), and neutralized with Ammonia (NH₃) solution. It was washed again several times with water until the filtrate was neutral, dried, and weighed. The concentration of lignin was estimated using the following formula.

$$\text{Lignin (\% on dry basis)} = 100 \times \text{Residue} / \text{dry material wt} \quad (4)$$

Cellulose estimation

2 g of dewaxed and defatted sample was cut into small pieces. To this was added 100 ml of 3% sulphite solution, and then the mixture was filtered. The residue was washed in a beaker and made up to 100 ml with water, and 5ml of 1.78 % sodium chlorite (NaClO_2) was added. After standing for 10 min, the fibre was filtered off and returned to the beaker, and the volume made up to 50 ml with water and 50 ml of 6% sodium sulphite. The entire mixture was boiled for 20 min, and the two previous steps were repeated. The material was suspended in 100 ml of water and 5 ml of hypochlorite with 2 ml of 20% sulphuric acid. The pH was adjusted to 4 with H_2SO_4 . After incubating for 10 min and filtering, the residue was made up to 50 ml with water and 50 ml sulphite (to remove all lignins). The mixture was refluxed and boiled for 1 h, washed, filtered (G_3 filter), and neutralized with NH_3 solution. After washing well and drying, the total cellulose content was estimated as follows:

$$\text{Total cellulose on dry basis} = 100 \times \text{Residue} / \text{dry material weight} \quad (5)$$

Physico-mechanical parameters

The processed and split culm strands (50 count dyed, 100 count dyed, 120 count dyed, and 120 count undyed) were analyzed for properties such as tex, actual strength, percent elongation, breaking force, and tenacity. The fibre samples were weighed, and their length was measured. The tex count (weight in g) was calculated using the following formula:

$$\text{Tex count} = \text{wt (g)} \times 1000 / \text{length (m)} \quad (6)$$

Tenacity, elongation, and breaking force

Determination of the elongation percent and breaking force (Davies *et al.* 2007) was done by a modification according to the standard procedure followed at SITRA (South India Textiles Research Association) laboratories, Coimbatore, India, which was based on a constant rate of extension. The instrument (INSTRON Universal Strength Testing Installation INSTRON, 6021 series UK) was fitted with the pneumatic grip to hold the culm strands for the strength test. The top jaw was connected to the load cell. The cross head, on which the movable jaw was fixed, moves at a constant rate of extension. The specimen extends and finally breaks, which determines the end point of the test. The maximum force to break was recorded, while the extension or elongation of the specimen at F_{max} was also noted as the breaking extension in %. From a series of tests using at least 25 culm strands, the mean breaking strength (actual strength) and the mean breaking elongation percent was calculated. The (Coefficient of variance) CV% of strength and elongation was also calculated. The tenacity was calculated using the following formula:

$$\text{Tenacity} = \text{Breaking strength (g)} / (\text{Tex/denier}) \quad (7)$$

Statistical analysis was done using data on fibre dimension of the rind and core regions. The arithmetic mean and standard deviation (SD) were determined. Student's 't'

test and correlation (two tailed analysis) was applied for the physico-mechanical properties of culm strands in order to correlate the strength (tenacity) and elongation properties of the culm strands.

RESULTS

The major contributions of the present study include the first time description of the fibre properties of the mat sedge (*C. pangorei*), including anatomical, physical, chemical, and physico-mechanical properties of the fibres. These descriptions provide insights into interesting observations that could be used for interpretation of the strength and tenacity of the fibres and culm strands.

Fibre Anatomy

The anatomy of the culm includes an outer rind region comprised of the epidermis, hypodermis, and varied types of compactly arranged vascular and fibrovascular bundles. The inner core consists of more or less uniform-type vascular bundles sparsely distributed in the ground parenchyma and aerenchyma. Beneath the epidermis, there is a discontinuous patch of sclerified cells (fibrous sheath) that are interrupted by a few sub-epidermal parenchyma cells (Fig. C-F). In view of the association of the fibrous sheath with the vascular bundles, the term fibrovascular bundle has been used. The fibrovascular bundles are compactly arranged in one to two rows towards the periphery of the culm, also referred as rind, and the inner region with sparsely distributed fibrovascular bundles, parenchyma, and large aerenchyma forms the core. The fibrous sheath is present only in the protoxylem pole in four to eight layers, forming a crescent in the vascular bundles of the core region (Fig. E). The rind region shows remarkable differences in the size and frequency of vascular and fibrovascular bundles in all the three regions of the culm (Table 1).

