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Studies on pulp and paper — making characteristics of some indian non-woody fibrous raw materials: Part 1

Dharm Dutt*, J S Upadhyaya, R S Malik and C H Tyagi

Department of Paper Technology, Indian Institute of Technology Roorkee, Saharanpur Campus, Saharanpur 247 001

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Indian pulp and paper industries are facing many problems in which availability of better quality of wood fibres is one of them. Hence the Indian pulp and paper industry could not match their final product vis-à-vis to the finished products in globally competitive market. Attempts are made to investigate the unique chemical and morphological characteristics of some potentially available non-woody fibrous plants that lie in close vicinity of softwood and bamboo in some properties that can be used to develop certain specific quality papers. In this paper industrial potential application of *Ipomea carnea*, *Cannabis sativa* and *Sesbania aculeata*, are discussed, in order to augment their utilization for manufacturing of high-quality cultural papers. Out of three, two non-woody plants are native of South America and Australia and are available in plenty in all the states of the India by adapting Indian climatic conditions. *Ipomea carnea* that is native to South America resembles with *Pinus kesia* and *Picca abies* in lumen and fibre diameter. Although the fibres are short, yet it gives stronger paper due to high collapsing index. *Cannabis sativa*, which is popularly known as 'true hemp', its long bast fiber strands or ribbons are extensively used for manufacturing of quality papers. *Sesbania aculeata* produces high quality bast fibers resembles with jute

Keywords: Paper production, Pulp production, Raw materials, Non-woody fibrous plants, *Ipomea carnea*, *Cannabis sativa*, *Sesbania aculeata*.

Introduction

Indian pulp and paper industries are facing multifarious problems like tough competition from imports, obsolete technology, soaring environmental costs, depreciation of money and inadequate supply of low-cost fibre to survive in the globally competitive market. This combination has compelled the Indian pulp and paper industry to spend heavily on imported long wood fibre each year. If India cannot overcome its lack of domestic wood fibre as well as revamp and improve its end products to match imports, then the Indian pulp and paper industry will stagnant and decline.

The shortfall of domestic wood fibre can also be solved up to a certain extent by using some of the potentially available non-woody fibrous plants, i.e., both agro-based residues and other non-conventional raw materials. In present scenario, pulp from non-woody plants represents only 7 per cent of the total world pulp production, but at over 10 m t/y it still represents a substantial quantity. About 70 per cent of these non-wood pulp productions occur in India and China where domestic wood fibre fails to sustain a continuous supply of fibres to pulp and paper industry. The estimated total availability of non-woody fibrous plant is 2300 mt of which about 50 per cent are straws[1].

Another agro-based residue available in plenty is bagasse. In India, total current production of sugar has touched a high figure of 9.95 mt. The total cane crushed in this sector is estimated at 113.6 mt. Therefore, bagasse produced in this sector will be around 42 mt[2]. It is hoped that even if only 20 per cent of this quantity can be made available to Indian pulp and paper industry then there should be no difficulty in meeting the targeted demand of paper and board products.

Besides agro-based residues, plenty of other non-woody fibrous plants are available in India, whose morphological characteristics have tempted the pulp and paper technologists for their augment use for manufacturing of low-cost and high-quality value

*Author for correspondence
Tel: 0132 2711740
E-mail: dharm-dutt@rediffmail.com

added specialty papers where strength is the main criterion. The non-woody fibrous plants are able to meet the most of the requirement, which are those form hard wood. Surprisingly the chemical and morphological characteristics of selected non-woody fibrous plants indicate that they may be better substitute for expensive long fibered plants except some strength deficiency. The selected non-woody fibrous plants, due to their open and loose anatomical features and low lignin contents can be pulped easily with milder cooking condition, to produce easy bleachable grade pulp. The fibre dimensions data and unbeaten pulp freeness values indicate that they do not require extensive refining to develop fibrillation, hydration and inter-fibre bonding properties.

The present communication aims at evaluating the morphological and other paper making characteristics of some abundantly available non-woody plants like *Ipomea carnea*, *Cannabis sativa,* and *Sesbania aculeate* other than agro-based residues.

