

A Review on Morphological, Chemical and Structural Properties of Wood and Non-wood Fiber Species

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Abstract: A comprehensive knowledge of wood or non-wood fiber characteristics is essential for its best utilization, because of its cellular nature and complex cell wall structure. The fibers have different chemical, physical and anatomical properties that influence its commercial value. The properties of paper are dependent on structural properties of fiber network and strength of individual fibers. The cells normally found in the pulp fibers are tracheids, parenchyma, vessels and epidermal cells. The composition and structure of these different cells determines the papermaking quality and acceptability of the fiber source. Generally, lignocellulose materials from wood and non-wood plant consist of lignin, hemicelluloses, extractive and inorganic matter. Information on the chemical composition is important in deciding the techno-commercial suitability, pulping method and paper strength of a particular wood material. Therefore this review focuses on the wide variability between morphological, chemical and strength properties of two widely used fiber species in Indian pulp and paper industry i.e hardwoods (*Eucalyptus* and *Subabul*) and non-woods (*Bagasse* and *Wheat straw*) and also discusses their practical implication in pulp and paper production.

Keywords: Fiber, Lignocellulose materials, Hardwoods, Non-woods, Strength properties.

I. Introduction:

Fiber, the basic component material in papermaking, comprises of elongated, dead and hollow stem cells, which are classified as plant fibers. Paper industry utilizes these fibers for producing paper, which finds applications in almost all activities of human life. The consumption of paper and paperboard products are a yardstick of development of a society. Paper finds importance as a medium for communication and knowledge assimilation [1]. Presently the pulp and paper industry is using woody and non woody plants to meet the fiber demand for making paper i.e. wood contributes towards 30-35%, agro residues 20-22% and recycled fibers 45-50% respectively (Indian Paper Industry report 2018). In India, hardwoods (eg: *Eucalyptus*, *Subabul*, *Casuarina* etc) with short rotation cycles (average fibre length of 0.2-4mm, cell wall thickness of 3-4 mm) are mostly used as a fibre source for paper and board manufacture [2]. Overall the world, the growing rate of paper consumption is fast and the world production of pulp and paper is around 400 million tons and is predictable to reach 600 million tons by 2020 [3] (Figure 1). Recently, owing to the growth in the global request for fibrous raw materials, the shortage of trees in many counties, and growing sustainability consciousness, non woods/agricultural residues have become one of the most important substitute resources [4, 5]. Production of the pulp and paper from non-wood materials has many

benefits, such as easy to pulp, good-quality bleached pulp, and excellent sources for special types of paper [6, 7].

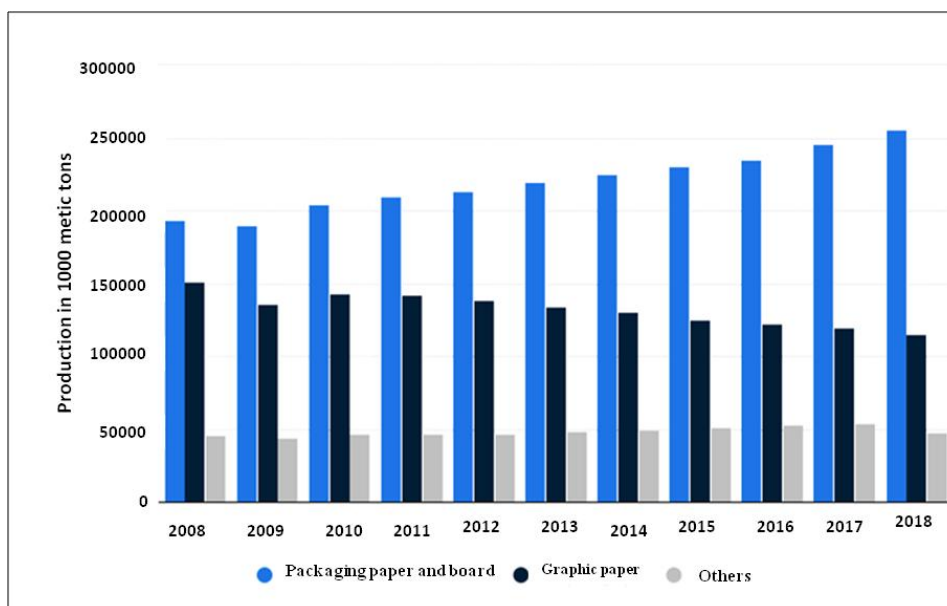


Figure 1. Global paper production volume from 2008 to 2018 (Statista 2021)

