CHAPTER 5

Chemical Composition of Fibers

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CONTENTS

1. CHEMISTRY

The major chemical component of a living tree is water, but on a dry weight basis, all plant cell walls consist mainly of sugar-based polymers (carbohydrates) that are combined with lignin with lesser amounts of extractives, protein, starch, and inorganics. The chemical components are distributed throughout the cell wall, which is composed of primary and secondary wall layers. Chemical composition varies from plant to plant, and within different parts of the same plant. Chemical composition also varies within plants from different geographic locations, ages, climate, and soil conditions.

There are hundreds of reports on the chemical composition of plant material. In reviewing this vast amount of data, it becomes apparent that the analytical procedures used, in many cases, are different from lab to lab, and a complete description of what procedure was used in the analysis is not clear. For example, many reports do not describe if the samples were pre-extracted with some solvents before analysis. Others do not follow a published procedure, so comparison of data is not possible.

This chapter will present a general description of the chemistry of plant components followed by suggested analytical procedures that could be used by all future laboratories so that consistent, comparable results may be obtained. The final section will be a listing of the chemical components of many different types of plants.

1.1 Carbohydrates

1.1.1 Holocellulose

The carbohydrate portion of the vast majority of plants is composed of cellulose and hemicellulose polymers with minor amounts of other sugar polymers such as starch and pectins. Table 5.1 shows the chemical analysis of the major components of plant fibers. The combination of cellulose and the hemicelluloses are called holocellulose and usually accounts for 65–70 percent of the plant dry weight. These polymers are made up of simple sugars, mainly, D-glucose, D-mannose, D-galactose, D-xylose, L-arabinose, D-glucuronic acid, and lesser amounts of other sugars such as L-rhamnose and D-fucose. Table 5.2 shows the sugar content of different plant holocelluloses. These polymers are rich in hydroxyl groups, which are responsible for moisture sorption through hydrogen bonding.

1.1.2 Cellulose

Cellulose is the most abundant organic chemical on the face of the earth. It is a glucan polymer of D-glucopyranose units, which are linked together by β - (1—4)-glucosidic bonds (Figure 5.1). Actually the building block for cellulose is cellobiose, since the repeating unit in cellulose is a two-sugar unit. The number of glucose units in a cellulose molecule is referred to as the degree of polymerization (DP), and the average DP for plant cellulose ranges from a low of about 50 for a sulfite pulp to approximately 600, depending on the determination method used (Stamm, 1964).

Table 5.1 Chemical Composition of Some Common Fibers (% of total)

Type of Fiber	Cellulose	Lignin	Pentosan	Ash	Silica
Stalk fiber					
Rice	28–48	12–16	23–28	15–20	9–14
Wheat	29–51	16–21	26–32	4.5–9	3–7
Barley	31–45	14–15	24–29	5–7	3–6
Oat	31–48	16–19	27–38	6–8	4–6.5
Rye	33–50	16–19	27–30	2–5	0.5–4
Cane fiber					
Bagasse	32–48	19–24	27–32	1.5–5	0.7–3.5
Bamboo	26–43	21–31	15–26	1.7–5	0.7
Grass fiber					
Esparto	33–38	17–19	27–32	6–8	—
Sabai	—	22	24	6	—
Reed fiber					
Phragmites communis	44–46	22–24	20	3	2
Bast fiber					
Seed flax	43–47	21–23	24–26	5	—
Kenaf	44–57	15–19	22–23	2–5	—
Jute	45–63	21–26	18–21	0.5–2	—
Hemp	57–77	9–13	14–17	0.8	—
Ramie	87–91	—	5–8	—	—
Core fiber					
Kenaf	37–49	15–21	18–24	2–4	—
Jute	41–48	21–24	18–22	0.8	—
Leaf fiber					
Abaca (Manila)	56–63	7–9	15–17	3	—
Sisal (agave)	47–62	7–9	21–24	0.6–1	—
Seed hull fiber					
Cotton	85–90	0.7–1.6	1–3	0.8–2	—
Wood fiber					
Coniferous	40–45	26–34	7–14	<1	—
Deciduous	38–49	23–30	19–26	<1	—

Table 5.2 Sugar Content of Selected Plant Holocelluloses

	Sugars Present, %				
Fiber	Glucose	Xylose	Galactose	Arabinose	Mannose
Cotton	92.0	—	—		—
Southern Pine	49.0	5.4	2.4		19.2
Aspen	53.3	18.5	1.0	—	1.4
Bamboo	52.0	21.7	—	0.8	
Bagasse	47.4	27.6	—	1.7	—
Kenaf	47.2	17.7	1.4	0.9	1.4
Jute	63.8	13.1	1.2	—	0.6
Penny Wort	39.0	3.5	2.8	0.8	2.9
Water Hyacinth	37.2	8.7	5.0	11.4	1.4

This would mean an approximate molecular weight for cellulose ranging from about 10,000-150,000.