Ipomea carnea — Ipomea carnea is a common weed and locally known as 'Besharam'. Because of its high adaptability and resistance towards adverse climatic conditions, it may grow in all types of climate and soils-marshy as well as dry. A large diffused or straggling shrub with milky juice native to South America, it was introduced in India as an ornamental plant. The plant was originally used for making fens for the roadside fields, but due to its massive growth and rapid propagation, it has grown rapidly in barren waste lands both under rained and irrigated conditions. Plantation of *Ipomea carnea* may be undertaken in the month of June-July with the onset of monsoon. Shoots are fast growing and attain optimum size in about a year's time. The yield of *Ipomea carnea* is about 15 to 20 BDMT/ha/y[3].

Cannabis sativa — Cannabis sativa is commonly known as 'True hemp' or 'Soft hemp'. The Indian hemp is commonly known as "Bhang" in Hindi. Typically, it attains a height of 1.5 m at maturity. The cellulose content of hemp fibre increases as the plant matures. Since lignification does not take place so quickly in female plant the male plant is generally believed to be superior for paper-making. An average crop yield is 2-3 t dry stems/ha from which ½- ¼ t of clean fibre is obtained[4]. In most countries hemp harvesting is done by hand, although it can be performed mechanically, using a modified sugar cane harvester. Timing is important, as early harvesting can result in poor yield and weak fibre while delayed harvesting makes it difficult to extract the fibre bundles or ribbons from the core of the stem during retting, thus producing a much coarser and harsher fibre.

Sesbania aculeata— Sesbania aculeata is commonly known as 'Dhaincha' in Hindi. It is a shrub and belongs to the family *Leguminoceae* that helps in fixing of atmospheric nitrogen with its root nodules. About 18.175 t of *Sesbania aculeata* ploughs in 1 ha yield about 77 kg of nitrogen[5]. An annual wood yield of 12 to 16 BDMT/ha is reported in the plantation trial[6]. Even presuming a lower annual yield of 10 BDMT/ha, a pulp and paper industry of 200 TPD capacity will require a plantation area of about 18,000 to 20,000 ha, as compared to 10 to 20 times more in the case of bamboo and still many times in the case of tropical hardwood[7]. On maturity, *Sesbania aculeata* attains a maximum height of 15 to 22.5 cm in three to six month's time. The annual plant yield in Northern India ranges from 11.3 to 13.8 t/ha. It is a lightweight material with a packing density of 120-135 kg/cm^3. Mostly the fibres are used in making fishing nets and ropes as it is considered to be very durable underwater. The fibre is coarse, silken in appearance, resembling hemp and is resistance to water[8]. The yield of bast fibres is around 9 per cent after retting and drying.

Experimental Methodology

Raw Materials Preparation — The stalks of *Ipomea carnea, Cannabis sativa* and *Sesbania aculeata* were collected in the vicinity of Saharanpur, located in the foot hills Shivalik in Northern India and chopped by hand. The chips were then screened and those passing through30 mm screen but retain on a 20 mm screen were collected. The accepted chips were air dried under atmospheric condition in polythene bags.

Morphological Studies — For morphological studies the samples were subjected to a chemo-physical maceration to segregate the individual cellular elements by dissolving middle lamella without damage. It involves the use of hot aqueous solution of CH_3COOH and $NaClO_2$. The slides for microscopic examination were prepared as per BIS specification 5285-1969. Fibre length, fibre width, fibre diam and cell wall thickness were measured by projecting the image at a magnification of 160 X.

Pulping Studies — Screened chips were digested in electrically heated rotary digester of 0.02 m^3

capacity by soda, soda-AQ, alkali-O_2, alkali-O_2-AQ, Kraft, Kraft-AQ, AP and PA processes, alkaline sulphite, alkaline sulphite-AQ, semi alkaline sulphite, semi alkaline sulphite-AQ and NSSC pulping processes at optimum conditions. The pulping variables like chemical doses, time and temperature have been optimised in the PhD thesis of the authors[9]. The pulp was screened through a laboratory vibratory flat WEVERK screen with 0.15 mm slits. The pulp yield, screening rejects and kappa number were determined. The pulps were bleached by CEHH bleaching sequences. Both unbleached and bleached pulps were beaten in WEVERK valley beater and hand-sheets were prepared on British sheet-forming machine. The hand-sheets were evaluated as per BIS method for various physical strength properties.