Table 1. Frequency, Dimensions, R/T Ratio of Core and Rind Fibro-Vascular Bundles from Three Regions of *Cyperus pangorei* Culms

CULM REGION	REGION	FREQUENCY OF BUNDLES		FIBRO-VASCULAR BUNDLES				R/T RATIO
		Mean	SD	R (μ m)	SD	T (μ m)	SD	
Lower most (1 cm from the base)	Rind	10.85	1.93	174.3	20.2	81.26	4.8	2.14
	Core	2.5	0.59	283.0	33.1	195	11.18	1.45
Middle	Rind	20.2	2.44	189.5	15.8	98	7.23	1.93
	Core	3.2	0.74	235.0	25.3	156	15.6	1.50
Upper most (1cm from the tip)	Rind	23.15	3.39	138.4	17	86.7	6.3	1.59
	Core	6.25	1.92	139.0	11.3	122	8.7	1.13

T: Tangential width; R: Radial height

The frequency of the fibrovascular bundle increases from the lower region to the upper region, and the average size in terms of R/T ratio is inverse to the frequency. The frequency of fibrovascular bundles in the middle region is 20.2 with an average size in terms of R/T ratio of 1.93. The vascular bundles without the fibre sheath connection also have an equal frequency, with an average of 1.98. In the lower-most regions the frequency of vascular bundles without fibre sheath is highly reduced, with an average of 0.25.