Cellulose molecules are randomly oriented and have a tendency to form intra-

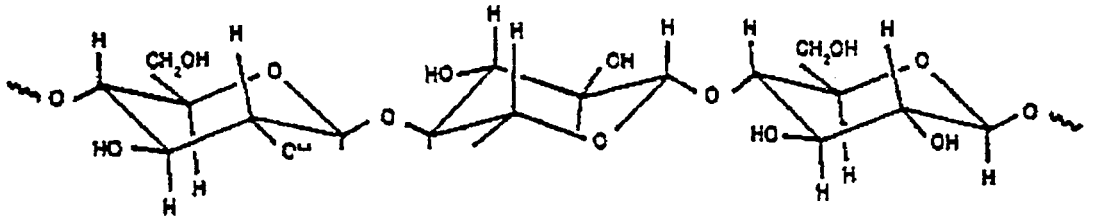


Figure 5.1 Partial structure of cellulose.

crystalline regions are formed. Most plant-derived cellulose is highly crystalline and may contain as much as 80% crystalline regions. The remaining portion has a lower packing density and is referred to as amorphous cellulose. Table 5.1 shows the range' of average cellulose contents for a wide variety of plant types (Atchison, 1983). On a dry weight basis, most plants consist of approximately 45-50% cellulose. This can vary from a high (cotton) of almost 90% to a low of about 30% for stalk fibers. The cellulose content of many different types of plants is listed in the table at the end of this chapter.

1.1.3 Hemicelluloses

In general, the hemicellulose fraction of plants consists of a collection of polysaccharide polymers with a DP lower than cellulose and containing mainly the sugars D-xylopyranose, D-glucopyranose, D-galactopyranose, L-arabinofuranose, D-mannopyranose, and D-glucopyranosyluronic acid with minor amounts of other sugars (Figure 5.2). They usually contain a backbone consisting of one repeating sugar unit linked β -(1–4) with branch points (l–2), (1–3), and/or (l–6).

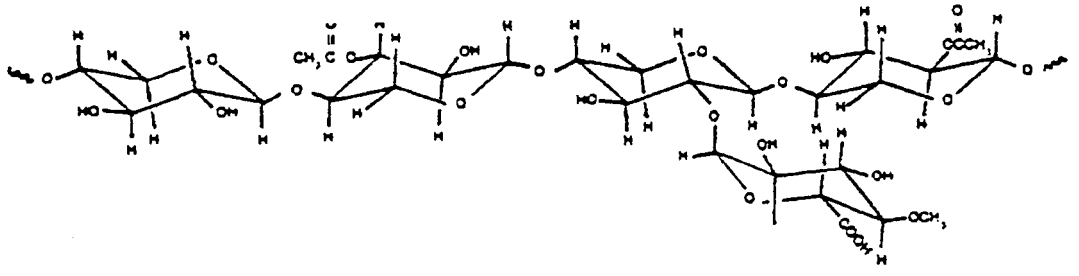


Figure 5.2 Partial structure of glucuronoxylan, a hardwood hemicellulose.

Hemicelluloses usually consist of more than one type of sugar unit and are sometimes refereed to by the sugars they contain, for example, galactoglucomannan, arabinoglucuronoxylan, arabinogalactan, glucuronoxylan, glucomannan, etc. The hemicelluloses also contain acetyl and methyl substituted groups.

The hemicelluloses from bamboo consist of a backbone polymer of D-xylopyranose, linked β -(l–4) with an average of every eight xylose units containing a side chain of d-glucuronic acid attached glycosidically to the 2-position of the xylose

sugar (Bhargava, 1987). The hemicelluloses from kenaf also contain a backbone polymer of D-xylopyranose with side chains of D-galactose and L-arabinose (Cunningham et al., 1986).