Results and Discussion

Ipomea carnea — Table 1 shows the morphological characteristics of *Ipomea carnea* with bagasse, bamboo, *Pinus kesia,* and *Picca abies.* The fibres of *Ipomea carnea* are tapering at one end and slightly tapering at another end. Most of these fibres show variable thickening in cell wall. Cell wall cavity is wide and nearly empty with little amount of cell sap. The average fibre dimensions are, length 0.62 mm, width 33.17 μm, lumen width 31.33 μm and cell wall thickness 1.47 μm. The *Ipomea carnea* fibres are shorter in length but the fibre width is much higher than those of bagasse and bamboo. This resembles with softwood like *Pinus kesia* and *Picca abies.* Flexibility coefficient of *Ipomea carnea* fibres is comparable with those of tropical pines and spruce. However, runkel ratio is comparatively low. The fibres having lower wall fraction and runkel ratio give stronger paper. The thin walled wide lumen fibres of *Ipomea carnea* collapse readily to double walled ribbon structure on delignification and exhibit plastic formation, thus offering more surface contact and fibre bonding [10,11]. This gives good physical strength properties with more opaque sheet and less porosity. Sheet formation characteristics of *Ipomea carnea* are quite good.

Table 2 shows the pulp evaluation data of *Ipomea carnea* pulps, obtained by various pulping methods. The total cooking cycles of *Ipomea carnea* is short, requires milder cooking conditions and produces higher pulp yield than those of conventional non-woody fibrous materials. The *Ipomea carnea* pulp can be bleached to very high brightness level of above 90 per cent brightness using lesser amount of bleached chemicals. The mechanical strength property data indicate that the blend of *Ipomea carnea* pulp with long fibred pulps can be used to develop wide variety of specialty papers.

The pulp blend containing 60 per cent of *Ipomea carnea* and 40 per cent *Cannabis sativa* hemp ribbon pulps, after beating separately to 40 ^{0}SR freeness level suitable for manufacturing of razor blade wrapper[12-13]. A pulp blend of 30 per cent *Ipomea carnia* and 70 per cent *Cannabis sativa* hemp ribbon, oxygen delignified pulps beaten to 75^0 SR separately, which on addition of 45 per cent precipitated $CaCO_3$ (on o.d. furnish) to valley beater after proper mixing rise the freeness level from 75 to 85 ^{0}SR, is found suitable for the development of cigarette paper[14]. Specific pulp

Table 1— Morphological characteristics of *Ipomea carnea*, bagasse[18], bamboo, *Picca abies* and *Pinus kesiya*

Sl No.	Particulars	*Ipomea carnea*	Bagasse[18]	Bamboo[19]	*Picca abies*[21]	*Pinus kesiya*[21]
1	Fibre length (L), mm	0.622	1.2	1.70	2.25	2.32
2	Fibre width (D), μm	33.18	—	23.60	41.70	40.70
3	Lumen width (d), μm	3.34	20.0	9.50	35.70	34.75
4	Cell wall thickness (w), μm	1.47	—	7.00	6.00	5.85
5	Flexibility Coefficient d/Dx100	91.46	—	40.56	85.54	85.62
6	Slenderness ratio L/D	18.68	85.0	72.03	53.96	57.00
7	Rigidity coefficient 2w/D	0.09	—	0.59	0.29	0.29
8	Wall fraction (2w/D) x 100	8.89	—	59.30	29.0	29.0
9	Runkel ratio, 2w/d	0.97	—	1.47	0.39	0.34
10	Ratio of wall thickness to lumen width w/d	0.05	—	0.74	0.17	0.17
11	d/R ratio	0.09		0.59	0.34	0.29