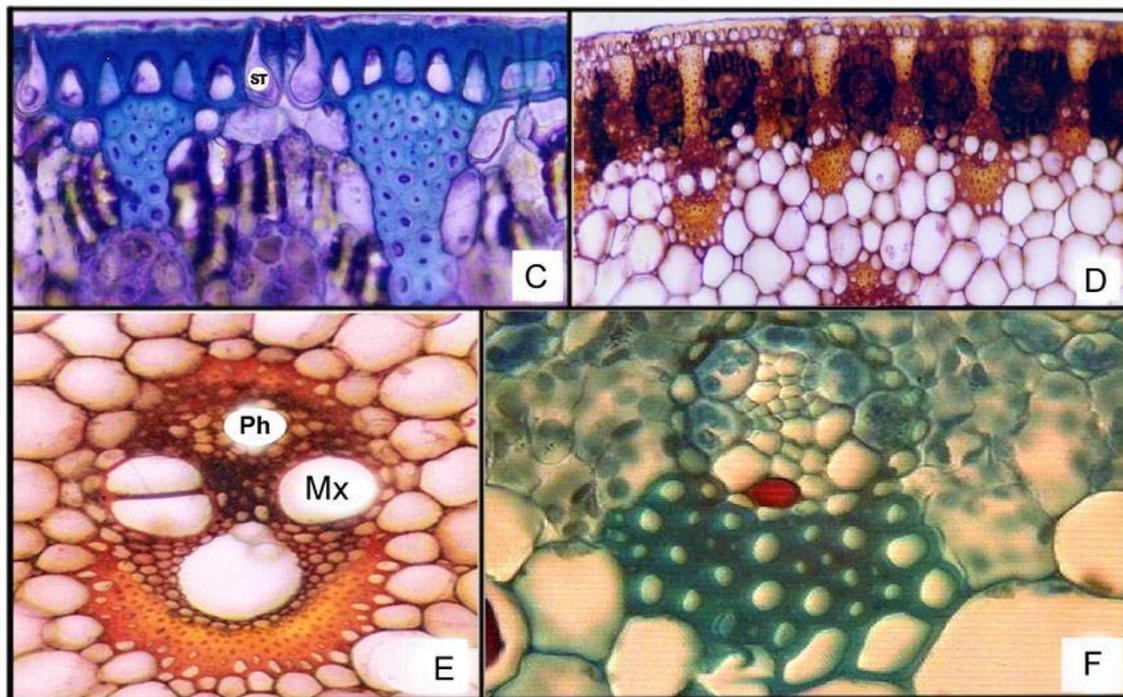


Fig. C. Transverse section stained with TBO, where the fibrous sheaths are interrupted and attached to the vascular bundles (girders) towards the inner side. Epidermal cells are tooth-like and covered with a thick cuticle, X 400; **Fig. D:** Section stained with a natural dye obtained from sappan wood. Lignin rich regions appear yellow to orange in colour. X 100; **Fig. E:** Core fibrovascular bundle stained with sappan dye. Lignin rich regions appear yellow to orange. Cellulose rich regions appear pink to red, one of the metaxylem is partitioned, X 200; **Fig. F:** Developing fibre sheath near the vascular bundle stained with fast green, thick walls of sclerenchymatous cells are darkly stained, X 1000.

Histochemistry of Cell Wall Substances

Lignin, which is an important component of the cell wall, stained bright red with safranin, and appeared blue to bluish green on staining with Toluidine blue 'O', a metachromatic dye (Fig. C). Staining with the histochemical reagents revealed that the fibres in close association with the vascular strand were thick walled, while the fibres away from it were thin walled. Staining with Acridine orange and Coriphosphene 'O' indicated that different kinds of lignin might be present (Fig. G, J and H). Highly lignified cells appeared greenish yellow, while less lignified cells appeared bright yellow. Sappan, a natural dye, also stained lignified cells. Highly lignified cells appeared yellow,

while less lignified cells take up an orange colour (Fig. D and E). Cellulose was localized using Calcofluor white (Fig. I). Only parenchymatous cells showed high intensity of fluorescence, indicating their cellulose-rich nature.

