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Coconut fibre: its structure, properties and applications

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Leena Mishra, Gautam Basu
ICAR-National Institute of Research on Jute and Allied Fibre Technology, Kolkata, West Bengal, India

10.1 Introduction to coconut fibre

In the world of industrial fibres, coconut fibre (*Cocos nucifera* L.) is extracted from the husk of coconut, although a secondary crop occupies a prominent position as regards of its bulk production. Annual yield of coconut is 50–100 fruits per tree, which require a year to ripen. Mature fruits are ovoid or ellipsoid in shape, 30–45 cm in length, and 15–20 cm in diameter; have a thick, fibrous husk surrounding the single-seeded nut (Encyclopaedia Britannica., 1982). The fruit is around 1–2 kg in weight, which contains about 30% husk. Coconut fibre, production areas, are found mostly along the coastal regions in the wet tropical areas of India, Sri Lanka, Philippines, Indonesia, Malaysia, Fiji Islands, Vietnam, Hawaii Islands, Papua New Guinea, and Solomon Islands. For more than a century, India (largest producer) and Sri Lanka (Ceylon) have grown practically about 90% of world's production (Table 10.1) (FAO, 2013).

FAO report (FAO, 2013; FAO, 2015) shows that, there is a steady growth of production of coconut fibre (at the rate of 37%) and it's yarn (at the rate of 10%) in India (Fig. 10.1) due to growing consciousness for using eco-sustainable, biodegradable, natural materials in the world. It is interesting to observe, the trend of growth of world production for coconut fibre is greatly at par with the growth trend of production of coconut fibres in India (Table 10.1). It can be observed in Table 10.1 that the production of brown fibre (extracted through mechanical means from matured brown husk) is sharply enhancing from 335 to 459 thousand tonnes, whereas there is a steady reduction in production of white fibre (from 95 to 81 thousand tonnes) extracted through conventional backwater retting practicing in India.

The traditional method of fibre extraction i.e. 'retting' (dipping coconut husk for 6–12 months at backwater lagoon) to obtain whiter, softer and spinnable retted fibres is abolishing rapidly in India due to various technological and societal concerns. The major problem of the conventional water retting is pollution to open backwater bodies and its surrounding air. The conventional extraction (retting) causes occupational diseases especially to the women folk involved in this profession and subsequent manual yarn manufacture is also a reason of massive human drudgery, due to which production of yarn in India has been persistently declining (Fig. 10.1). Reduction in production of the yarn in India affects the global export of the yarn and the finished products (mats, matting and rugs) (Fig. 10.2) based on it (FAO,

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Table 10.1 Production of coconut fibre (in 1000 tonnes).

	2007	2008	2009	2010	2011	2012	2013	2014
Brown fibre								
India[a]	335.0	340.8	394.0	415.5	425.0	431.5	455.8	458.8
Sri Lanka[a]	100.1	101.6	169.6	149.8	135.0	131.2	123.7	150.4
Thailand	53.7	55.5	64.6	63.7	49.9	45.7	64.8	68.1
Vietnam	72.2	74.7	91.1	103.0	97.6	115.1	105.9	143.3
Other countries	11.0	11.0	57.7	66.5	81.9	84.8	79.3	97.6
White fibre								
India	95.0	97.0	97.0	100.0	100.5	100.0	80.4	81.0
Totalrowhead	667.0	680.6	923.6	952.7	949.0	988.1	973.6	1064.0

[a]India and Sri Lanka production data does not include coir pith.

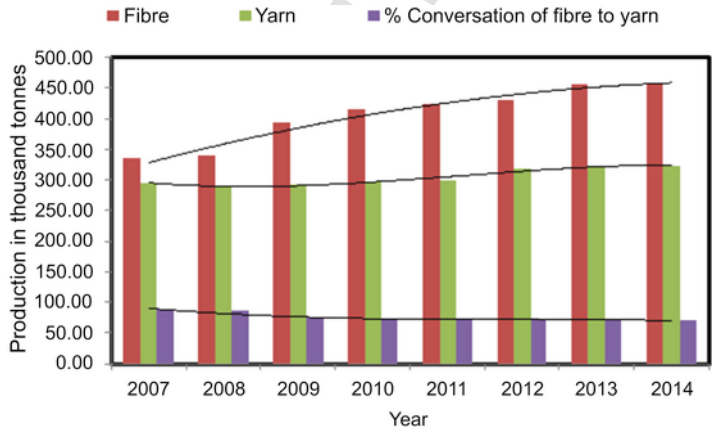

Figure 10.1 Production of coconut fibre and yarn in India.

2013; FAO, 2015). The raw fibre extracted through mechanical means is bound to export (from 97 to 505 thousand tonnes) to global market without any value addition (Fig. 10.2). Thus, the present challenges of the coconut fibre sector is to find a suitable replacement of conventional fibre extraction method (backwater retting) to produce good quality of coconut fibre and mechanized processing of the fibre to manufacture finer and good quality yarns/products without any human drudgery and environmental pollution.

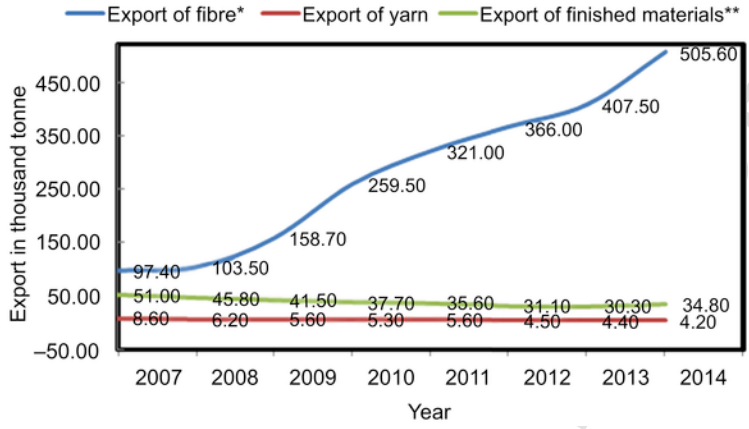

Figure 10.2 Export of coconut fibre yarn and finished material from India.

10.1.1 Husk of coconut

Coconut husk represents the entire fibrous material enveloping the fruit constituting both the inner endocarp (liquid and solid food part) and outer mesocarp (fibrous part) (Fig. 10.3). The mesocarp, which is an assemblage of fibres and elastic cellular cork like parenchymatous cells cementing the fibrous materials dispersed throughout the mass. Retting in water of this material causes separation of the leathery exocarp (thin outer slippery cover) from spongy fibrous mesocarp. The fibrous strands are composed of a highly lignified form of cellulose, hence are harsh and rigid. These non-fibrous parenchymatous cells of husk are referred as coconut pith and accounts for as much as 50%–70% of the total weight of husk. There are about 300 eco-types in coconut and there are variations in the quality and quantity of the fibre. Even in the same variety, the fibres vary in length and thickness. The husk is not collected qualitywise (eco-type) and hence the mixture of coconut fibre from different eco-

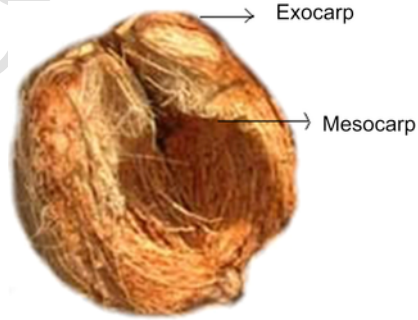

Figure 10.3 Coconut husk.

types results in fibre of lower quality having high variation in length and diameter. Age of husk is an important factor for the selection of good quality fibre. Husks from near ripe to ripe nuts are reported to give best fibres (Meenatchisundarm, 1979).

10.2 Segregation and commercial grading of fibre

Fibre content of a husk distinctly shows three groups viz. coarse, medium and fine. Spinning of coconut fibre yarn is made from the mixture of all the three groups of fibres. Coconut fibre yarn is coarser and its products are also coarser and of low value. When we are aiming at production of value added diversified products of finer quality, segregation of fibres into three grades as coarse, medium and fine is needed. Thorough and good cleaning of fibres is also needed.