Table 2 — Pulp evaluation characteristics of *Ipomea carnea* jacq

Pulping processes	Cooking conditions			Pulp yield (unbleached) per cent	Kappa no.	Brightnes s per cent (Elrepho)	Freene ss ^{0}SR	Burst index Kpam^2/g	Tear index MN m^2/g	Tensile Index Nm/g	Double fold (no.)
	Alkali dose per cent (as Na_2O)	Max cooking temp, ^{0}C	Max cooking time, min								
Soda	16	165	186								
Soda-AQ[1]	16	165	180	43.89	26	78.5	44	3.62	3.50	70.21	128
Alkali-oxygen[2,3]	16	160	120	45.00	29	81.0	45	3.66	4.21	69.06	175
Alkali-oxygen-AQ[1, 2,3]	16	160	120	46.10	27	80.5	45	3.68	4.37	70.02	179
Kraft[+]	16	15	126	46.40	29	81.0	43	3.84	4.65	71.50	190
Kraft – AQ[1, 4]	16	165	120	46.60	23	80.5	44	4.00	4.48	72.50	195
Alkali-peroxide Process (Double stage) [3,5]	13 in Ist and 3 in 2nd stage	180 in Ist and 90 in 2nd stage	180 in Ist and 90 in 2nd stage	45.41	30	82.5	44	3.82	3.72	70.42	180
Peroxide-alkali PA process (single stage) [3,5]	16	180	186	45.81	27	83.0	44	4.42	3.86	72.24	185
Alkaline – sulphite[6]		170	180	48.50	31	82.3	45	3.88	3.68	69.92	186
Alkaline – sulphite [AQ1, 6]	—	170	180	49.21	29	81.5	44	3.94	3.97	68.21	190

1 = 0.1per cent anthraquinone on (o.d. wood basis), 2 = Oxygen pressure 5 kg/cm^2, 3 = 0.1 per cent $MgSO_4$ (on o.d. wood basis), 4 = Sulphidity 20 per cent

5 = 1.0 per cent hydrogen peroxide, 6 = Sodium sulphite as (Na_2O) 10.5 per cent, Sodium hydroxide 6.5 per cent, 7 = Bath ratio 1:4

blend studies on *Ipomea carnea* need to be carried out for many paper grades to optimise the degree of substitution as well as to gauss the cost impact of *Ipomea carnea* pulp in specific furnishes.

Cannabis sativa — Table 3 shows the morphological characteristics of *Cannabis sativa* and comparison with *Eucalyptus citridora* and bamboo. The bast fibres are rectangular in shape; moderately thin to thick walled that may be equal to or greater to the wall thickness. The bast fibres have smooth, thick walled narrow lumen filled with solid material, lower lignin content and are known as libriform fibres. The long hemp fibre averaging 20 mm in length is also moderately wide averaging 22 µm in width. The lumen is equal to or greater than the thickness of the cell wall that is distinguished by longitudinal striations and transverse fractures with somewhat swollen fissures, which are conspicuous. The bast fibres are longer than those of bamboo fibres, but cell wall thickness, lumen diam. — and fibre diam resembles with bamboo. The ratio of cell wall thickness to lumen diam - the runkel ratio is comparable with that of bamboo and about 4.5-times than that of *Pinus kesia*. The fibres become less flexible and show less plasticity. These fibres have lesser degree of collapseness and a lower degree of conformability within the sheet, thereby tend to produce more open sheet having higher bulk and air permeability. The rigidity coefficient and wall fraction of bast fibres resembles with bamboo fibres. Such fibres on delignification tend to retain their tubular structure i.e. do not collapse readily to double walled ribbon structure completely on delignification. The narrow lumen and thick walled fibres principally influence the tearing strength of paper. The felting power of bast fibres is about 16 times to that of *Pinus kesia* fibres. Hence, these fibres have great tendency to flocculate in the head box that is detrimental for formation characteristics of these fibres. Hemp ribbon fibres need high-energy requirements for cutting and refining during stock preparation. Due to poor formation, flocculation problems and high raw material cost, hemp ribbon pulp is always used as a blend with hard wood short fibred pulp, in order to improve formation with structural properties of paper.