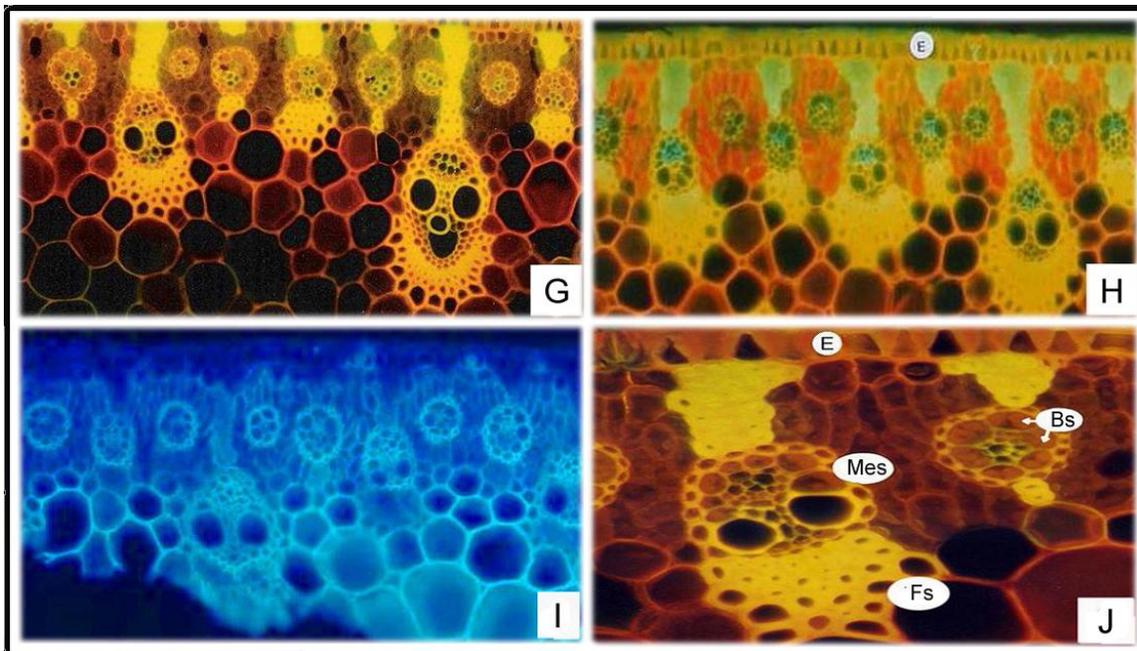


Fig. G. Section stained with acridine orange and observed under fluorescent microscope with blue excitation, AO shows high affinity for lignin that appears bright yellow, X 200; **Fig. H.** Section stained with Coriphosphine O under blue excitation, lignin rich regions appear bluish yellow to bright yellow, phloem appears blue in colour, X 200; **Fig. I.** Section stained with Calcofluor White, cellulose rich region fluoresce and appear blue in colour, X 200; **Fig. J.** An enlarged view of fibrovascular bundle stained with AO, X 400

Chemical composition of culm strands

The processed culm strands obtained from silk mat weavers of Pathamadai were analyzed for chemical properties. The culm strand consist the following chemical constituents;

- ◆ Holocellulose – 82.92%
- ◆ Alpha cellulose – 41.79%
- ◆ Hemicellulose – 41.13%
- ◆ Lignin – 13.28%
- ◆ Waxes – 1.73%
- ◆ Moisture – 9.2%

Fibre dimensions and derived values

Four different types of fibres were identified based on the relative thickness of the cell walls seen by staining the macerated fibres of rind and core regions. The observations showed significant variations between the rind and core fibres. The rind region showed the presence of very thick walled (vtkf) and thick walled fibres (tkf) (Figs.

K and O). The fibres were much longer and had forked, acuminate, one side tapering, and cleft tips (Figs. K to N). The average length of the fibres was 650 μm , and the wall thickness was 7.53 μm . The average diameter of the fibres was 9.85 μm , with a lumen width of 2.62 μm . Fibre wall lamellations varied from 4 to 5 layers. Pitting was uniseriate in vtkf (Fig. K) and biseriata in tkf. Thin walled (Tnf) and very thin walled fibres (vtnf) were the major fibres in the core region (Figs. N and P), although thick-walled and very thick walled fibres were also found. Pitting was biseriata in thin walled fibres and uniseriate in thick walled fibres. The average length and width of the core fibres was between 799.3 μm and 9.35 μm , and the wall thickness was 4.15 μm respectively, with a lumen width of 5.2 μm (Table 2). TEM studies revealed that the fibre walls possess several primary and secondary wall layers with a compound middle lamella. The region appeared black and darkly stained (Figs. Q and R). The fibre dimensions were used to calculate the slenderness ratio (SR), flexibility ratio (FR), and Runkel ratio (RR) of the rind and core fibres. The rind fibres had an SR of 66, an FR of 26.59, and RR of 5.74, and the core fibres had a high SR of 85.48, a high FR of 55.61, and a low RR of 1.59, when compared to the rind fibres as presented (Table 2).

Table 2. Fiber Dimensions and Derived Values of Rind and Core Fiber Macerates from *Cyperus pangorei*

Region	Length (L) μm	Diameter (D) μm	Wall Thickness (WT) μm	Lumen width (LW) μm	Slenderness ratio (SR)	Flexibility Ratio (FR)	Runkel Ratio (RR)
Rind	650.1	9.85	7.53	2.62	65.98	26.59	5.74
Core	799.3	9.35	4.15	5.2	85.48	55.61	1.59