Wood fiber is a chemical complex of 40-50% cellulose, 25-30% hemicellulose, 25-35% lignin and (1-5%) extractives [8]. Cellulose is the main component of the fiber. It is a straight chain polymer composed of glucose residues and it is the structural material out of which the fiber is built. Cellulose is very important to paper properties because the attraction between cellulose molecules in different fiber surfaces is the principal source of fiber to fiber bonding in paper [9]. Hemicellulose is the second major component in a wood fiber. It is built up of branched molecule chains of glucose and other monosaccharides. The molecule chains are much shorter than cellulose. They are very important in papermaking because they promote the development of fiber to fiber bonding through their influence on the ability of fibers to take up water during processing and their direct participation in the bonding [10]. The third major component in a wood fiber is lignin. It is covalently linked to hemicellulose and cellulose, confers the mechanical strength to the cell wall (Figure 2). Lignin is an integral part of middle lamella (cell interfaces) and secondary cell walls especially S2 layer. It serves as a binding agent or matrix to the cellulose fibrils and protects the wood from outside environment. Lignin prevents the formation of fiber to fiber bonding in paper and this reduces the paper strength. The aim of paper manufacturing processes or viscose rayon production processes is to obtain the pulp having negligible lignin content but retaining the cellulose.

Today's cellulose industry offers a growing range of pulp and papers produced by different hardwood and non-wood fiber species. Each pulp has unique characteristics, depending on the fiber's original properties and fiber modifications that are introduced by the pulping and bleaching processes. Fiber morphological and chemical characteristics therefore play a key role to determine suitability of any raw materials for pulp and paper manufacturing. Though work has been carried out on the potentials of many wood species for pulp and paper production, no detailed review on important fiber properties have been documented to serve as the benchmark for researchers and for selecting any wood/non-wood material for paper production. Therefore this paper, attempts to review the morphological, chemical and strength properties of wood (hardwoods) and non-wood (agro residues) fiber species and discusses their practical implications in pulp and paper making.

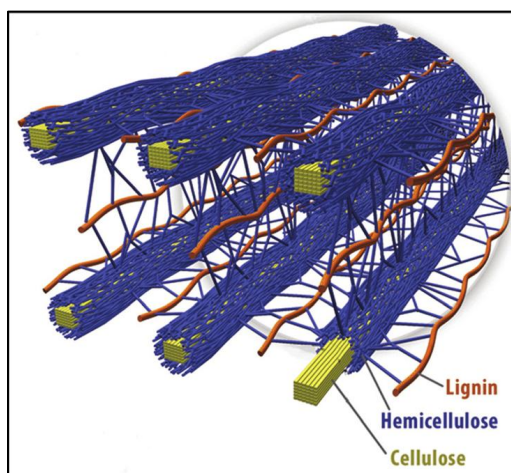


Figure 2. Spatial arrangement of cellulose, hemicellulose and lignin in the cell walls

II. Wood and Non-wood Fiber Species

The hardwoods fiber species are widely used for paper making in India. Hardwoods by comparison are heterogeneous and contain only about 50% tracheid fibers with a large number of vessel cells and ray cells [11]. The fibers are mostly spindle shaped with sharp pointed ends and have pits which are smaller. Hardwood fibers are shorter and thinner giving better paper formation than softwood fibers. Therefore they are used in products requiring a smooth printing surface and high opacity. The pulps are easier to bleach because it contains less lignin compared to softwood [2].

Non-wood fibers, also referred to as “alternate fibers”, are non-woody cellulosic plant materials from which papermaking fibers can be extracted. Most non-wood plants are annual plants that develop full fiber potential in one growing season. The dimensions of non-wood fibers are between those of hardwoods and softwoods. The cellulose content of most of non-woods is comparable to that of woods commonly used for papermaking, while the lignin content is much lower than for woods. Hence, the delignification of non-woods is relatively easy and consumes less chemicals [12].

Wood and agro residue pulp fibers have significant structural differentiation due to their origin and growth patterns which substantially affects the paper properties. Therefore, two fast growing and high yielding raw materials, hardwood (*Eucalyptus*, *Subabul*) and agro-residue (sugarcane bagasse, wheat straw) were selected for systematic study on chemical, morphological, and strength characteristics of fibers (Figure 3 and 4).

(a). *Eucalyptus*:

The genus *Eucalyptus* belongs to the family Myrtaceae. In India, mainly four species of *eucalyptus* viz. *E. tereticornis*, *E. camaldulensis*, *E. grandis* and *E. citriodora* have been planted extensively owing to their faster growth rate and short rotation for various end uses including pulp, wood, sawn timber, fencing pole, firewood and extraction of aromatic oils. *Eucalyptus tereticornis* is one of the most extensively planted *eucalyptus* species known as Mysore gum in India. *Eucalyptus* is currently available in over 90 countries and is spread over more than 22 million hectares worldwide. As a fiber source is well accepted by papermakers due to specific qualities, such as moderate density, good formation, high bulk, high opacity, moderate bonding properties and good tear [13]. *Eucalyptus* pulp is widely used in high-grade writing paper, copy paper, white paperboard, security paper, cigarette paper, toilet paper, napkin and other paper manufacture.