The *Cannabis sativa* stalk fibre shows fibre of about to 1.11 mm in length, width 29.54 µm, lumen width 15.21 µm and cell wall thickness 17.056 µm. The flexibility coefficient of hemp stalk fibres is comparable to that of *Eucalyptus citridora*. Rigidity coefficient, runkel ratio and wall fraction is also in close proximity with *Eucalyptus citridora*.

A decrease in these variables, which are measures of the flexibility and wet plasticity of fibers, results in:

- A greater degree of fibre collapse and
- A higher degree of conformability within the sheet, which gives rise to a sheet of a higher density or lower bulk.

Table 4 indicates the pulp evaluation properties of *Cannabis sativa* (whole stalk without removing

Table 3 — Morphological characteristics of *Cannabis sativa* woody fibres, *Eucalyptus citridora*, *Cannabis sativa* hemp ribbons and bamboo

Sl No.	Particulars	*Cannabis sativa* woody fibres	*Eucalyptus citridora*[20]	*Cannabis sativa* hemp ribbon	Bamboo[19]
1	Fibre length, (L) mm	1.11	0.97	21.00	1.70
2	Fibre width (D), µm	29.54	15.00	22.00	23.60
3	Lumen diameter (d), µm	15.21	7.10	8.50	9.50
4	Cell wall thickness (w), µm	7.05	4.00	6.70	7.00
5	Flexibility coefficient (d/D) x 100	51.48	47.30	38.63	40.56
6	Slenderness ratio L/D	37.60	64.79	954.50	72.00
7	Rigidity coefficient 2w/D	0.48	0.53	0.61	0.59
8	Wall fraction (2w/D) x 100	47.80	53.30	60.90	59.30
9	Runkel ratio 2w/d	0.92	1.13	1.57	1.47
10	Ratio of wall thickness to lumen ratio	0.46	0.56	0.78	0.76
11	d/R[1] ratio	0.48	0.53	0.61	0.59

[1]Radius of the fibre

Table 4 — Pulp evaluation characteristics of *Cannabis sativa*[7] (Whole stalk without retting)

Pulping processes	Cooking Conditions			Pulp yield (unbleached) per cent	Kappa no.	Brightness per cent (Elrepho)	Freeness ^{0}SR	Burst index kPa m^2/g	Tear index mN m^2/g	Tensile Index Nm/g	Double fold (no.)
	Alkali dose per cent (as Na_2O)	Max. cooking temp, ^{0}C	Max. cooking time, min								
Soda	16	165	180								
Soda-AQ[1]	16	165	180	50.50	29	76.50	45	5.70	4.78	75.55	223
Alkali-oxygen[2, 3]	16	160	120	51.85	32	78.00	44	6.70	5.45	74.90	225
Alkali-oxygen-AQ[1, 2,3]	16	160	120	53.50	26	77.00	45	6.50	5.61	76.50	240
Kraft[4]	16	165+2	96	53.86	29	78.00	44	7.12	7.51	75.55	277
Kraft – AQ[1, 4]	16	165+2	96	54.00	22	77.50	43	7.25	7.02	80.20	275
Alkali-peroxide process (Double stage) [3,5]	13 *in* I^{st} *and* 3 *in* 2^{nd} *stage*	165 *in* I^{st} *and* 90 *in* 2^{nd} *stage*	180 *in* I^{st} *and* 90 *in* 2^{nd} *stage*	55.15	31	81.00	44	6.53	6.73	76.21	270
Peroxide-alkali PA process (single stage) [3,5]	16	160	180	55.98	26	82.0	44	6.96	6.95	79.61	274
Alkaline – sulphite[6]	—	175	180	56.00	32	79.5	45	6.85	6.85	76.98	275
Alkaline – sulphite AQ[1, 6]	—	175	180	56.5	30	78.6	45	7.03	7.21	76.50	282