Physico-Mechanical Properties of Culm Strands

The physico-mechanical parameters were determined for the processed culm strands used in mat making viz., 50 count dyed, 100 count dyed, 120 count dyed, and 120 count un-dyed (Fig. B). Properties such as actual (breaking) strength, tex count, percent elongation, breaking force, and tenacity were determined (Table 3). The breaking strength (weight in grams for 25 strands) was highest for 50 count dyed (1920.9 g) and lowest for 120 count dyed (772.1 g). The percentage elongation (7.37) and tenacity (13.33 g /tex), was highest for 120 count un-dyed strands, followed by 100 count dyed (12.41 g/tex), 120 count dyed (6.92 g/tex), and 50 count dyed (4.99 g/tex) strands respectively. Breaking force in joules was maximum for 100 count dyed, followed by 120 count un-dyed, 120 count dyed, and 50 count dyed. However, when the values were statistically analyzed using ANOVA, the F value was 0.10 at 5 % level of significance, which was less than the table value of 3.86. Correlation analysis revealed that the breaking strength was negatively correlated with the tenacity and elongation ($r = -0.085$; $r = -0.23$), whereas elongation percent and tenacity were positively correlated ($r = 0.98$), which means that when the weight (actual strength in grams) increases the elongation percent and tenacity decrease and vice versa. Elongation percentage and tenacity in turn influence each other positively.

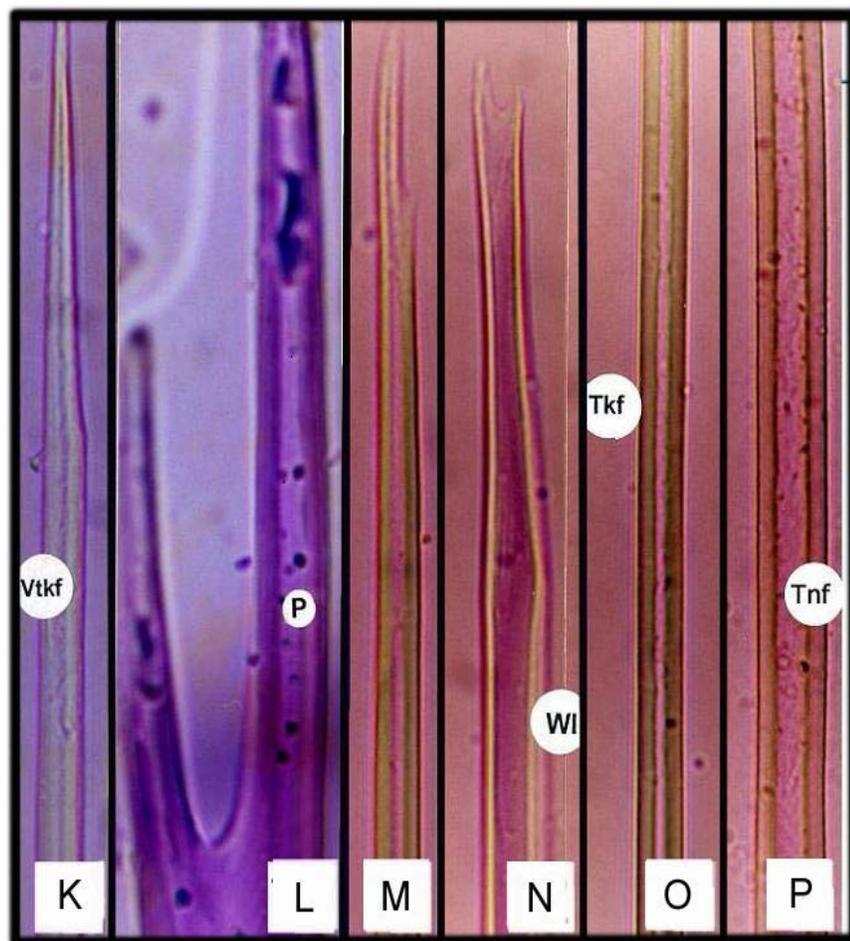


Fig. K. Very thick walled rind fibre with one side tapering end, X 400; **Fig. L.** Forked end of a macerated fibre, X 1000; **Fig. M.** Thick walled fibre with forked tip, X 400; **Fig. N.** Very thin walled fibre with forked tip and distinct wall lamellations, X 400; **Fig. O.** Thick walled fibre, X 400; **Fig. P.** Thin walled fibre with distinct wall lamellations and uniseriate pits, X 400.