(b). Subabul:

It is commonly known as wild tamarind in English and Subabul in Hindi. Its botanical name is *leucaena leucocephala*. In recent years, *Leucaena* has gained a great attention for its utilization as raw material on large scale for pulp and paper industries and manufacturing of packaging material. Some of the important characteristics include porous structure, light in weight, longer fiber, high holocellulose and low lignin content [14]. Some recent articles provides knowledge and perspectives of *Leucaena* such as optimum stand density for wood production, changes in fiber length and some pulp chemical properties in different varieties, valorisation for energy and chemicals, manipulation of lignin [15]. About 100,000 ha of *Leucaena* has been planted in India to use it as a potential raw material for pulp making.

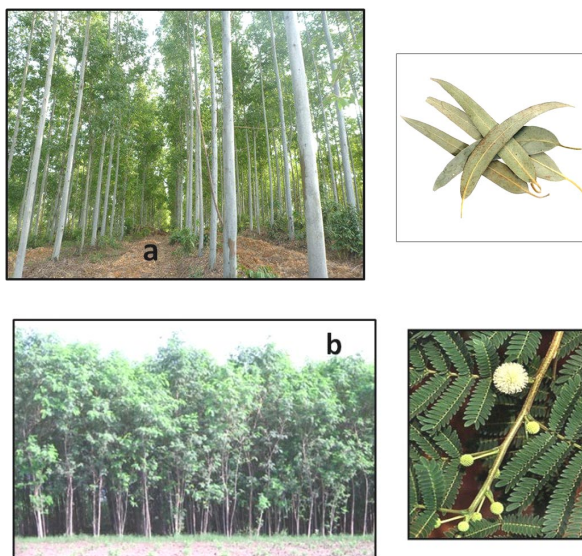


**Figure 3. (a). Eucalyptus plantation at Uttar Pradesh, India;
(b). Subabul plantation at Tamilnadu, India.**

(c). Sugarcane bagasse:

Sugar cane (*Saccharum officinarum*) residue, commonly known as bagasse is one of the prime papermaking fiber source. About 10-12 million tonnes of bagasse is produced per annum in India. It constitutes about 50% of cane processed for production of sugar, which is used as a fuel for cogeneration of steam and power to meet the process requirements. Depending upon the energy efficiency, sugar mills also save bagasse, ranging from 6% to 12% on cane. This spare bagasse is used for production of pulp, paper and particleboard. Bagasse is found to be the best alternative of wood for papermaking because of its low cost, longer fiber than straw, low refining energy consumption and good sheet formation and paper smoothness, enabling the *S. officinarum* to meet the quality requirements for newsprint and fine paper manufacture [16].

(d). Wheat straw:

Wheat straw is a good fiber material, produced annually in huge quantities worldwide and has much shorter growing cycle than wood. With contrast to wood fibers, wheat straw fibers are characterized as shorter in average fiber length and narrow in width, and there are more non-fiber cell contents. After proper pulping, cleaning, and screening, pulps from wheat straw can be used for manufacturing various paper product grades, such as linerboard, corrugated medium, writing and printing papers, etc. It also can be used in cigarette paper furnish with less than 30% proportion to adjust paper's air

permeability. With contrast to wood materials, there are less lignin and more hemicellulose contents in wheat straw and extremely high content of extractives by 1% caustic soda solution, but its biological organizations are bulky and loosened, which is helpful for pulping process [17].



Figure 4. Sugarcane bagasse (left), Wheat straw (right)

III. Morphological Characteristics of Pulp Fibers

The basic component material in paper manufacturing is the fiber, which determines the paper properties. Fibers are the most useful cellulose material in the pulp. These are normally long, flexible and form the basic network (web) in the paper [13]. Fiber morphological characteristics therefore play a key role to find out suitability of any wood species or other raw materials for pulp and paper manufacturing. In general, the average length of hardwood and non-wood fibers lies in between 0.7 to 1.6 and 0.5 to 30 mm respectively and fiber diameter is 20-40 and 8-30 μm . Comparison of fiber dimensions of selected hardwood (Eucalyptus & Subabul) and non-woody (Bagasse & Wheat straw) pulps is depicted in Table 1.