One of the main hemicelluloses from softwoods contains a backbone polymer of D-galactose, D-glucose, and D-mannose (Sjöström, 1981). The galactoglucomannan is the principal hemicellulose (ca. 20%), with a linear or possibly slightly branched chain with β -(1–4) linkages. Glucose and mannose make up the backbone polymer with branches containing galactose. There are two fractions of these polymers differing by their galactose content. The low galactose fraction has a ratio of galactose:glucose:mannose of about 0.1:1:4, while the high galactose fraction has a ratio of 1:1:3. The D-galactopyranose units are linked as a single-unit side chain by a (l–6) bond. The 2- and 3-positions of the backbone polymer have acetyl groups substituted an average of 3–4 hexose units. Another major hemicellulose polymer in softwoods (5-10%) is an arabinoglucuronoxylan consisting of a backbone of β -(1–4) xylopyranose units with (l–2) branches of D-glucopyranosyluronic acid on the average of every 2–10 xylose units and the (l–3) branches of l-arabinofuranose on the average of every 1.3 xylose units.

The major hemicellulose from hardwoods contains a backbone of D-xylose units linked β -(1–4) with acetyl groups at C-2 or C-3 of the xylose units, on an average of 7 acetyls per 10 xylose units (Sjöström, 1981). The xylan is substituted with side chains of 4 -*O*- methylglucuronic acid units linked to the xylan backbone through a link (l–2) with an average frequency of approximately 1 uronic acid group per 10 xylose units. This class of hemicelluloses is usually referred to as glucuronoxylans. Hardwoods also contain 2–5% of a glucomannan composed of β -D-glucopyranose and β -D-mannopyranose units linked (1–4). The glucose: mannose ratio varies between 1:2 and 1:1, depending on the wood species.

The major hemicellulose from kenaf is similar to a hardwood xylan (Duckart et al., 1988). It has a backbone of β -(1–4) D-xylopyranose with side chains of 4 -*O*-methylglucuronic acid linked (l–2) with an average frequency of 1 uronic acidgroup per 13 xylose units. There are terminal rhamnose and arabinose units linked (1–3), but the nature of the glycosidic linkage is unknown. The major hemicellulose from bamboo is composed of a backbone of β -(14) D-xylopyranose residues with an average of every eighth xylose unit containing a side chain of D-glucuronic acid, attached glycosidically to the 2-position of the xylose unit (Bhargave, 1987).

The detailed structures of most plant hemicelluloses have not been determined. Only the ratio of sugars these polysaccharides contain have been studied. Table 5.3 shows the sugar analysis of the two major hemicelluloses from several types of plant stalks (Jones et al., 1979). The table at the end of this chapter lists the sugars present in a wide variety of plant sources.

1.1.4 Pentosans

Part of the hemicellulose fraction consists of pentose sugars, mainly D-xylose and L-arabinose. The polymers containing these five carbon sugars are referred to as pentosans. Identification of this fraction in a plant material has been important

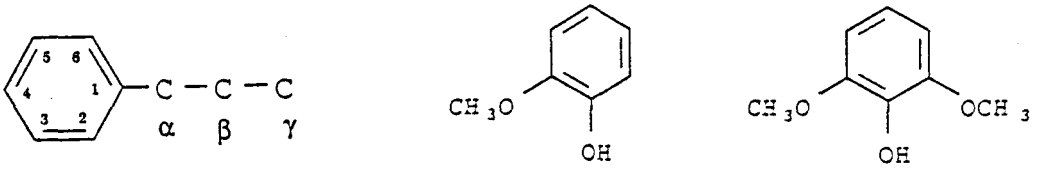
Table 5.3 Sugar Content of Selected Plant Stalk Hemicelluloses

Fiber	Sugars Present %				
	Glucose	Xylose	Galactose	Arabinose	Mannose
Corn					
Hemicellulose A	10.9	70.5	—	4.3	—
Hemicellulose B	12.1	43.8	3.6	9.7	1.0
Bagasse					
Hemicellulose A	6.1	60.9	trace	3.5	trace
Hemicellulose B	13.9	33.0	3.6	9.0	2.7
Sunflower					
Hemicellulose A	19.0	5.8	—	0.9	21.8
Hemicellulose B	11.8	24.5	3.6	3.4	12.6

to indicate its potential utilization for furan-type chemicals. It is therefore common to see tables of chemical composition data include pentosan content.