Depending upon fibre quality attributes viz. fineness and length; coconut fibres are graded into three varieties, viz. (1) finest and short length fibre, (2) moderately coarser and longer length fibre, and (3) hardest and very long fibre. The finest and shortest fibres are used as inner fillings of mattresses. The medium length and moderately softer fibres are the fibres, which have suitability in textile applications, whereas the hardest and longest length fibres are used in making of brushes and brooms. Again depending on colour, coconut fibres were segregated into white and brown. No other major fibre quality parameters (strength, moisture content, presence of non-fibrous material, rigidity), which are essential for commercial uses, are yet established. Also, no machine has so far been commercialized to segregate the fibres precisely according to the above grades.

10.2.1 Fibre extraction

The separation of tightly bound fibres i.e. extraction of fibres can be done by manual and/or mechanical means. Fibre is attached to the mesoderm with pectinous matter. So, for extraction of fibre, the husk is to be essentially softened. The conventional practice of harvesting coconut fruit is above 12 months to obtain high copra content (Encyclopaedia Britannica., 1982). The husk at this maturity stage is about to dried and thus the fibres were brown, coarse and rigid. Being a secondary crop, not much attention is given on the fibre quality.

10.2.1.1 Extraction of white fibres (manual) through conventional retting

Retting of coconut fibre is best suited using fresh husks separate from the nuts within a few days after the plucking. Husks exposed to the sun or longer storage become rigid and brown and thus do not yield good fibre. Conventional retting in saline backwater lagoons is comparatively cheap and manually manageable biological method based on fermentation. In the process of retting, generally green husks (10–11 month old nuts) are kept immersed in water (slow running or stagnant) for a very long period of about 6–10 months depending on the seasonal variation in temperature, humidity and other conditions. Each retting yards usually

contains about 1000 husks either tied into a bundle or in a coconut fibre nets. These are allowed to remain in the water bodies until they get fully soaked. The soaked husks are either immersed down by piling their tops with mud and slimes or tied down to bamboos buried in the mud on the coast but within the reach of tidal waves. During high tides, the lagoons get filled with fresh saline water by exclusion of some muddy dark retting liquor, thus conventional backwater retting facilitate more whiter fibres and softer fibre than the artificially water retted coconut fibres.

Process of retting happens in two stages viz. physical and biological. In the first stage, the husk absorbs water and the plant tissues swell. The swelling helps in leaching of carbohydrates, glucosides, tannins, nitrogen compounds. During the second stage, a variety of micro-organisms develop at the expense of the extracted substances, thereby creating suitable conditions for the microbes decomposing the binding materials of the tissues. The microbes secrete various enzymes that act upon the carbohydrates and nitrogen compounds releasing different organic acids and gases, followed by a rise in temperature. The evolution of the gas results in the frothing of liquor. When the frothing subsides, a whitish film of fungi covers the surface of water (particularly seen in stagnant retting water bodies). At the stage, the anaerobic decomposers dissolve the pectin in the middle lamella of the parenchymatous tissues and separate the coconut fibres. After the retting, the soaked husks are subjected to manual beating with wooden mallets for removal of the outer epithelial layer (exocarp) and to loosen the retted white fibre (Fig. 10.4) and pith in the mesocarp. The thrashed husks are fed to a disintegrator first and then to a spiked opener for removal of pith from the fibres. The fibres possess good elasticity and colour. The fibres so extracted are of good quality and are suitable for spinning–weaving operations and are mainly used in export quality rope and woven mat (including tufted) manufacturing. Such retted fibres from green husks have also been found preferred for preparation of bleached and dyed coconut fibre products (Meenatchisundarm, 1979).

Figure 10.4 Manual defibering of retted husk.

10.2.1.2 Extraction of brown fibres (mechanical)

Direct extraction of fibre from brown coconut 'husk' (12-month-old nuts) is mechanically done for production of 'Brown fibre' (Fig. 10.5). The husk either may be soaked in pits for a couple of days (2–3 weeks) or may not be soaked at all. Coconuts are dehusked with a double-ended sharp shovel. Then the husks are fed to a cylinder with 6–8 bar lags that is driven by motor (30–50 HP) to disintegrate the fibre from the husk. The disintegrated fibres are soaked and washed with water and again fed to a defibering machine. This machine has a feeding passage and a cylinder with series of sharp nails projecting from its periphery. The nails help in further opening of the exposed disintegrated fibre coming from the feed passage and remove the pith and throw the cleaned fibres out. The fibres are sun dried for a day or two before further processing. All these operations are done sequentially involving excessive machining with unscientific utilization of space and power. Brown fibre is used mainly in making brushes, doormats, mattresses, sack of inferior quality, rubberized coir, automobile upholstery, and as geotextiles (nonwoven mat) for soil erosion control (Meenatchisundarm, 1979).

Figure 10.5 Opening of coconut fibre using spiked pin rotating roller.

10.2.1.3 Yield of coconut fibre

The yield and quality of coconut fibre depends on the factors like age of husk, variety of husk, season local conditions and practices, and the location of retting yards. Husk weighs about 35% of the weight of a nut, containing 30%–50% of fibre. So apparently, the yield of fibre is 10%–17.5% of weight of a nut. Generally, in Sri Lanka 1000 husks yield about 140 kg of fibre as compared to 90 kg in India. Further a 1000 husks qualitywise produced 31.75 kg (13.9%) bristle fibre, 59.0 kg (25.9%) of mattress fibres with dust/pith of 137.0 kg (60.2%) (Meenatchisundarm, 1979).

10.2.2 Post-extraction processing

10.2.2.1 Yarn manufacturing

The households and co-operative sectors account for more than 75% of the coconut fibre yarn. For a good quality yarn there is a need for good quality fibre. In Southern India (Kerala), spinning is mostly done by using the simple traditional 'ratt' (spinning wheel), which is driven manually. To prepare a 2-ply coconut fibre yarn on the spinning wheel, a set of two wheels, one stationary and the other movable are needed. While one person rotates the stationery wheel (Fig. 10.6a), two people release the fibres in small quantity continuously, keeping the fibre bundle in their armpits. Simultaneously, they walk backward till the required length of strand is reached (Fig. 10.6b). The strands are then passed through a grooved wooden gadget (Fig. 10.7) and tied together into the notch of the spindle. While the grooved wooden gadget is being allowed to move forward, the movable wheel is turned in the opposite direction to insert the doubling twist. The people thus are to walk up and down in the spinning yard for drawing the individual strands and for the doubling operation. The yarn produced is uneven in cross-section and twist. This traditional wheel spinning requires at least three people per spinning head to produce about 12–15 kg of yarn per day (Senan, 2014).

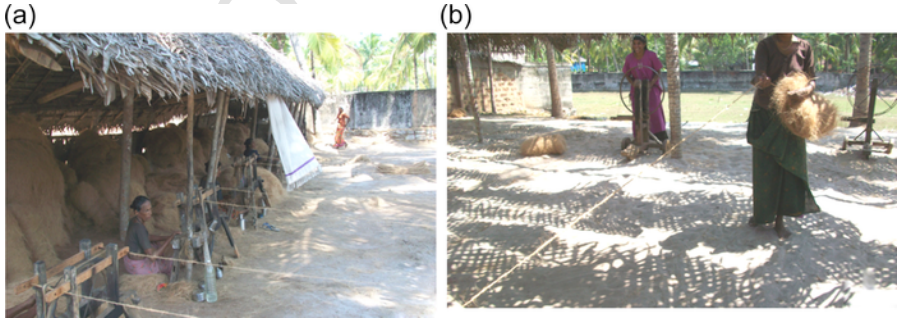

Figure 10.6 Traditional ratt/wheel spinning of coconut fibre showing (a) stationary wheels to form single strands (b) moving wheels to form yarns from twisting of two single strands.

Figure 10.7 Grooved wooden gadget used in traditional ratt/wheel spinning of coconut fibre.

As an improvement, the manually operated traditional ratt has been motorized. By rotating the spinning wheel with a motor, it has become possible to reduce one worker out of the three used earlier, thus increasing the labour productivity. However, there has not been much improvement in machine productivity and the quality of yarn problems exist in such methods of spinning. In a further development, an automatic version of spinning machine has been introduced with much higher productivity (50 kg/h) and which can be operated by a single operator. The coconut fibres in the form of either a loose stock or slivers are fed on the feeder of the machine before falling on to a 'W' shaped tray. The fibres are carried forward by a core high-density polyethylene/low-density polyethylene/nylon continuous filament thread before being twisted by a rotating grip. Two such strands are doubled to form 2-ply yarn and wound on to a bobbin. But the machine suffers from the following drawbacks:

(i) It is not 100% natural yarn, but a yarn with synthetic core covered with coconut fibres.
(ii) It lacks the soft feel which was prevalent in the yarn produced by the traditional ratt.
(iii) Yarn surface is more hairy and twist can be varied only in a narrow range.
(iv) Spinning limit is very low, i.e. produces much coarser yarn which is used for making rope.
(v) The machine is devoid of any safety mechanism including the covers for the rotating components.