Table 3. Physico-Mechanical Properties of Processed and Split Fibers of Korai Used in Mat Weaving

S. No	Parameter	50s Dyed	100s Dyed	120s Dyed	120s Un dyed
1	Tex (cm)	385.13	117.6	111.6	106.4
2	Actual strength (g)	1920.9	1459.0	772.1	1418.0
	CV% of Strength	71.61	55.80	57.07	39.29
3	% Elongation	0.469	0.7282	0.5758	0.7370
	CV% of Elongation	38.72	26.07	36.20	30.21
4	Breaking Force (joules)	0.0039	0.0099	0.0043	0.0094
5	Tenacity (g/tex)	4.99	12.41	6.92	13.33

F value = 0.1035 at 0.05 level of significance

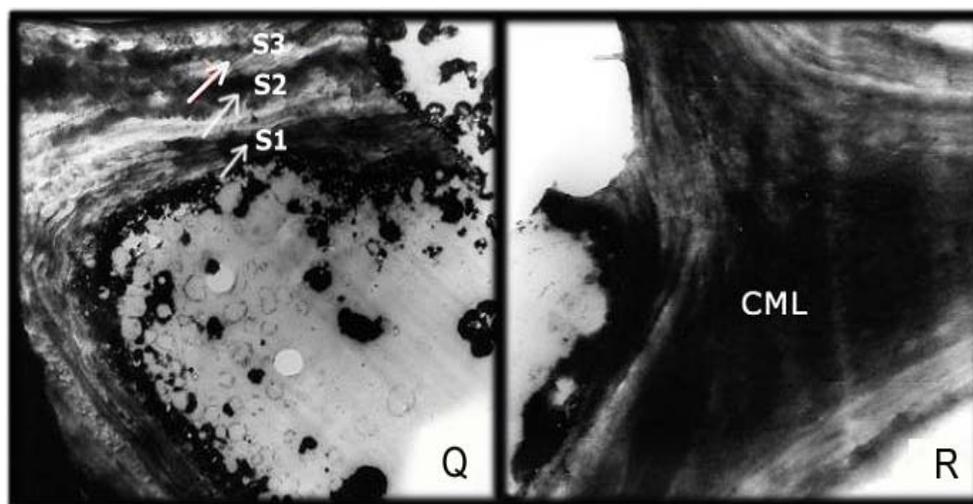


Fig. Q. TEM view showing several layers of the fibre cell wall. The thickness indicates the intensity of lignification on the S1, S2, and S3 cell wall layers, X 11,500; **Fig. R.** TEM view: the intercellular space and middle lamella are merged and appear as compound middle lamella (CML), X 11, 500.

DISCUSSION

The members of *Cyperaceae* are less understood biologically and not much economically exploited. However, the use of *C. pangorei* and other sedges is restricted to handicraft products, papermaking, perfumery, and insecticidal compounds. Consequently the scientific consideration of this family is necessary, especially in the understanding of parts used in handicrafts and other sectors. Sedge mat and mat products made in India are unique and vary from place to place. The silk and super fine mats produced using *Cyperus pangorei* at Pathamadai in Tamil Nadu has international recognition and appreciation due to its exemplary and intricate artistic value. Hence, quantities of mats have been complimented as a means of respect and greetings to celebrities, including Queen Elizabeth II. The present study had been fortunate to unravel the culm and fibre anatomy, as well as chemical and physicochemical properties of the culm strands used in silk mat making. Fibre characteristics of *C. pangorei* were studied, which determine the quality, fine texture, and strength of the silk mats. This analysis was performed to relate tissue components and their relevance towards the making of silk and superfine mats.

Beneath the epidermis alternating patches of fibrous sheath (sclerenchyma) and translucent parenchyma cells constitute the hypodermis. The fibrous sheath is a multilayer of 7-12 cells with lignified thick walls, which are often associated with vascular bundles. These fibrous sheaths appear in the form of long columns (baculiform) extending from the epidermis and are referred to as girders that provide mechanical support to the vascular bundles (Metcalf 1971). The durability and tenacity of the culm strands in mat weaving has been attributed to this characteristic feature (Benazir 2010). The presence of too many parenchyma cells between the girders will lead to breakage;

however this is overcome by drying of the culm strands, causing shrinking of the parenchyma and bringing the fibre strands closer together.