Table 1. Properties of Pulpwoods [2, 13, 18]

Particulars	Eucalyptus	Subabul	Bagasse	Wheat straw
Fiber length, mm	0.30 to 1.71	0.22 to 2.0	0.3 to 4.0	0.52 to 2.37
Fiber diameter, μm	6 to 40	6 to 38	10 to 40	7-45
Fiber/cell wall thickness, μm	5.4	5.46	7.65	5.95
Runkel ratio	3.18	1.19	3.75	3.60
Kink index (1/mm)	2.15	1.62	2.52	2.14

The heterogeneity of the fiber population influences the papermaking. The knowledge and understanding of fiber length distribution is essential in predicting the behaviour of a raw material in the papermaking process. The average fiber length varies from 3.5 mm in softwoods, 0.8-1.2 mm in hardwoods, 2-5 mm in bast and leafy fibers and 1.0 mm to 2.5mm in straws, bagasse and bamboo. The fibers in a paper web are randomly distributed. Depending on fiber length the number of fiber crossings increase or decrease. If the number of fiber crossings increase due to longer fibers, the web is stronger. Fiber length is also associated with the number of bonding site available on an individual fiber. Many researchers have confirmed that tearing resistance and to a lesser extend folding endurance are basically dependent upon the fiber length. Generally, long fibers have a strong positive correlation with tearing strength i.e greater the fiber length, higher will be the tearing resistance of paper [19, 20]. On the other hand, longer fibers tend to give a more open and less uniform sheet structure. In the paper web, when the fibers cross over randomly, the area of bonding is influenced by fiber width. If the fibers are wide, then the area per cross over increases where the fibers are held

together that contributes to the strength of paper web. For a given fiber length, the fibers with higher fiber width gives higher paper strength due to increased cross over area per fiber. Length to width ratio is known as slenderness of fiber. Depending on the fiber wall thickness, the fibers response to refining varies. Fibers with thin cell walls collapse readily. Increase in fiber wall thickness leads to increase in fiber coarseness (mass per unit length). Fibers of higher coarseness are stiff and difficult to collapse which leads to poor bonding due to less bonding area and lower strength. This will result in increased porosity and surface roughness of the paper. However, the fibers with higher coarseness often give higher tearing strength to the papers. Therefore it can be stated that, fiber diameter and wall thickness govern the fiber flexibility. The runkel ratio (twice the thickness of the cell-wall divided by the width of the lumen) of bagasse is higher than hardwoods which inevitably will have negative effect on tensile and bursting strengths. The fibers with Runkel ratio above 1.0 are considered as thick walled fibers which are stiffer, less flexible and form bulky paper of lower bonded area [21]. Kink is an abrupt change in the curvature of a fiber which give rise to dislocations, eventually leading to reduced fiber strength. Kink affects the wet strength and wet rupture energy of the paper.

IV. Properties of Non-Fibrous Tissue

In papermaking, fibers are the cell elements (vessels, tracheids, parenchyma) that impart strength to the paper sheet (Table 2) (Figure 5).

Table 2. Properties of Non-Fibrous Tissue [2, 13, 18]

Particulars	Eucalyptus	Subabul	Bagasse	Wheat straw
Length of vessel, μm	360	297	287.5	195
Width of vessel, μm	140	31	101.4	27.2
Length of Parenchyma, μm	69	122.4	358.5	193
Width of Parenchyma, μm	23	25.5	78.2	44.2
Arithmetic Fines (%)	25.59	27.37	61.9	56.9

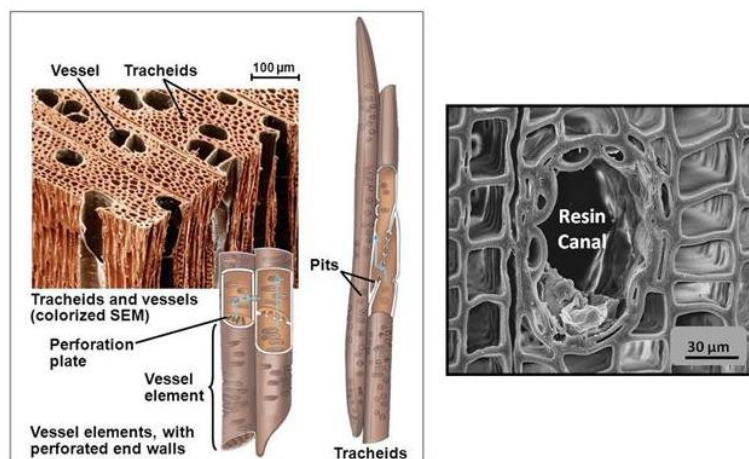


Figure 5. Cross-section of hardwood block revealing different cells

Vessels are short, wide, open ended cells which function for water conduction (Figure 6). Vessel elements are not wanted in the pulp, as they cause problems such as vessel picking. Vessel element, based on amount actually found in a typical hardwood furnish, has little effect on tensile strength. The function of parenchyma cell in plant is to store water, nutrient and assimilated products. In papermaking, parenchyma cells with spherical and small cells are considered to decrease the raw material quality [22]. Parenchyma has low density and decreases the bulk density of the chip charge

to the pulp digester. It also consumes chemicals without participating in paper strength and it makes pulp water drainage more difficult. The proportion of parenchyma cell in fibers used for papermaking is between the range of 20 – 50%.