10.2.2.2 Bleaching of coconut fibre yarn

Bleaching is a prior requirement to improve penetration of dyes resulting in the colouration with brighter shades. In coconut fibre sector, bleaching attempts at the yarn stage to impart ornamentation to coconut fibre prior to making value-added products, like mats, matting, rugs, carpets etc. Bleaching is mainly done using hydrogen peroxide and sodium silicate. Generally 100 kg of coconut fibre-based rope/yarn requires 12–20 times of water, respectively, using hydrogen peroxide. However, there are wide variations in the recipe of bleaching as well as the degree of whiteness (Anto et al., 1997; van Dam, 2002). Bleaching of coconut fibre yarn

was also done using eco-friendly fungal *Trametes versicolor* and bacterial consortium *Coirret*. The bio-treatment could impart an improvement in softness of the yarn to an extent of 38% using bacterial treatment and 46% using fungal treatment. An increase of 10% in brightness index of the *Trametes versicolor* treated yarn was observed without any reduction of strength of fibre (Ravindranath and Sarma, 2010).

10.2.2.3 Dyeing of coconut fibre yarn

Dyeing of coconut fibre yarn is done to improve the aesthetic value of coir products leading to increased marketability. Traditionally, coconut fibre is dyed in large vessels heated by fuel wood. The required quantities of dyestuff (depending on the depth of shade required) and chemicals are added as a paste to the liquor in the vessel and dyeing is carried out at the required temperatures for the specific time period. For dyeing, 60 kg of coconut fibre yarn at fibre to liquor ratio of 1:12 is used, while smaller quantities of coconut fibre (30 kg) are dyed at 1:20 ratio. The dye bath is stirred manually and the material is turned frequently to obtain even distribution of the dye. After dyeing, the material is removed, washed with cold water and air dried in the shade. Some mechanical improvements include the use of special-purpose fixed stainless steel vats equipped with a valve for draining dye effluents, having heating facilities using electrical elements built inside the housing of the vat (van Dam, 2002). In the conventional process, dyeing is carried out in an indolium/copper/GI vat, which is heated from below using locally available wood. The dye bath is stirred manually and frequently for level dyeing. The material to liquor ratio is maintained at 1:12 and the batch size is 50–60 kg of yarn, which is boiled in the bath for about an hour. Thereafter, the yarn is taken out, washed in cold water and dried under shade (van Dam, 2002; Mohanan et al., 1997).

10.3 Properties of coconut fibre

Some discrete reports are available on investigation of physical, mechanical and other properties of coconut fibre (Bledzki et al., 1996; Stern and Stout, 1954; van Dam et al., 2006; Rahman and Khan, 2007; Coirboard, 2016; NIRJAFT, 1990; Wei and Gu, 2009; Satyanarayan et al., 2007; Brígida et al., 2010; Satyanarayana et al., 1982; Ray and Bandyopadhyay, 1966; Kaswell, 1953; Varma et al., 1984; Meredith, 1945; Banik and Ghosh, 2008), which have been compiled and given in Table 10.2. Similar properties were compared with jute (Satyanarayan et al., 2007; Kaswell, 1953; Mahato et al., 1993) (jute being the highest available lignocellulosic fibre). Coconut fibres' length is in range between 8 and 337 mm. The fibres amount with length range of 15–145 mm is 81.95%. Weight of fibres with the length range of 35–225 mm accounted for 88.34%. The average fineness of is 27.94 tex (Wei and Gu, 2009). Study of fibre diameter revealed a large variation between the fibres within a husk. Longer fibres (more than 10 cm) usually had higher diameters (van Dam et al., 2006; Wei and Gu, 2009) having average diameter, 337 ± 55 µm (Brígida et al., 2010). Density of unretted raw coconut fibre is reported to be 1.15 g/cm^3

Table 10.2 Physical, mechanical and moisture properties.

	Coconut fibre	Jute (C. Olitorius)
Dimension of ultimate cell		
Length (mm)	0.8–1.06 (van Dam et al., 2006; Rahman and Khan, 2007; Coirboard, 2016; NIRJAFT, 1990)	0.75–6.0 (Satyanarayan et al., 2007)
Width ($\times 10^{-3}$) (mm)	14–16 (Rahman and Khan, 2007; Wei and Gu, 2009)	5–25 (Satyanarayan et al., 2007)
Length/width	95–536 (Rahman and Khan, 2007; Wei and Gu, 2009)	110 (Satyanarayan et al., 2007)
Area of cross-section of cell(10^{-4} mm^2)	1.6 (van Dam et al., 2006)	–
Lumen (%)	38(Rahman and Khan, 2007)	–
Dimension of fibre		
Length (mm)	8–337 (Brígida et al., 2010)	–
Fibre fineness (linear density) (tex)	25–50 (Satyanarayan et al., 2007)	2–5(Satyanarayan et al., 2007)
Fibre diameter (μm)	69–870 (Coirboard, 2016; Satyanarayana et al., 1982; Ray and Bandyopadhyay, 1966; Kaswell, 1953)	–
Coefficient friction	–	0.45 (Satyanarayan et al., 2007)
Fibre density (g/cm^3)		
True density (g/cc)	1.40 (Satyanarayan et al., 2007)	1.45–1.52 (Satyanarayan et al., 2007; Kaswell, 1953)
Apparent density (g/cc)	1.15–1.32 (NIRJAFT, 1990; Satyanarayan et al., 2007; Brígida et al., 2010; Varma et al., 1984)	1.23 (Satyanarayan et al., 2007)
Tensile properties		
Single fibre tenacity(g/tex)	10.0–15 (Wei and Gu, 2009; Satyanarayan et al., 2007)	35–50(Satyanarayan et al., 2007)
Bundle tenacity (g/tex)	10–15 (Satyanarayan et al., 2007)	16–35(Satyanarayan et al., 2007)

Table 10.2 (Continued)

	Coconut fibre	Jute (C. Olitorius)
Single fibre breaking elongation(%)	15–37 (van Dam et al., 2006; Wei and Gu, 2009; Kaswell, 1953; Varma et al., 1984)	1–2(Satyanarayan et al., 2007)
Torsional modulus ($x10^{10}$ dyn/cm^2)	0.2–1.5 (Varma et al., 1984)	0.25–1.3 (Satyanarayan et al., 2007)
Flexural modulus (dynes-cm^2)	150–250 (Varma et al., 1984)	3.5–6(Satyanarayan et al., 2007)
Initial modulus (g/denier)	38.3(Varma et al., 1984; Banik and Ghosh, 2008)	130–220 (Satyanarayan et al., 2007)
Young's modulus (Gpa)	4–6 (van Dam et al., 2006; Coirboard, 2016; NIRJAFT, 1990)	0.86–1.94 (Satyanarayan et al., 2007)
Work of rupture	–	0.30 (Mahato et al., 1993)
Moisture relation		
Moisture regain(%) at 65% R.H. 27°C	8–12.5 (van Dam et al., 2006; NIRJAFT, 1990; Wei and Gu, 2009)	12.5 (Satyanarayan et al., 2007)
Transverse swelling in water (%)	5–15 (Satyanarayan et al., 2007)	20–22 (Satyanarayan et al., 2007)
Electrical resistance		
Volume resistivity, 100 V (Ω cm × 10^5)	9–14(Satyanarayana et al., 1982)	–

, considering the adhered pith particles of lower density (0.11 g/cm^3) on surface. The fibres after retting are found to have density (van Dam et al., 2006) of 1.32 ± 0.03 g/cm^3. Coconut fibre tenacity (10–15 g/tex) is low as compared to other popular rope making lignocellulosic fibres. Coconut fibres having short fibre length are stronger than the long fibres. The permanent increase in coconut fibre length (plastic deformation) was calculated by loading the fibres at 50 and 100 mm span length within 1 min. The permanent deformation was calculated to 11% of the span length (van Dam et al., 2006). Moisture regain of coconut fibre was reported to be 8%–12.5% at 65% relative humidity. Transverse swelling of coconut fibre in water

has been observed to be about 15% in diameter and it increases appreciably up to 34% after 15 min. Longitudinal swelling was reported to be 0.9% after 15 min of wetting (van Dam et al., 2006). Untreated coconut fibre sample showed water uptake up to 61% (Rahman and Khan, 2007).