The distribution of fibrovascular bundles varies in the rind and core regions throughout the culm (Table 1). In general the strength of each fibrovascular bundle is determined by its R/T ratio. A high R/T ratio is indicative of strength and has been reported earlier in monocots like bamboo and sugarcane (Sekar 1992; Saravanan 1996).

C. pangorei fibres, as observed in light and electron microscopic studies, are multicellular and polylamellated. Such polylamellated fibres are also known to occur in bamboo and sorghum (Parameswaran and Leise 1975; Manimekalai *et al.* 2002) and are known to impart strength to finished products.

C. pangorei fibres are rich in their chemical composition. The holocellulose content of fibres was 83%. The combination of hemicellulose and celluloses are called holocelluloses and account for 65-70% of plant dry weight, and the alpha cellulose content is 41.79% in *C. pangorei*, which is similar to that of hemp and reeds such as *Phragmites communis* (43 %) (Hurter 2006). Plant materials with 34% and over of alpha cellulose content are characterized as promising for pulp and paper manufacture. Cellulose imparts strength and makes the culm strand liable to synthetic and natural dye fitness and binding. This property has a significant role in the strength and dye binding properties of the silk mats. Hemicellulose is responsible for the water absorption by plant fibres and serves to reduce inter-fibrillar cohesion and to relieve internal fibre stress (Baley 2002).

The lignin content in the culm strand is 13.28%, which is greater than that of pineapple leaf fibres (10.5 %) (Khalil *et al.* 2006), is similar to hemp stalk fibres (9-13%), and less than kenaf, wheat, bamboo, grass, and reed fibres (Hurter 2006). Generally the high lignin content makes the fibre tougher and stiffer, thereby giving strength to mats, as reported in coir (Khalil *et al.* 2006). Lignin also imparts brittleness to the fibre, and hence the percent elongation of culm in this study is low. Partial removal of lignin will cause the other components such as cellulose to become more compact and thereby increase the strength and flexibility, as reported in areca nut fibres (Rajan *et al.* 2005). The flexibility of culm strands of *C. pangorei* during mat weaving may be attributed to the nature of fibres and fibrous sheath.

The moisture content in *C. pangorei* culm strands is 9.2%. The moisture content is directly related to strength and extension of fibres, besides dye absorption. Low moisture content enhances drying (Fathima and Balasubramaniam 2006). The moisture content of *C. pangorei* is similar to that of jute fiber (9.9 %), however less than that of pennywort (18.3 %) (Rowell *et al.* 2000) and therefore may influence better performance of the culms used in silk mats. Moisture content at a given relative humidity can have a great effect on biological performance of materials made of fibres, as they are more prone to decay.

From the maceration studies, four different types of fibres were recognized based on the relative thickness of the cell walls viz. very thick walled (vtkf), thick walled (tkf), thin walled (tnf), and very thin walled (vtnf). Fibre wall thickness is an important feature in imparting stiffness to the mats. Wall thickness increases from the pith towards the periphery; i.e. the rind fibres are very thick walled as compared to the core fibres. Similar observations were made relative to fibres of grasses like bamboo and sugarcane (Sekar

1992; Saravanan 1996). The mean length of the fibres of *C. pangorei* is 724.7 μm with an average diameter of 9.6 μm , which is close to the fibres of *C. papyrus*, whose minimum length is 300 μm , maximum length is 1500 μm and, diameter between 5 and 25 μm (Rowell *et al.* 2000). The fibres vary in length between the core and rind regions of *C. pangorei* culms, as also reported by Lwin *et al.* (2000) in case of bamboo, where there are variations even within the same plant. Fibre dimension as well as length influences the physico-mechanical properties such as toughness, tensile, and static bending strength, which in turn affect the workability (Parameswaran and Leise 1975; Espiloy 1987; Widjaja and Risyad 1987). Thus longer fibres show higher tenacity. These qualities present in long rind fibres of *C. pangorei* make it suitable for weaving fine and superfine mats. It was further reported that an increase in the lumen width and fibre diameter also influences the strength properties of fibres. Core fibres have greater lumen width as compared to rind fibres. The lesser the lumen width, the stronger will be the fibre. Lumen width of the fibres shows a strong correlation with the mechanical properties. The mat weavers thus remove the pith region containing the core before splitting of the culm strands.