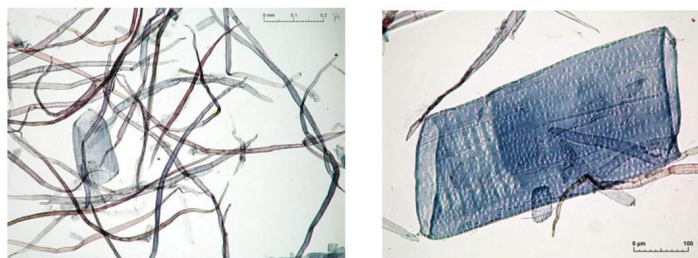


Figure 6. Fibres (left) and vessel elements (right)

Fines are defined as the fraction of pulp that is able to pass through a perforated plate having a hole diameter of 76 μm . The presence of high percentage of fines has been reported to be detrimental to bursting and tensile strengths [19]. Hardwoods fiber species are heterogeneous and contain about 50% tracheid fibers with a large number of vessel cells and ray cells [11]. Hardwood fibers are mostly spindle shaped with sharp pointed ends and have bordered pits. In hardwood fibers, the libriform fibers have simple pits and fiber-tracheids have bordered pits. The fiber-tracheid is considered to be a transitional form between tracheids and libriform fibers. The non-wood fibers are generally longer and more slender than wood fibers. The non-wood fibers are commonly 100 to 200 times longer than their width. In bagasse, the parenchyma cells are small to medium sized narrow rectangular and numerous. Vessels are ranging from 180 to 1600 μm and 30 to 220 μm long and narrow. Whereas in wheat straw, the parenchyma is abundant and barrel shaped and the vessel elements are slender and long. The higher slenderness ratio (aspect ratio) of parenchyma and vessel cells of any fiber species indicates that the cells do not readily collapse and form a very dense sheet with few pores. The smaller cell diameter and thin wall of parenchyma and vessel cells form a tissue component that contribute to strength.

V. Chemical Characteristics of Pulp Fibers

Chemical composition of pulp fibers is important in deciding the techno-commercial suitability, pulping method and paper strength of a particular wood/non-wood material [23]. The chemical composition of wood fibrous plants on an average contain around 45% cellulose, 20-28% lignin and high extractives (Table 3).

Table 3. Percentage Chemical Composition of Wood and Non-wood fibers [13, 24]

Appr. chemical composition (%)	Eucalyptus	Subabul	Bagasse	Wheat straw
Cellulose	44.6	40.4	41.7	39.2
Hemicellulose	27.7	35.2	29.8	34.8
Lignin	26.18	25.6	18.9	21.6
Ash	0.30	0.85	2.10	5.7
Cold water solubility	1.61	3.45	3.02	5.4
Hot water solubility	2.21	5.98	7.42	9.6
Alcohol benzene solubility	2.30	2.55	1.85	2.8

The rest of the wood fiber is made up of a mixture of polymer non-glucose carbohydrates, known as hemicelluloses in both non-wood as well as wood. Water solubility which affects the pulp yield to some extent provides a measure of tannins, gums, sugars, colouring matters and starches. The alcohol-benzene solubles provide a measure of resinous and substances like waxes, fats, flavanoids, phytosterols, non-volatile hydrocarbons, low-molecular-weight carbohydrates, salts, and other water-soluble compounds. It also affects the quality of paper due to shadow marking.

From the data it is observed that:

- Cellulose is comparatively higher for Eucalyptus. Carbohydrate decomposition is important in the development of physical properties. Paper strength depends on the cellulose content of the pulp and mechanical strength of the pulp (especially tensile strength) is directly proportional to the cellulose content [9]. Generally, plants with 34% and higher are characterized as promising for pulp and paper manufacture from chemical composition point of view.
- Bagasse exhibited less lignin content and alcohol benzene solubility. Therefore it will create less pitch problems and provide homogeneity in the paper sheet. The residual lignin present in the pulp influences the paper properties and causes the high stiffness in paper. Of significance is the fact that the structure of lignin in bagasse is more open and looser. The 'lignin' from hardwoods and non-woods differ in composition, chiefly in methoxyl substitution and the degree of carbon carbon linkage between phenyl groups. In this context, the lignin in bagasse is highly S-rich (60 in molar composition) [25]. This indicates that bagasse requires milder pulping conditions (lower temperatures and chemical charges) to attain a satisfactory Kappa number with improved strength properties.
- Wheat straw has high hemicellulose and ash content. In general, hemicellulose enhance pulp beatability, because its abundant end groups are more accessible to water molecules compared to cellulose and serves as an inter-fiber binding agent, that improves the strength properties of paper products. The ash content gives an estimation of the content of mineral salts and other inorganic matter in the pulp. High ash% are undesirable for pulping as they affect normal alkali consumption, give problems at recovery of cooking chemicals and results in operational problems in pulp washing and pulp beating.
- Water solubility of wheat straw is on higher side than other fiber species. Soluble materials comes under the category of extractives which are totally undesirable in pulp and paper making. It affects paper quality and drainage characteristics of paper machine.