10.4 Composition of coconut fibre

Main chemical constituents of coconut fibre are polysaccharides and lignin. Although a number of minor components, such as pectin, inorganic salts, nitrogenous substance, colouring mater, wax etc. are also found in them. Chemical composition of coconut fibre as compared to that of jute (popular rope making allied lignocelluloses fibre) is given in Table 10.3. Composition of coconut fibres contains slightly higher cellulose than its lignin content with varying amount of hemicelluloses. The total polysaccharide content (50.9%) of the fibre is substantially higher containing 32.8% glucose as the major constituent, largely derived from alpha cellulose. Major non-cellulosic polysaccharide contains of fibre is xylose and polyuronic acid present in the ratio of 3:1 present in hemicelluloses fraction of the fibre. Long and short fibres show similar composition even in different varieties. However, fibres at different maturity found to contain different chemical composition. Fibres harvested from 6 to 11 months showed a gradual enhancement in glucose may be associated in the formation of cellulose and lignin, while showed no change in other sugars and extractives (van Dam et al., 2006).

10.4.1 Elemental composition

Coconut fibre consists of 49.6% carbon, 6.1% hydrogen. The elemental composition did not change much after the various treatments with water, alkalis and acids (Wei and Gu, 2009). The surface elemental distribution of coconut fibre studied by X-ray photoelectron spectroscopy (XPS) analysis revealed the major element of the fibres are carbon (69.1%) and oxygen (27.4%) along with other minor elements like nitrogen (2.0%), silicon (1.1%) and calcium (0.5%). The oxygen to carbon (O/C) of raw coconut fibre surface is much lower (0.40) than the O/C ratio of the cellulose, hemicelluloses and pectin (0.83). However, the O/C ratio of lignin is 0.35, which indicates the surface content of the fibre is majorly lignin along with other waxy materials (Mahato et al., 1993). The apparent hydrophobic nature of coconut fibre is also due to presence of high carbon to carbon bonds (C–C) as compared to lesser carbon to hydrogen (C–H) bonds (Yueping et al., 2010) and consequent lower oxygen to carbon (O/C) ratio.

10.5 Morphology and structure of coconut fibre

The scanning electron micrograph (Fig. 10.8) shows the micro-fibrils by longitudinal parallel ridges. Coconut fibres contain impurities; wax, fatty and

Table 10.3 Chemical composition (in percent of bone dry weight) and fine structure parameters of coconut fibre and jute.

	Coconut fibre	Jute (C. Olitorius)
Cellulose	35–43 (Bledzki et al., 1996; van Dam et al., 2006; Rahman and Khan, 2007; Coirboard, 2016; Brígida et al., 2010; Satyanarayana et al., 1982; Varma et al., 1984; Meredith, 1945)	58–59 (Rahman and Khan, 2007; NIRJAFT, 1990; Meredith, 1945; Banik and Ghosh, 2008)
Lignin	40–45 (Bledzki et al., 1996; van Dam et al., 2006; Rahman and Khan, 2007; Coirboard, 2016; Brígida et al., 2010; Satyanarayana et al., 1982; Varma et al., 1984; Meredith, 1945)	12–14 (Rahman and Khan, 2007; NIRJAFT, 1990; Meredith, 1945; Banik and Ghosh, 2008)
Hemicellulose	0.15–24 (Bledzki et al., 1996; van Dam et al., 2006; Rahman and Khan, 2007; Coirboard, 2016; Brígida et al., 2010; Varma et al., 1984; Meredith, 1945)	14–25 (Rahman and Khan, 2007; Meredith, 1945; Banik and Ghosh, 2008)
Water solubles	5.25 (Coirboard, 2016; Meredith, 1945)	–
Pectins	3.3–4.0 (Bledzki et al., 1996; Rahman and Khan, 2007; Coirboard, 2016; Varma et al., 1984)	0.2–0.5 (Rahman and Khan, 2007; Banik and Ghosh, 2008)
Mineral matter (ash)	2.2 (Bledzki et al., 1996)	0.5–1.2 (Rahman and Khan, 2007; Banik and Ghosh, 2008)
Fats and waxes	–	0.4–0.9 (Banik and Ghosh, 2008)
Crystallinity (%)	25–33 (Ray and Bandyopadhyay, 1966; Varma et al., 1984)	52–60 (Treatise on Physical, 1988)
Herman's angle of orientation (degree)	41–45 degrees (Bledzki et al., 1996; Stern and Stout, 1954; Rahman and Khan, 2007; Satyanarayana et al., 1982; Ray and Bandyopadhyay, 1966; Varma et al., 1984)	7–9 degrees (NIRJAFT, 1990)

globular protrusions making the fibre surface extremely heterogeneous (Fig. 10.8a) with prominent cracks, micro-pores and irregular wax-like deposition are detectable. The surface morphology of backwater retted fibre (Fig. 10.8b) has more irregularities and impurities than the raw fibre, which might be due to formation of an additional salt coating through its backwater retting followed by air drying without washing. Comparing to raw and backwater retted coconut fibres, treated fibres appeared to be clean, with a smother surface and it is possible to observe a reduction on fats

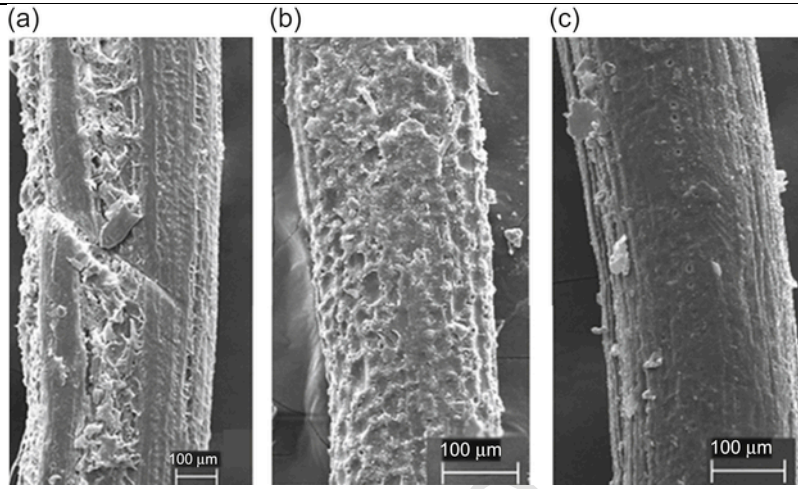

Figure 10.8 SEM micrographs of coconut fibre (a) raw (b) backwater retted (c) chemically retted.

and waxes. Washing with plain water could not remove these impurities; however, treatments of alkali can clean the surface exposing the surface pores called as pits (Fig. 10.8c) (van Dam et al., 2006; Rosa et al., 2009; Basu et al., 2015), which were not revealed on the surface of raw and backwater retted fibres.

The helical arrangements (Fig. 10.9 (left)) of micro-fibrils leads to much higher angle of orientation up to 45 degrees, which is reduced on extension (37 degrees) and cause enhancement in the crystallinity (by 3% on extension to rupture) of the fibre (Ray and Bandyopadhyay, 1966). Optical microscopy (Fig. 10.9 (right)) illustrates that the cross-section of fibre is circular having lumen. Circular cross-

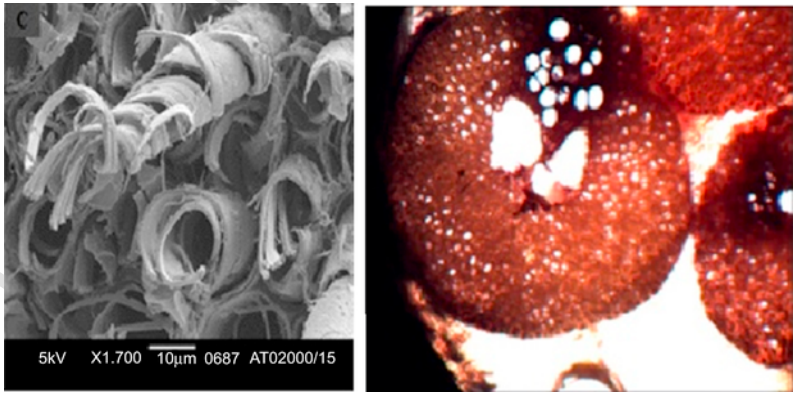

Figure 10.9 SEM of helical structure of elementary fibre cell wall and optical microscopic view of coconut fibre.

section makes the raw coconut fibre lustrous in appearance. Presence of numerous voids around lumen indicates its multi-fibrillar structure.