1 = 0.1 per cent anthraquinone on (o.d. wood basis), 2 = Oxygen pressure 5 kg/cm^2, 3 = 0.1 per cent $MgSO_4$ (on o.d. wood basis), 4 = Sulphidity 20 per cent, 5 = 1.0 per cent hydrogen peroxide, 6 = Sodium sulphite as (Na_2O) 10.5 per cent, Sodium hydroxide 6.5 per cent, 7 = Bath ratio 1:4

bast fibres) by various pulping methods. *Cannabis sativa* with milder cooking chemicals and short cooking cycle give higher pulp yield with excellent strength characteristics. Table 5 indicates the pulp evaluation properties of *Cannabis sativa* hemp ribbons by various pulping methods. The hemp ribbons with 9 per cent alkali (as NaOH) by soda process and 8 per cent active alkali (as Na_2O) and sulphidity 20 per cent by kraft pulping process gives screened pulp yield 64.00 and 67.25 per cent respectively. The hemp ribbon pulp shows excellent response toward bleaching. The higher brightness level can be achieved by using moderate amount of bleach chemicals.

Cannabis sativa hemp ribbon pulp is utilised as a source of long fibres in blend, in order to develop high-quality speciality paper such as, cigarette paper, mica paper, carbonising paper, capacitor tissue paper, automobile filter paper, razor blade wrapper and bond paper etc.

A mixture of 65 per cent hemp ribbon pulp and 35 per cent hemp stalk pulp is found suitable for manufacturing of cigarette paper. Similarly 50 per cent hemp ribbon pulp, 20 per cent hemp stalk pulp and 30 per cent kenaf (*Hibiscus cannabinas*) pulp; 65 per cent hemp ribbon pulp, 20 per cent hemp stalk pulp and 15 per cent reed (*Phargmites communis*); 50 per cent hemp ribbon pulp, 30 per cent hemp stalk pulp & 20 per cent jute (*Corchorus capsularis*) and, 60 per cent hemp ribbon pulp, 20 per cent hemp stalk pulp and 20 per cent birch pulp was found suitable for balancing the requirement of cigarette tissue with keeping the cost price within specific limits[14].

Table 5 — Pulp evaluation characteristics of *Cannabis sativa* hemp ribbons

Particulars	Pulping process	
	Soda	Kraft
Active alkali as Na_2O, per cent	9	8
Sulphidity, per cent	—	20
Max. Temperature, ^{0}C	165 ± 2	165 ± 2
Max. pulping time, min	180	120
Unbleached yield per cent (screened)	64.00	67.25
Kappa no.	31	28
Freeness ^{0}SR	40	40
Burst index, kPa m^2/g	5.16	6.34
Tear index, mNm^2/g	9.31	11.10
Tensile index, mN/g	62.71	66.26

A blend of 70 per cent hemp ribbon and 30 per cent of *Ipomea carnea* pulp was found satisfactory for cigarette tissue[15]. The hemp ribbon chemical pulp as a blend is used for manufacturing of special capacitor tissue paper of improved quality, capacitor paper with small dielectric losses, capacitor tissue paper of low humidity, capacitor tissue paper with increased electric strength and capacitor tissue paper of one-sided smoothness[15]. A mix of *Cannabis sativa* hemp ribbon pulp and *Ipomea carnea* pulp in the ratio 40:60 were used to develop razor blade wrapper.

Cannabis sativa hemp ribbon pulp is also used for manufacturing of new kind of filter paper and paper board for filtering air, liquid fuel and oil in the internal combustion engines used in aircraft, tractors, motors, trucks, agricultural machinery, railway transport for filtering fluids utilised in hydraulic system of an aircraft, material handling equipment, road construction and other machinery, for cooling the cutting tools in machine building and for other purposes[16]. M/s Tribeni Tissue, use hemp (*Cannabis sativa*) for manufacturing of cigarette paper, tissue for laminating (to metallic foil) and carbonising paper[17].