VI. Effect of Morphological Characteristics on Strength of Pulp Fibers

Strength properties of paper depend on structural properties of fiber network and strength of individual fibers. The fiber morphology plays an important role in deciding the strength of individual fibers (Table 4). Strength/mechanical properties (Table 5) are important for printing papers, packaging papers, boards and other papers.

Table 4. Effect of morphological characteristics on strength of paper [2]

Parameter	Tensile and bursting strength	Tearing strength	Folding strength	Sheet density
Fiber length	0 to +	++	0 to +	0 to –
Cell wall thickness	+	0 to –	++	++
Fiber length to width (L/D) ratio	-	-	+	-

0-No influence or no distinct influence ; + Marked positive influence ; ++ Decisive positive influence
 ; - Marked negative influence ; -- Decisive negative influence
 - Marked negative influence ; -- Decisive negative influence

Table 5. Strength properties of wood and non-wood bleached pulp fibers [18, 26, 27]

Parameter	Eucalyptus	Subabul	Bagasse	Wheat straw
PFI, rev	2000	2000	500	500
Burst index, kPa m ² /g	3.0	4.5	4.0	4.30
Tensile index, Nm/g	45	64.5	68.5	74
Tear index, mNm ² /g	5.0	6.2	4.10	3.80

The tensile properties describe the strength of the individual fibers, their arrangement and the extent to which they are bonded to each other. The degree of fiber bonding depends on flexibility and compressibility of individual fibers [19]. Greater the fiber flexibility, better the chance of forming well bonded paper. Similarly, an increase in the rigidity of fibers results in a decrease in fiber bonding. Therefore, fiber properties, fiber deformations and chemical compositions (eg: the fiber and paper strength and longevity of the paper depends on the purity of the cellulose) are all important for paper quality. Fiber length is one single major factor influencing the wet web tensile strength that contributes to the runnability. In a paper web the number of fiber crossings per fiber proportionally increases with fiber length, thereby increases the tearing strength of the paper. Fiber width influences the area of bonding. At a given fiber length, increase in fiber width increases the fiber bonding area which has direct impact on tensile, tear and bursting strength of paper. Fiber wall thickness indicates the mass of the wall material per unit length of the fiber. As the wall thickness increases, the fibers are difficult to collapse in the refining treatment.

Fiber length is one single major factor influencing the wet web tensile strength that contributes to the runnability. In a paper web the number of fiber crossings per fiber proportionally increases with fiber length, thereby increases the tearing strength of the paper. Fiber width influences the area of bonding. At a given fiber length, increase in fiber width increases the fiber bonding area which has direct impact on tensile, tear and bursting strength of paper. Fiber wall thickness indicates the mass of the wall material per unit length of the fiber. As the wall thickness increases, the fibers are difficult to collapse in the refining treatment. The paper strength improves with increasing fiber length and decreasing wall fraction (only to certain extent). Thick-walled fibers affect the bursting strength and tensile strength of paper negatively. The reason is that thick-walled fibers when pressed after delignification tend to retain their tubular structure as such without forming double walled ribbon structure. In this way, they provide less surface contact area for bonding. Therefore, the paper made from thick-walled fibers will be porous, more opaque, bulky and coarse-surfaced with a large void volume. Whereas, thin-walled fibers are effortlessly converted into double walled ribbon structure and comparatively provide more fiber surface contact area for bonding after pressing. The sheet made from thin-walled fibers will be less opaque, less porous, denser and well formed. In native wood, the fibers are normally relatively straight.

Pulp fibers are rarely straight and fiber curl, deformations and damages originate from several steps in the chipping, delignification process, medium-consistency unit operations etc which lead to lower strength of the paper. The use of curly fibers will lead to low tensile index and high tear-index. The curly fibers are also tended to form with low elastic modulus but higher stretch than sheets made from straight fibers. Kinks (the abrupt change in fiber curvature) are related to lowered tensile strength and elastic modulus of paper. Tear strength is used to predict the web runnability. Curly fibers give increased tear strength. The curly fibers do also distribute the damages over a larger area and more bonds are broken [28]. The increase in the number of dislocations in fibers causes an increase in tear strength but a decrease in bonding strength.