Crystallinity of coconut fibre is reported to be considerably low due to presence high amount of non-cellulosic impurities like lignin and hemicelluloses. Diffraction pattern (Fig. 10.10) illustrates polycrystalline nature of the fibre. Coupling of peaks 101 and 10$\bar{1}$ indicates amorphous contribution with non-uniform strain and texture. A broad peak at 002 is evident along with 004 peaks. Broadening of peak 002 shows bigger crystallite size and presence of large amount of non-cellulose matter (Basu et al., 2015). Crystallinity of cellulose of the coconut fibre has been calculated 37%–45% (van Dam et al., 2006; Basu et al., 2015) having inter-planer distances of the lattice structure of the peaks of (10$\bar{1}$) and (002) of 5.49 and 4.29 nm at 15.7 and 22.1 degrees diffraction angles (2θ) (Basu et al., 201).

Thermal analysis of coconut fibres (Fig. 10.11) showed the initial decomposition of fibre takes place for evaporation of water and volatile substances (low molecular weight waxes and fats) occurs between room temperature and 150°C. The

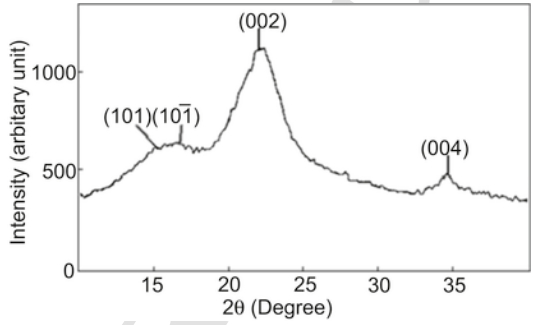

Figure 10.10 X-ray diffractogram of coconut fibre.

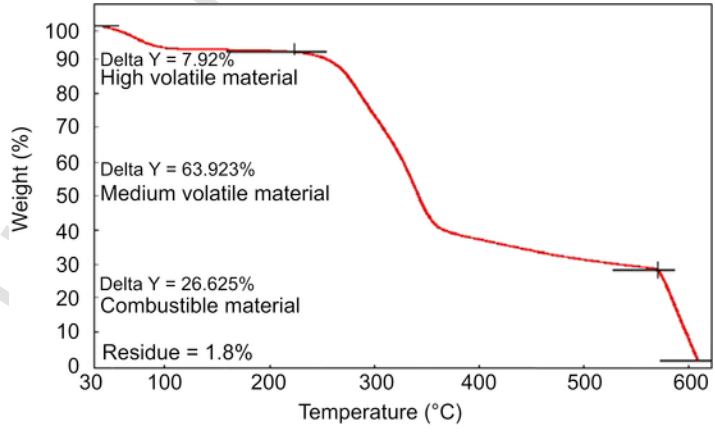

Figure 11.11 TG curve for coconut fibres.

second weight loss corresponds to hemicelluloses degradation, starts at about 190°C. Weight loss occurs between 290 and 360°C, mainly corresponds to cellulose degradation. Lignin degradation starts at about 280°C and continues even above 500°C (Rosa et al., 2009). Thermal degradation for the temperature range 125–295°C was found to 40% as compared to the 24% in the later temperature range 300–600°C indicating the presence of higher methyl-aryl ether groups than aromatic groups in lignin of coconut fibre (Basu et al., 2015). Similar trend was also observed through NMR (Rencoret et al., 2013).

FTIR spectroscopy of coconut fibre (Fig. 10.12) shows a broad and intense peak at 3375 cm^{-1} suggesting OH stretching vibrations from cellulose and lignin (Bilba et al., 2007). A peak at 2363 cm^{-1} is indicating the C–H stretching in polysaccharide chain units. The hemicelluloses, lignin and pectin are identified at the peak at 1731 cm^{-1} ascribed to conjugated CO stretching of ester and aldehyde (Samanta et al., 2008). Peak 897cm^{-1} is characteristic for β-linkages, especially for hemicelluloses (Cao and Tan, 2002). IR spectrum of coconut fibre also shows a characteristic C–O–C stretching absorbency peak at 1038 cm^{-1} of cellulose (Vasi and Shah, 1981), absorption peaks corresponding to 1250 cm^{-1} (lignin aromatic C–O stretching), and 1509 cm^{-1} (lignin aromatic ring stretching) (Mahato et al., 1993; Samanta et al., 2008). The characteristic absorbency peak in the wave number of 1608 cm^{-1} is obtained for lignin (Yueping et al., 2010).

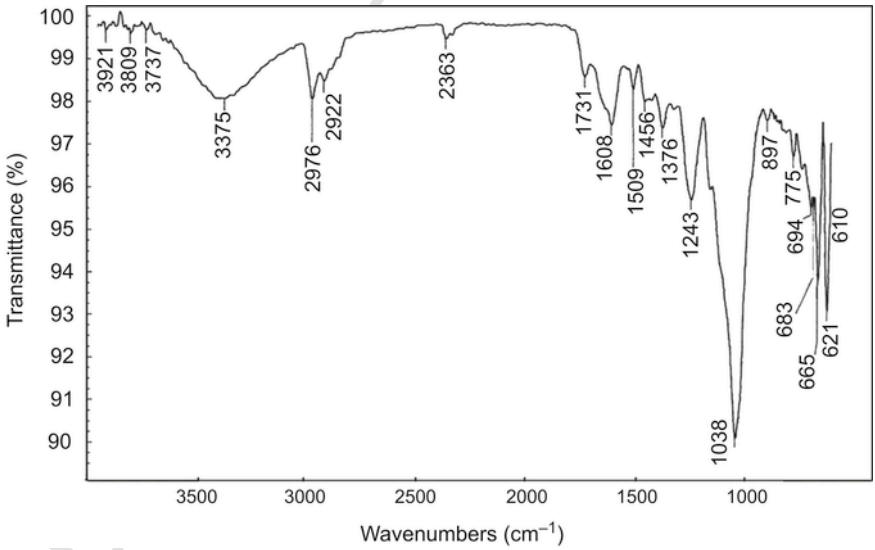

Figure 10.12 FTIR spectrum of coconut fibre.

10.6 Treatments of coconut fibre affecting the structure and properties of coconut fibre

10.6.1 Alkali treatments (NaOH)

Alkali treatments caused maximum weight loss (9.3 ± 1.5%) and also changed the colour of the fibres from pale yellowish brown to dark brown. The helical arrangements of micro-fibrils at an angle of orientation of 45 degrees impart crimp on coconut fibre due to differential shrinkage on treatment with 10% alkali (Varma et al., 1984). The weight loss of 12.65% is obtained by treatment with 20% NaOH at temperature 25°C (Rahman and Khan, 2007). The fibres also become finer due to reduction in diameter. The diametrical reduction of coconut fibre was found to be more for thicker fibres (43%) having thicker cell wall than thinner fibres (10%). The size of central lacuna also reduced considerably (van Dam et al., 2006; Varma et al., 1984). The coconut fibre bristle fibres got slightly lesser strength, due to possible rupture of alkali sensitive bonds existing between components of the fibre as a result of swelling and removal of hemicelluloses in alkali treatment (Varma et al., 1984). On the contrary, Rosa et al., 2009 reported a considerable improvement in tensile properties (10.2–13.6 Mpa) and initial modulus of the fibre on treatment with the NaOH (10%) (Rosa et al., 2009). The increase in tenacity in the fibre is resulting out of its reduction in non-cellulosic content enhancing the content and purity of cellulose, thus, enhanced the crystallinity index of the fibre (Varma et al., 1984). Also, the alkali treatment removes the cementing material between the fibrils causing slippage of molecular chains resulting in higher elongation at break. FTIR spectra of unretted and alkali-treated coconut fibre shows a disappearance of a small peak at 1740 cm^{-1}, due to removal of hemicelluloses (Brígida et al., 2010; Varma et al., 1984). The thermal analysis of alkali-treated fibre showed an inflection for mass loss in the temperature zone of 150–310°C possibly due to considerable loss in hemicelluloses and pectin (Rosa et al., 2009). Treatments of coconut fibre gradually from 5% to 30% NaOH convert the thermal curves having exothermic nature (cleavage of pectin, hemicelluloses and cellulose including a part of lignin) to endothermic nature. This may be interpreted as the initial treatment with lower concentration of alkali is reacting with the lignin and hemicelluloses of the fibre and degrades them only, while at higher concentrations of NaOH (above 15%) the cellulose also get degraded, which is reflected in its thermal instability. The activation energy, which also reveals the thermal stability shows initial enhancement of activation energy of coconut fibre on treatment with 5% NaOH followed by a drastic fall in the activation energy of the fibre up to treatment with 30% NaOH. Treatment of 5% NaOH, initially enhance the activation energy/thermal stability of coconut fibre due to removal of hemicellulosic mass only and give rise to lignin-cellulose complex. Hemicelluloses are less thermally stable than lignin and cellulose, hence, removal of it makes the fibre more thermally stable (Mahato et al., 1993). The coconut fibre treatments from 5% to 50% NaOH at different temperature