Sesbania aculeate — The morphological data of *Sesbania aculeata* (Table 6) reveal that the average length of bast fibre is 2.4 mm which falls in close proximity of softwood fibres, i.e., *Picca abis* (2.25 mm) and *Pinus kesia* (2.32 mm), whereas fibre

Table 6 — Morphological characteristics of *Sesbania aculeata* bast fibres and *Sesbania aculeata* whole stalk fibres

Sl No.	Particulars	*Sesbania aculeata* bast fibres	*Sesbania aculeata* whole stalk fiber
1	Fibre length (L), mm	2.40	0.77
2	Fibre width (D), μm	21.00	22.00
3	Lumen diameter (d), μm	8.30	15.40
4	Cell wall thickness (w), μm	6.70	3.30
5	Flexibility coefficient (d/D) × 100	39.50	70.00
6	Slenderness ratio L/D	114.00	35.00
7	Rigidity coefficient 2w/D	0.63	0.30
8	Wall fraction (2w/D) x 100	63.80	30.00
9	Runkel ratio 2w/D	1.61	0.42
10	Ratio of wall thickness to lumen width	0.81	0.21
11	d/R[1] ratio	0.79	0.30

[1]Radius of the fiber

diameter of *Sesbania aculeate,* i.e., 21 μm resembles with fibre diam of bamboo (23.6 μm) and hardwood (20-28 μm). The fibre diam and fibre lumen are narrower, resulting in high slenderness ratio or felting power i.e. L/D. = 114 and high flexibility coefficient (d/D × 100 = 39.5). Although the fibres are highly flexible yet due to more wall thickness and low lumen diam, it gives more d/R ratio, runkel ratio and wall factions. When this ratio is less than unity, then it gives dense, opaque, less porous, and high strength paper. The bast fibre of *Sesbania aculeata* shows low plasticity, which results in lower degree of fibre collapse, i.e., they tend to retain their tabular structure on pressing with lower conformability within the sheet. Such papers tend to show, more tear, porosity, bulk and less opacity. A mix of *Sesbania aculeata* bast fibres can be utilised to develop capacitor tissue paper of low humidity, Alkali Resistant & Soap Resistant (ARSR) paper, razor blade wrapper, currency papers[6] etc., due to their unique property of durability in water.

The fibre morphology data clearly show that the stalk fibres of *Sesbania aculeata* are short with average fibre length of 0.77 mm that fall in the range of hardwood fibre length (0.62-1.3 mm). The fibres' lumen is wider resulting in low slenderness ratio and high flexibility coefficient. In *Sesbania aculeata* and *Cannabis sativa* bast fibres the slenderness ratios are 954.5 and 114, respectively, against a slenderness ratio value of 35 in the case of *Sesbania aculeata* stalk fibre. The reason for this low value is the shorter fibre length and wider fibre diam. The d/R ratio, wall faction and runkel ratio are also low, i.e., 0.30, 30 and 0.42, respectively, indicating the low wet plasticity of these fibres. The flexibility coefficient value is 70, indicating the highly flexible nature of these fibres. Such fibres on pressing and drying readily collapse to form double walled ribbon like structure and provide greater fibre contact area with other fibres. Thus, morphological characteristics reveal that the sheet produced from such fibres have good physical strength with high density[21,22].

Table 7 reveals the pulp evaluation characteristics of *Sesbania aculeata* (whole stalk) by various pulping processes. The cooking chemical requirements are low with comparatively milder cooking conditions. The pulp yield ranges between 48 to 71 per cent with unbleached pulp brightness 35 to 51 per cent ^{0}GE. The wood is light with a packing density of 120-135 kg/m^3 and is more adaptable to continuous digester. The pulp shows good bleaching response and requires lower bleach chemicals. A pulp freeness of 45 ^{0}SR seems to be optimum to develop physical strength properties and to preserve tearing strength. In order to improve the tear, opacity and to run on high-speed paper machines, it is necessary to blend *Sesbania aculeata* whole stalk pulp with long fibred pulp, depending upon the requirement of end product[23,24]. It may be necessary to add high opacifying agent and optical whiteners for manufacture of quality writing and printing papers.