Hardwood fibers are short, the length-width ratio is mostly less than 60 times. Hardwood contains a large number of parenchyma cell, the paper made from hardwood pulp has low strength, loose paper quality, strong absorptivity, high opaqueness (Table 6). It is so applicable for printing paper manufacture. Bagasse fibers are dense walled, of changing length and have mostly blunt ends. The physical strength properties of bagasse are in the acceptable range for producing printing and writing paper, bristol board, tissue, glassine and greaseproof paper, duplex and triplex paper, corrugating medium, linerboard, wrapping and bag papers, and newsprint if mixes with various proportions of wood pulp. Because of high long fiber fraction, the zero-span tensile strength will be high thus confirming the possibility of making good quality writing and printing papers. Characteristics of bagasse paper include high density and tight stiffness. Wheat straw pulps can be characterized with good strength properties and good printability, etc., which is used to manufacture a wide range of paper and paperboard grades, such as light-weighted printing paper, letterpress printing paper, typing paper, writing paper, aluminum foil base paper, cylinder polished paper, tissue and sanitary papers, white board, coated ivory board, and almost all grades of paper and paperboard grades [29, 30]. To improve pulp stock wet-web run ability in paper machine, wheat straw pulp must be mixed with some portion of bleached wood pulps or bamboo pulps occasionally.

Table 6. Contribution of fiber source to various paper properties [18]

Eucalyptus	Subabul	Bagasse	Wheat straw
Chemical pulping			
Formation, opacity & surface smoothness		Formation, opacity	

VII. Conclusion

Physical properties of pulp fibers are very much dependent upon fiber characteristics. The most contributing fiber characteristics were fiber length and cell wall thickness. Chemical composition of pulp fibers is important in deciding the techno-commercial suitability, pulping method and paper strength of a particular wood/non-wood material. Fiber network structural properties and individual fiber strength are two factors which influence strength characteristics of a paper. In deciding the strength of individual fibers, fiber morphology plays a crucial role. Therefore morphological, chemical and strength properties of fibers are the ultimate factors that determine the overall performance of wood or non-wood as valuable raw material for pulp and paper making.

VIII. References

1. Kulkarni, H. D., Pulp and paper industry raw material scenario - ITC plantation a case study. IIPTA, vol. 25, no. 1, (2013), pp. 79-90.
2. Karlsson, H. Fiber Guide: Fiber Analysis and Process Applications in the Pulp and Paper Industry, AB Lorentzen and Wettre Sweden (2006).
3. Jahan, M.S., Uddin, M.N., Akhtaruzzaman, A.F.M., An approach for the use of agricultural by-products through a biorefinery in Bangladesh. For. Chron. vol. 92, no. 4, (2016), pp. 447–452.
4. Gharekhani, S., Yarmand, H., Goodarzi, M.S., Shirazi, S.F.S., Zubir, M.N.M., Amiri, A., Solangi, K., Ibrahim, R., Kazi, S.N., Wongwises, S., Experimental investigation on rheological, momentum and heat transfer characteristics of flowing fiber crop suspensions. Int. Commun. Heat Mass Transf, vol. 80, (2017), pp. 60–69.
5. Bhardwaj, N.K., Kaur, D., Chaudhry, S., Sharma, M., Arya, S., Approaches for converting sugarcane trash, a promising agro residue, into pulp and paper using soda pulping and elementalchlorine-free bleaching. J. Clean. Prod. vol. 217, (2019), pp. 225–233.
6. Atchison, J.E., Twenty-five years of global progress in non-wood plant fiber pulping – historical highlights, present status and future prospects. TAPPI Non-wood Plant FiberProgress, vol 22, (1995), pp. 111–130.
7. Franciele, A.N., de Costa, F., de Araújo Jr., A.T., Fett, J.P., Fett-Neto, A.G., Multiple industrial uses of non-wood pine products. Ind. Crop. Prod. vol. 130, (2019), pp. 248–258.
8. Smook, G. A. Handbook for Pulp and Paper Technologist. Vancouver: Angus Wilde Publications Inc. (1992).