ranges from 0 to 100°C indicates variable weight loss and fibre length shrinkage. The highest shrinkage (5.88%) was observed at 0°C with 20% alkali (Rahman and Khan, 2007). Such type of action is also seen in case of jute fibre when treated with 18% NaOH at low temperature (0–5°C), resulting in severe crimp generation in fibre due to differential shrinkage of the molecular chain (Saha et al., 1961; Lewin et al., 1959). Coconut fibre treated with NaOH, from 2% to 10% (w/v), showed enhancement in moisture regain (from 16.87% to 20.13%) (Samal et al., 1995). Treatment of the fibre with 2% NaOH increased tensile strength (from 130 to 161 kg/cm^2) but reduced the strength to 152 kg/cm^2 on treatment with 8% and 10% NaOH (Brígida et al., 2010; Samal et al., 1995).

10.6.2 Acid treatments (HCl, CH_3COOH, HNO_3)

Hydrochloric acid (10%) and acetic acid (10%) treatment caused about 7.5 ± 0.5% and 6.5 ± 1% weight loss in fibre, respectively, while no notable change in colour was observed. Moisture regains of coconut fibre increased considerably from 8% to 16% on hydrochloric acid treatment (Varma et al., 1984). Treatments of sulphuric acid (40% and above) at ambient temperature, resulted in surface carbonization with gradual solubilization (complete or partial) of the fibre. However, for concentration of 30% and below for H_2SO_4, the fibres resist the treatment for 1 h without any surface carbonization. The action of HCl was milder than H_2SO_4, which shows no surface carbonization under the treatment conditions. However, the treatments made the fibre brittle during storage even after alkali neutralization, probably due to hydrolysis of cellulose polymers by the acids (Meredith, 1945). The treatment of coconut fibre with concentrated nitric acid also reduced the fibre strength (Varma et al., 1984; Meredith, 1945).

10.6.3 Oxidizing treatments (NaOCl, H_2O_2)

Pre-treatment of NaOCl (4%–6%) prior to treatment caused higher removal of waxy materials, causing disappearance of the peak 1238 cm^{-1} for the CO– group attributed mainly to a presence of waxes and fats (esters, ethers and phenol). Hydrogen peroxide treatment oxidizes the OH groups in cellulose present on the surface and thus enhance the peak intensity of the existing CO group at 1728 cm^{-1}. Treatments of NaOCl and H_2O_2 caused enhancement in oxygen to carbon (O/C) ratio due to reduction in hydrophobic surface impurities (fats and waxes), lignin and thus increasing cellulose exposition and making the fibre more hydrophilic. Although, the H_2O_2 treatment caused highest removal of fats and waxes but could not able to remove surface lignin hence not able to enhance the wettability of the fibre, . The treatment of NaOCl (4%–6%) prior to NaOH (10%) caused considerable mass and volume loss (diameter reduced from 495 to 165 µm) enhancing the fibre density. The treatment also enhanced the percentage cellulose content (from 45.9% to 62.8%) probably due to much higher removal of hemicelluloses and alkali soluble lignin (reduced by 50%) and other impurities (Brígida et al., 2010).

10.6.4 Treatment with ethylene dimethacrylate (EMA) and UV radiation

Coconut fibre possesses high moisture absorption, poor wettability and insufficient adhesion between untreated fibre and polymer matrix that lead to debonding with age in the composites. To resolve these problems the fibres are pre-treated with UV radiation. In some cases, fibres are treated with NaOH (5%–50%) and then with ethylene dimethylacrylate and methanol solution followed by exposure of UV radiation for different time and doses. Notable change in mechanical properties of coconut fibre was observed after pre-treatment with UV radiation up to a certain doses (125 passes). Increase in UV radiation enhanced fibre tensile strength by 33%, elongation by 39% and modulus. The improved mechanical properties under UV exposure may be due to cross-linking between the molecular chains of cellulose. The EMA loading of 19.12% are highest at 50% in methanol at 125 passes of UV radiation. Grafting of alkali treated fibre showed an increase of polymer loading (about 56%) and tensile strength (about 27%) than 50% EMA grafted raw fibre. UV radiation exposure followed by NaOH treatment considerably improved the surface morphology and assists in better interfacial bonding in the modified fibre-matrix interfaces (Rahman and Khan, 2007).

10.6.5 Treatment involving dinitrophenylation, diazo coupling and combined diazo coupling-cyanoethylation

Treatment of coconut fibre (preswelled with alkali (NaOH) solution) with 5% 2, 4 –dinitro chlorobenzene in acetone at 60°C (dinitrophenylation) caused much higher improvement in tensile strength (from 130 to 185 kg/cm^2). The treatment also induces hydrophobicity to the fibre to a greater extent i.e. reduced the moisture regain from 16.9% to 4.1%. Treatment with diazotized aniline solution in ice bath (diazo coupling) followed by treatment with cyanoethylate (combined diazo coupling-cyanoethylation) for various time also showed enhancement in tensile strength (178 kg/cm^2) and reduction in moisture regain (11.78%). Reduction of moisture regain was confirmed through FTIR by reduction of the peak intensity at 3446 cm^{-1} for the –OH stretching in both dinitro-phenylated and diazo coupled cyanoethylation treated fibre (Samal et al., 1995).

10.6.6 Treatment with urea on mercerized and acid hydrolyzed coconut fibre (Cocos nucifera) fibres photocured 1,6-hexanediol diacylate

Coconut fibres were modified with 30% 1, 6-hexanediol diacrylate (HDDA) with photo-initiator Irgacure-500 (2%) in methanol by using ultraviolet radiation. The treatment leads to enhancement of polymer loading by 17% and tensile strength was 50%. Urea of different concentrations (0.5%–2%) was incorporated with 30% HDDA to monitor its effect on the properties and 1% urea produced the enhanced polymer loading (25%) and tensile strength (82%). Further improvement of the properties was attempted by treating the fibres with alkali (5% potassium

hydroxide) at various mercerizing times in hot and normal conditions. Among all the mercerized fibres, the fifers treated with hot alkali for 6 h and cured under optimized condition demonstrated the maximum enhancement of polymer loading (35.5%) and tensile strength (130%). The fibres were also subjected to acid hydrolysis for different times with different concentrations of sulphuric acid (H_2SO_4). Again the effect of urea (1%) on the properties of the pre-treated fibres was scrutinized. Water uptake and degradable properties of the treated and virgin fibres were performed (Khan et al., 2005).

10.6.7 Accelerated chemical softening in combination of strong reducing agent and alkalis

It was observed that the optimum combination of 40% Na_2S, 15% Na_2CO_3 and 6% NaOH caused highest weight loss (about 28%) without affecting the tensile property. The treatment reduced flexural rigidity (from 1273 to 361 cN-mm (FAO, 2013)), linear density (from 53 to 34 tex), and diameter (from 345 to 225 μ) significantly resulting in enhancement of length to diameter ratio (from - 991) . It is assumed that, the combination of alkalis (NaOH, Na_2CO_3) might enhance the effect of Na_2S. In the chemical retting process, the presence of strong reducing agent Na_2S sustainably hydrolyzed to produce NaOH, making the bath highly alkaline. The rate of hydrolysis is increased with increase in temperature. In presence of high alkaline medium at elevated temperature, all components are reacting with alkali. Na_2S being a reducing agent, the incorporation of the same in the bath retards the alkaline hydrolysis and oxidation of cellulose reduce the possibility of cellulose degradation, while NaOH alone is used for softening process. Apart from this, NaSH reacts with lignin to introduce –SNa group which increases its acidity and consequently its solubility in alkaline medium (Basu et al., 2015).