Conclusions

1 The lumen width, fibre diam and cell wall thickness of *Ipomea carnea* resembles softwood like *Pinus kesia* and *Picca abis*. Due to low wall faction and high collapsing index the paper sheet shows improved wet plasticity with more surface contact area for bonding; thereby leading to produce paper with good physical strength properties.

2 The chips of *Ipomea carnea* are found suitable for various pulping methods as mentioned in Table 2. The pulp yield ranges from 42.56 to 49.21 per cent and kappa number ranges from 34 to 29, respectively. By selecting an appropriate pulp blend the quality papers can be developed by taking the mechanical properties and optical properties in to consideration.

3 Hemp ribbon fibres need high-energy requirements for cutting and refining during stock preparation. Due to poor formation, flocculation problems and high raw material cost, hemp ribbon pulp is always used as a blend with hard wood short fibred pulp, in order to improve formation with structural properties of paper.

4 The chips of *Cannabis sativa* (whole stalk) are suitable for various pulping methods. The pulp yield ranges from 49.50 to 56.50 per cent and kappa number ranges from 33 to 30, respectively. The pulp produced by various methods shows excellent mechanical and optical properties. By blending *Cannabis sativa* hemp ribbon pulp with hard wood pulp in appropriate proportion new kind of quality papers can be developed.

5 The fibres of *Sesbania aculeata* are highly flexible yet due to more wall thickness and low lumen diam; it gives more d/R ratio, runkel ratio and wall factions.

Table 7 — Pulp evaluation characteristics of *Sesbania aculeata*[25].

Parameters	Alkali per cent	Max temp,^{0}C	Max cooking time, min	Pulp yield per cent	Kappa no.	Brightness per cent Elerebho	Freeness ^{0} SR	Burst index kPam^2/g	Tear index mNm^2/g	Tensile index Nm/g
Soda	16 (as NaOH)	165	180	47.60	31.0	68.0	44	4.95	4.65	70.7
Soda-AQ[1]	16 (as NaOH)	165	120	48.22	32.0	69.0	45	4.92	4.42	71.0
Kraft[2]	14 (as Na_2O)	160	90	49.80	30.4	71.0	45	6.90	5.30	81.0
Kraft – AQ[1, 2]	14 (as Na_2O)	160	60	50.70	31.0	70.2	40	6.83	5.92	81.2
Alkaline – sulphite[3]	—	175	180	50.80	32.0	72.6	44	5.60	5.76	76.5
Alkaline – sulphite AQ[1, 3]	—	175	120	51.20	31.0	73.5	46	5.85	5.80	73.2
Semi alkaline sulphite	16 (as Na_2O)	170	210	60.90	53.2	74.4	44	5.30	5.90	68.2
Semi alkaline sulphite AQ[1]	16 (as Na_2O)	170	180	60.20	41.2	74.6	41	5.35	5.90	73.0
NSSC[4]	—	160	120	71.20	114	—	39	3.90	5.35	48.9

1 = 0.1 per cent anthraquinone on (o.d. wood basis), 2 = Sulphidity 20 per cent, 3 = Sodium sulphite as (Na_2O) 10.35 per cent, Sodium hydroxide 4.65 per cent, 4 = Total Na_2O, 6 per cent and Na_2CO_3: Na_2SO_3 = 30:70,5 = Bath ratio 1: 4

6 The pulp yield ranges between 48 to 71 per cent with unbleached pulp brightness 35 to 51 per cent ^{0}GE The wood of *Sesbania aculeata* is light, having a packing density, of 120-135 kg/m^{3} and easier to chip. Due to its low packing density, it is more adaptable to continuous digester. The pulp shows good bleaching response with higher brightness stability. The whole stalk pulp blended with long fibred pulp seems to be essential to run on high-speed paper machine as well as to improve tear and opacity value. A mix of *Sesbania aculeata* bast fibres can be utilised to develop tissue paper of low humility, ARSR paper, currency papers, and razor blade wrapper due to its unique property of durability in water.

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