9. Madakadze, I. C., Radiotis, T., Li, J., Goel, K., & Smith, D. L., Kraft pulping characteristics and pulp properties of warm season grasses. *Bioresource Technology*, vol. 69, no. 1, **(1999)**, pp. 75-85.
10. Akhtar, R. S., Studies on pulping and bleaching of poplar deltoids. Institute of Paper Technology, Ph.D. Thesis, University of Roorkee, Uttarakhand, India, **(2001)**.
11. Hurter, R.W., Non-wood plant fiber characteristics, Hurter ConsultIncorporated, extracted from "Agricultural Residues", TAPPI 1997 Nonwood fibersshort course notes, updated and expanded February **(2006)**.
12. Essam S. Abd El-Sayed, Mohamed El-Sakhawy and Mohamed Abdel-Monem El-Sakhawy. Non-wood fibers as raw material for pulp and paper industry. *Nordic Pulp & Paper Research Journal* **(2020)**.
13. Monga, S. Study on Fiber Morphology of Pulps from Eucalyptus. Report Forest Research Institute **(2017)**.
14. Malik RS, Dutt D, Tyagi CH, Jindal AK, Lakharia LK, Morphological, anatomical and chemical characteristics of *Leucaena leucocephala* and its impact on pulp and paper making properties. *J Sci Ind Res*, vol. 63, no. 125, **(2004)**.
15. Prasad JVNS, Korwar GR, Rao KV, Mandal UK, Rao GR, Srinivas I, Venkateswarlu B, Rao SN, Kulkarni HD, Optimum stand density of *Leucaena leucocephala* for wood production in Andhra Pradesh, Southern India. *Biomass Bioenergy* vol. 35, **(2011)**, pp. 227–235.
16. Pekka, N., Pekka, K. and Harri, A. Global competitiveness of the Indian paper industry **(2002)**.
17. Plazonić I, Barbarić-Mikočević Ž, Antonović A. Chemical composition of straw as an alternative material to wood raw material in fiber isolation. *Drvena Industrija*, vol 67, no. 2, **(2016)**, pp. 119-125.
18. Subramanyam, S. V., Godiyal, R., Janbade, V. and Sharma, A. Monograph of different fibrous materials used by Indian paper industry. CESS project, CPPRI, India **(2004)**.
19. Dutta, T., Sengupta, R., Sahoo, R., Sinha, R.S., Bhattacharjee, A. and Ghosh, S. A novel cellulase free alkaliphilic xylanase from alkali tolerant *Penicillium citrinum*: production, purification and characterization, *Lett. Appl. Microbiol.*, vol. 44, **(2007)**, pp. 206–211.
20. Dwivedi, P., Vivekanand, V., Pareek, N., Sharma, A. and Singh, R. P., Bleach enhancement of mixed wood pulp by xylanase–laccase concoction derived through co-culture strategy, *App. Biochem. Biotechnol.*, vol. 160, no. 1, **(2010)**, pp. 255 -268.
21. Istek, A., "Effect of *Phanerochaeta chrysosporium* white rot fungus on the chemical composition of *populus tremula* L", *Cellulose Chem. Technol*, vol. 40, no. 6, **(2006)**, pp. 475-478.
22. Karjalainen, M., Ammala, A., Rousu, P., and Niinimäki, J., Method for Automatic Analysis of Wheat Straw Pulp cell types. *Bioresources*, vol. 7, no. 1, **(2012)**, pp. 827- 840.
23. Abdul-Khalil, H.P.S., A.F. Ireana-Yusra, A.H-Bhatand M. Jawaaid. Cell wall ultra-structure, anatomy, lignin distribution and chemical composition of Malaysian cultivated Kenaf fiber In *Crops Pods*, vol. 31, **(2010)**, pp. 113-121.
24. Malik, R. S., Dutt, D., Tyagi, C. H., Jindal, A. K., and Lakharia, L. K, Morphological, anatomical and chemical characteristics of *Leucaena leucocephala* and its impact on pulp and paper making properties," *J. Sci. Ind. Res*, vol. 63, **(2004)**, pp. 125-133.
25. Del Rio, J. C., Gutiérrez, A., González-Vila, F. J., Martín, F. and Romero, J. Characterization of organic deposits produced in the kraft pulping of *Eucalyptus globulus* wood. *J. Chromatogr. A*. vol. 823, **(1998)**, pp. 457–465.
26. Riki, J. T. B., Sotande, O. A. and Oluwadare, A. O. Anatomical and Chemical Properties of Wood and their Practical Implications in Pulp and Paper Production: A Review. *Journal of Research in Forestry, Wildlife & Environment*, vol.11, no. 3, **(2019)**.
27. Agnihotri, S., Dutt, D. and Tyagi, C. H. Complete characterization of bagasse of early species of *saccharum officinerum*-Co 89003 for pulp and paper making. *BioResources*. vol. 5, **(2010)**, pp. 1197–1214.
28. O. Joutsimo, R. Wathén, T. Tamminen, "Effects of fiber deformations on pulp sheet properties and fiber strength", *PaperijaPuu – Paper and Timber*, vol. 87, no. 6, **(2005)**, pp. 392-397.
29. Zhang Q, Peng JJ, Chen LH, Shen ZH. Manufacture of low density printing paper using wheat straw chemical pulp. *China Pulp & Paper*, vol. 36, no. 8, **(2017)**, pp. 30-34.
30. Zhao SZ, Li YL, Ying SY, Ye JL. A new application technology of chemicals to decrease wet-deformation and to increase surface strength of wheat straw-base paper. *World Pulp and Paper*. vol. 20, no. 4, **(2001)**, pp. 16-22.