10.7 Applications of coconut fibre

10.7.1 Yarns of coconut fibre

The most popular product of coconut fibre is its yarn which is made of two ply single thread spun from coconut fibre by hand with the help of traditional ratts, as well as by semi or fully automatic spinning machines, as discussed earlier. In India, the yarn is of different qualities/grades (27) based on the quality of fibre used, the nature of twist, presence of impurities etc., available in different forms like hydraulically pressed bales, spools bobbins, balls etc., cut length for various industrial and agricultural purposes. The price of Angengo 240 yarn (best quality yarn) started from $ 100–143 USD/100 kg and the price of inferior quality yarn available from Vaikom known as Vaikom −180, 160 yarn is available at the price of Rs. 3500 per 100 kg. In this regard, it is noteworthy to mention the price of yarn made from conventionally retted fibre ($ 97 USD/100 kg, Beypore yarn 90) is

twice in price than that of yarn produced from their unretted fibre ($ 53 USD/100 kg) (Coirboard, 2015).

10.7.2 Coconut fibre mat and mattresses

Raw coconut fibre had been conventionally used to make mats and mattresses in Indian subcontinent. Presently, due to the technological advancements of natural as well as synthetic rubber latex, value added rubberized coconut fibre mattresses and mats are getting much popularity for its much better resiliency, lighter weight with adequate load bearing capacity. These are used as cushioning materials for beddings, settee, automobile seats, mats etc.

10.7.3 Geotextile and agrotextile mat

Geotextiles made out of coconut fibre made to give high tensile strengths by using high twisted with low runnage twines by weaving them closely. Depending upon the tightness of the weave (the grid openings) coconut fibre geotextiles can be made to prevent erosion of high gradient slopes and easily erodible loose or small particle soils. The coconut fibre mat as needle punched sheets present above soil has the ability to absorb and retain moisture and therefore invariably help the growth and development of vegetation.

10.7.4 Coconut fibre log

Coconut fibre log is a cylindrical tube made of coconut fibre netting or knotting filled with natural coconut fibre and thickly compacted. It is mainly used for shoreline protection to prevent scouring of soil from the shoreline. It can also be produced pre-seeded to allow establishment of vegetation when it comes to contact with water after installation.

10.7.5 Composites of coconut fibre

Efforts have also being made to manufacture synthetic matrix composites reinforced with coconut fibre (van Dam et al., 2006; Rahman and Khan, 2007; Rosa et al., 2009). Starch and polyethylene vinyl alcohol copolymer blended with the coconut fibre as fillers for reinforcement and decreasing stiffness has received increased attention for making of biocomposites, particularly for reduction in price and high volume application (Rosa et al., 2009). However, not much success story large-scale trials of this product are available. Coconut fibre in lightly twisted (hand-spun) yarns are cut in a specified length and flocked on an adhesive-coated (mostly polyvinyl-based) wide continuous length of rubber sheet to produce wider matting. Reports on effect of coconut fibre content on the physical and mechanical properties as well as fracture behaviour of composite cement reinforced material and also to partially remove sand are striking (Aggarwal, 1992; Asasutjarit et al., 2007).

10.7.6 Bioethanol production from coconut fibre

The alkaline pre-treated coconut fibres were hydrolyzed enzymatically and fermented with *Saccharomyces cerevisiae* yeasts for ethanol production. The alkaline pre-treatment promoted an efficient solubilization of lignin (80%) converted 87% of the sugars and the ethanol fermentation consumed 81% of the substrate, leading to a sugar to ethanol conversion efficiency of 59.6%. These results points out that green coconut husks are a promising alternative to the production of renewable energy (Silva et al., 2016).

10.7.7 Nano-whiskers from coconut fibre

Nanometre-sized single crystals of cellulose, commonly referred to as whiskers, nano-whiskers or nano-fibrils, can be obtained from delignified/bleached coconut fibres through sulphuric acid hydrolysis to obtain cellulose nano-whiskers with diameters as low as 5 nm and aspect ratio of up to 60. The presence of higher residual lignin content induces higher thermal stability to nano-whiskers (Rosa et al., 2010).

10.7.8 Coconut fibre absorption for dyes

Coconut fibre husk is a cheap and readily available agricultural by-product that can be turned into value-added product which effectively removed methyelene blue and malachite green dye to nearly 93.3%. Furthermore, this study also shown that granular form of coconut fibre husks absorbed methyelene blue and malachite green dye more effectively compared to filament form which may be due to the higher surface area which made readily contacted to the surrounding environment much better if compared to its filament form (Wong et al., 2013).

It was found that percentage adsorption varied linearly with the amount of adsorbent and concentration with time but varies non-linearly with pH. Adsorption equilibrium data were represented by isotherm, kinetics and thermodynamics models. FTIR analyses of the adsorbent suggest that adsorption of the dye was through a chemical interaction of the functional groups on the surface of the adsorbent (Etim et al., 2016; Ong et al., 2013).

10.7.9 Absorption of heavy metals by coconut fibre

The applications of coconut fibre for absorption of heavy metals like lead (Pb), zinc (Zn) (Kathrine, 2008) and chromium (Cr VI) (Tan et al., 1993) were studied extensively. It is found that metal ions are absorbed by the xylems and cell wall facing the lacuna across the secondary wall. Investigation also suggests the absorption of heavy metals like Pb and Zn are positively correlated with pectin of coconut fibre composition.

10.8 Conclusion and future trends

Coconut fibre possesses highly variable fibre length, and large diameter (320 μm) resulting in low length-diameter ratio. So segregation of long and finer fibre from the fibre bulk may give better spinnabilty and short fibres can be used for making composites. The fibre has low breaking tenacity (11.25 cN/tex), initial modulus (200 cN/tex), but higher breaking elongation (21.5%) property causing notably high specific work of rupture (13.4 mJ/tex.m). The fibre shows high flexural rigidity and lower inter-fibre frictional resistance for which it is difficult to spin finer yarn and indicates its suitability for coarse textile applications. Coconut fibre is circular and multi-fibrillar. Moisture regain is moderate (11.7%). Thermal and component analyses reveal the presence of similar amount of lignin and celluloses in the fibre. SEM image revealed that surface of the fibre was waxy, irregular, and having micro-imperfections. Microbial resistance makes the coconut fibre suitable for using it in different engineering and geotechnical applications in conjunction with soil and water.

The optimum value addition of coconut fibre can be realized, when a fully systematic supply chain of quality fibre with proper gradation system can be developed. Spinning of finer coconut fibre-based yarn using mechanized systems is the key area of the processing line for diversifying and improving the coconut fibre-based products line. The fibres can be highly suitable to form compressed mat for various products of geotextile, agro-textiles, and sound and heat insulators with improved softness and fineness property. Lastly, coconut fibre should not need to be treated as a secondary crop; rather some fibre crop varieties or dual varieties have to be developed, which will concentrate on the fibre quality than the food obtained from it. So, the future scope of coconut fibre sector is to establish the cash crop coconut from the status of food to the status of fibre.

References

Aggarwal, L.K., 1992. Studies on cement-bonded coir fibre boards. Cement Concr. Compos. 14 (1), 63–69.

Anto, I.R., Ravi, P.K., Sarma, U.S., 1997. Studies on imparting softness to coir yarns. In: Workshop on Wet Processing of Coir, Alleppey, December. 1–27/Coir News. 27, pp. 19–28, (3) (1998).

Asasutjarit, C., Hirunlabh, J., Khedari, J., Charoenvai, S., Zeghmati, B., Cheul, U.S., 2007. Development of coconut coir-based lightweight cement board. Constr. Build. Mater. 21 (2), 277–288.

Banik, S., Ghosh, S.N., 2008. Pectinolytic effect of microorganisms in piling of jute. Indian J. Fiber Text. Res. 33, 151–156.

Basu, G., Mishra, L., Seiko, J., Samanta, A.K., 2015. Accelerated retting cum softening of coconut fibre. Ind. Crops Prod. 77, 66–73.

Basu, G., Mishra, L., Samanta, A.K., 201. Investigation of structure and property of Indian Cocos nucifera L. fibre. J. Inst. Eng. (India) Ser. E (Springer) 98 (2), 135–140.

Bilba, K., Arsene, M.A., Ouensanga, A., 2007. Study of banana and coconut fibers, Botanical composition, thermal degradation and textural observations. Bioresour. Technol. 98 (1), 58–68.

Bledzki, A.K., Riehmane, S., Gassan, J., 1996. Properties and modification methods for vegetable fibers for natural fibers composites. J. Appl. Polym. Sci. 59 (8), 1329–1336.