The derived values of fibre dimensions are slenderness ratio (SR), which is indicative of tear resistance that is more in the rind fibre, when compared to the core fibres. The higher the SR, the stronger will be the resistance to tearing. The preferred SR ratio for use in textile industries is between 200 -3000 (Maiti 1980). However, the SR of the rind and core fibres of *C. pangorei* is lesser than 100 and therefore may not be suitable for textile industries, but adequate for mat industries. However, when compared with *Miscanthus* and switch grass (used in paper making), the SR of *C. pangorei* fibres can be considered good, as they will have high tear indices and bursting strength. Flexibility ratio is inversely proportional to tensile strength. Thus the FR of the rind fibres is less, and thereby the tensile strength is more (Kasim and Jalil 1991; Table 2 and 3). However, fibres with high FR are flexible, crumple readily, and produce good surface contact and fibre-to-fibre bonding, yielding low bulk paper that may not be suitable for the mat industries. Thus, the low FR in fibres of *C. pangorei* can be justified based on their suitability in the mat industries. The Runkel ratio (RR) is related to lumen width and thickness of the fibre, thereby indicating the suppleness of the fibre. The RR of the rind fibres is 5.74 and that of core fibres is 1.59. RR values between 1 and 2 render the fibres suitable for use in textiles, while RR of 1 or less than 1 is considered to be favorable for papermaking (Tamolong *et al.* 1980).

The physico- mechanical properties such as actual strength, elongation-breaking force, and tenacity of the processed culm strands (50s dyed, 100s dyed, 120s dyed, and 120s undyed) are given in Table 3. The culm strands of different counts had no differences in their physico-mechanical properties. Flexibility of fibres had a direct correlation with elongation. Maximum percent elongation was in 120s undyed strands (7.37%), and the values correspond to that of ramie yarn (Cheng *et al.* 1992). The tenacity of the fibre is an important factor in selecting a particular fibre for a specific application (Rowell *et al.* 2000), and the tenacity of *C. pangorei* culm strands is higher than that of kenaf and pineapple leaf fibres, however lower than that of cotton (Duraiswamy and Chellamani 1993). The tenacity of fibre depends on the breaking load of the fibres and is inversely proportional to the fineness or tex of the fibres, as found in

C. pangorei, which is in conformity to previous reports in Bhendi (Fathima and Balasubramanian 2006). The 120s undyed has the minimum tex count and thereby maximum tenacity (Table 3). It is clear from the table that when tex is high, tenacity is low and vice versa, as reported (Rasheed and Dasti 2003). Statistical analysis explains the fact that the split and dyed culm strands have equivalent strength properties. This implies that processing and splitting of culms into fine strands and subsequent boiling in dye bath does not have an impact on the strength properties of the culm strands. The maximum tenacity was observed in the case of 120-count culm strand. This shows that the thinner the culm strand, the higher will be the tenacity, similar to that of SR, which is high in long thin fibres, and thus giving more tear resistance and burst properties. In addition, the fibre length and diameter may also influence the tenacity of the fibres. The tensile strength and percent elongation increases with fibre length, which may be the case with *C. pangorei* fibres. However, in most applications as in the mat industry, fibre bundles or strands are used rather than individual fibres, and using such whole stems is more attractive, as it bears significant practical and economic advantage (Ververis *et al.* 2004).

CONCLUSION

The present study based on anatomy, wall substances, morphology, derived values of fibre dimensions, and physico-mechanical properties reveals that the rind fibres, as aptly used by the mat weavers of Pathamadai, possess favorable characters for its efficient utilization in the silk mat industries and the manufacture of other coarse products. Furthermore, the easy adaptability of the plant to different ecological conditions, the annual harvesting period, and the high biomass productivity, combined with appropriate chemical composition, makes *C. pangorei* very attractive as an alternative fibre source for miscellaneous plant fibre applications.

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