Brígida, A.I.S., Calado, V.M.A., Gonçalves, L.R.B., Coelho, M.A.Z., 2010. Effect of chemical treatments on properties of green coconut fiber. Carbohydr. Polym. 79, 832–838.

Cao, Y., Tan, H., 2002. Effects of cellulase on the modification of cellulose. Carbohydr. Res. 337 (14), 1291–1296.

http://coirboard.gov.in/wp-content/uploads/2015/09/weeklyprice-of-coir-yarn-kerala.pdf.

www.coirboard.gov.in, 27.08.2016; 16:15 hrs.

Encyclopaedia Britannica, 1982. Micropaedia, Encyclopaedia Britannica, Inc, Chicago, USA, vol. 15, 1032, (2).

Etim, U.J., Umoren, S.A., Eduok, U.M., 2016. Coconut coir dust as a low cost adsorbent for the removal of cationic dye from aqueous solution. J.Saudi Chem. Soc. 20 (1), 67–76.

FAO, 2013. Jute, Kenaf, Sisal, Abaca, Coir and Allied Fibers Statistics. Food and Agriculture Organization of the United Nations, Rome, December, 2013.

FAO, 2015. Jute, Kenaf, Sisal, Abaca, Coir and Allied Fibers Statistics. Food and Agriculture Organization of the United Nations, Rome, December, 2015.

Kaswell, R.E., 1953. Textile Fibres, Yarns and Fabrics. Reinhold Publishing Corporation, New York, USA.

Kathrine, C., 2008. Correlation between the distribution of lignin and pectin and distribution of sorbed metal ions (lead and zinc) on coir (Cocos nucifera L). Bioresour. Technol. 99 (17), 8476–8484.

Khan, M.A., Taslima, R., Mustafa, A.I., 2005. Role of urea on the physico-mechanical and degradable properties of mercerized and acid hydrolyzed coir (Cocos nucifera) fibers photocured with 1,6-Hexanediol Diacylate. Polym.-Plast. Technol. Eng. 44 (5), 1003–1023.

Lewin, M., Shiloh, M., Banbaji, J., 1959. The crimp of alkali treated jute fibers. Text. Res. J. 29 (5), 373–385.

Mahato, D.N., Mathur, B.K., Bhattacharyay, S., 1993. Effects of alkali treatment on electrical and spectral properties of coir fiber. J. Mater. Sci. 12, 1350–1353.

Meenatchisundarm, R.I., 1979. Retting of coir–A review. Ceylon Coconut Plant. Rev. 7, 20–28, 1975–1980.

Meredith, R., 1945. The tensile behavior of raw cotton and other textile fibers. J. Text. Inst. 36, T107–T130.

Mohanan, K.G., Antonel Vaz, P.C., Sunilduth, J., Radhakrishnan, A., Sebastian, V.A., Sarma, U.S., 1997. In: Proceedings of the International workshop on Wet processing of Coir 8–9. pp. 58–81.

NIRJAFT, 1990. Fifty years of research 1939-89. In: Pandey, S.N., Anantha Krishnan, S.R. (Eds.), Jute Technological Research Laboratories. Indian Council of Agricultural Research, Kolkata, India.

Ong, S., Ho, L., Wong, Y., Zainuddin, A., 2013. Adsorption behavior of cationic and anionic dyes on to acid treated coconut coir. Separ. Sci. Technol. 48 (14), 2125–2131.

Rahman, M.M., Khan, A.M., 2007. Surface treatment of coir (Cocos nucifera) fibers and its influence on the fibers' physico-mechanical properties. Compos. Sci. Technol. 67 (11–12), 2369–2376.

Ravindranath, A.D., Sarma, U.S., 2010. Economical and ecofreindly wet processing of coir using Trametes versicolor and Coirret. Coir News 39, 11–16.

Ray, P.K., Bandyopadhyay, S.B., 1966. An X-ray study of coir fibre. Indian J. Phys. 39 (9), 421–427.

Rencoret, J., Ralph, J., Marques, G., Gutierrez, A., Martínez, T.A., Río, C.J., 2013. Structural characterization of lignin isolated from coconut (Cocos nucifera) coir fibers. J. Agric. Food Chem. 61, 2434–2445.

Rosa, M.F., Chiou, B., Medeiros, E.S., Wood, D.F., Williams, T.G., Mattoso, L.H.C., Orts, W.J., Imam, S.H., 2009. Effect of fiber treatments on tensile and thermal properties of starch/ethylene vinyl alcohol copolymers/coir biocomposites. Bioresour. Technol. 100, 5196–5202.

Rosa, M.F., Medeiros, E.S., Malmonge, J.A., Gregorski, K.S., Wood, D.F., Mattoso, L.H.C., Glenn, G., Orts, W.J., Imam, S.H., 2010. Cellulose nanowhiskers from coconut husk fibers: effect of preparation conditions on their thermal and morphological behaviour. Carbohydr. Polym. 81 (1), 83–92.

Saha, P.K., Chatterjee, K.K., Sarkar, P.B., 1961. Woolenised Jute as a Wool Substitute. Indian Central Jute Committee Monograph.

Samal, R.K., Rout, S.K., Panda, B.B., Mohanty, M., 1995. Effect of chemical modification on FTIR spectra; Physical and chemical behavior of coir. J. Appl. Polym. Sci. 12, 229–234.

Samanta, A.K., Basu, G., Ghosh, P., 2008. Enzyme and silicon treatments on jute fibre. Part I: effect on textile-related properties. Text. Inst. 99 (4), 295–306.

Satyanarayan, K.G., Guimaraes, J.L., Wypych, F., 2007. Studies on lignocellulosic fibres of Brazil. Part 1 – source, production, morphology, properties and applications. Compos. Part A 38, 1694–1709.

Satyanarayana, K.G., Pillai, C.K.S., Sukumaran, K., Pillai, S.G.K., Rohatgi, P.K., Vijayan, K., 1982. Structure property studies of fibres from various parts of the coconut tree. J. Mater. Sci. 17 (8), 2453–2462.

Senan, D.C., 2014. Occupational Diseases and Health Awareness through Multimedia: A Case Study Among Women at Risk Employed in Coir Retting in Kerela. Partridge Publishing, India.

Silva, C.E.F., Cabral, M.M.S., Abud, A.K.S., Almeida, R., 2016. Bioethanol production from coconut husk fiber. Ciência Rural. 46 (10).

Stern, F., Stout, H.P., 1954. Morphological relation in cellulose fibre cells. J. Text. Inst. Trans. 45 (12), T896–T911.

Tan, W.T., Ooi, S.T., Lee, C.K., 1993. Removal of chromium (VI) from solution by coconut husk and palm pressed fibre. Environ. Technol. 14, 277–282.

A treatise on physical and chemical properties of jute. In: International Jute Council (International Jute Organisation, Dhaka, Bangladesh), IJC (X)/11. pp. 1988. 20–24, 30.

van Dam, J.E.G., 2002. COIR PROCESSING TECHNOLOGIES Improvement of drying, softening, bleaching and dyeing coir fibre/yarn and printing coir floor coverings Common Fund for Commodities. Netherland 35, 7–27.

van Dam, J.E.G., Van den Oever, M.J.A., Teunissen, W., Keijsers, E.R.P., Van der putten, J.C., Anayron, C., Josol, F., Peralta, A., 2006. Process for production of high density high performance binderless boards from whole coconut husk. Part 2: coconut husk morphology, composition and properties. Ind. Crops Prod. 19, 96–104.

Varma, D.S., Varma, M., Varma, I.K., 1984. Coir Fibres: Part I effect of physical and chemical treatments on properties. Text. Res. Inst. 54, 827–831.

Vasi, I.G., Shah, P.R., 1981. In Spectroscopic Data Tables. Mahajan Brothers, Ahemadabad, India), 4–13.

Wei, W., Gu, H., 2009. Characterization and utilization of natural coconut fibers composites. Mater. Des. 30, 2741–2744.

Wong, Y.C., Senan, M.S.R., Atiqah, N.A., 2013. Removal of methylene blue and malachite green dye using different form of coconut fibre as absorbent. J. Basic Appl. Sci. 9, 172–177.

Yueping, W., Ge, W., Haitao, C., Genlin, T., Zheng, L., Feng, X.Q., Xiangqi, Z., Xiaojun, H., Xushan, G., 2010. Structures of bamboo fiber for textile. Text. Res. J. 80, 334–343.