1.2 Lignin

Lignins are amorphous, highly complex, mainly aromatic, polymers of phenylpropane units. Lignins can be classified in several ways but they are usually divided according to their structural elements (Sjöström, 1981). All plant lignins consist mainly of three basic building blocks of guaiacyl, syringyl, and *p* -hydroxyphenyl moieties, although other aromatic type units also exist in many different types of plants (Figure 5.3). There is a wide variation of structures within different plant species. The phenylpropane can be substituted at the α, β, and γ positions into various combinations linked together both by ether and carbon to carbon linkages (see Figure 5.4).



Phenylpropane unit Guaiacyl Syringyl

Figure 5.3 Building blocks of lignin.

Lignins from softwoods are mainly a polymerization product of coniferyl alcohol and are called "guaiacyl lignin." Hardwood lignins are mainly "syringyl-guaiacyl lignin" as they are a copolymer of coniferyl and sinapyl alcohols. The ratio of these two varies in different lignins from a ratio of 4:1 to 1:2.

Lignins found in plants contain significant amounts of constituents other than guaiacyl- and syringyl-propane units (Sarkanen and Ludwig, 1971). Lignin from corn contains vanillin and syringaldehyde units along with substantial amounts of *p* -hydroxybenzaldehy de. Bamboo lignin is a mixed dehydration polymer of coniferyl, sinapyl, and *p* -coumaryl alcohols (Bhargava, 1987). A recent study showed

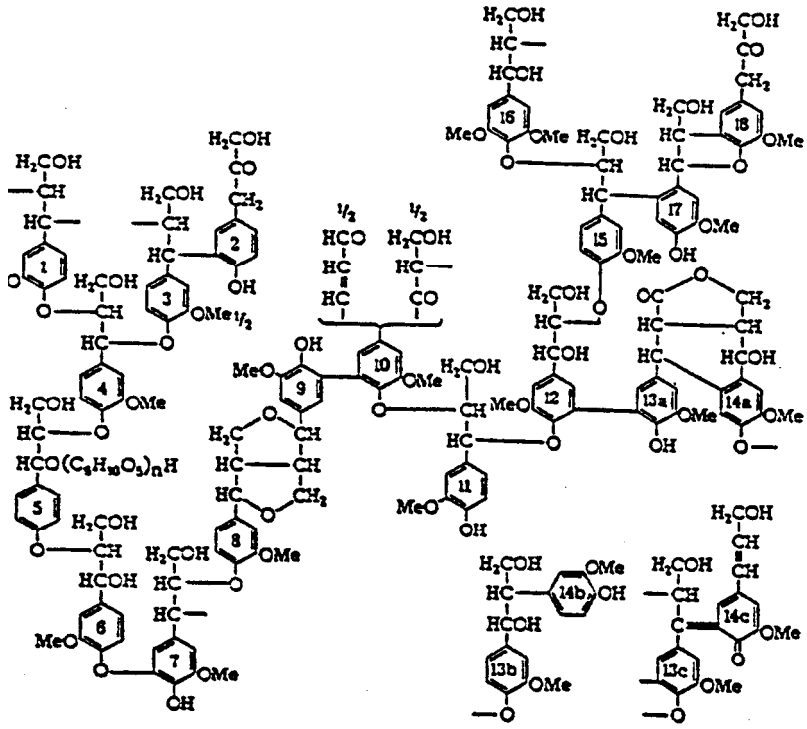


Figure 5.4 Partial structure of one type of lignin.

that the lignin from kenaf contains a very high level of syringyl functionality (Ralph et al., 1995).

Lignin in wood is distributed throughout the secondary cell wall with the highest concentration in the middle lamella. Because of the difference in the volume of middle lamella to secondary cell wall, about 70% of the lignin is located in the secondary wall.

The function of lignin in plants is as an encrusting agent in the cellulose/hemicellulose matrix It is often referred to as the plant cell wall adhesive. Both lignin and extractives in plants reduce the digestibility of grasses to animals (Jung et al., 1993). Ligins are also associated with the hemicelluloses, in some cases forming lignin-carbohydrate complexes that are resistant to hydrolysis even under pulping conditions.

1.3 Inorganics

The inorganic content of a plant is usually referred to as ash content, which is an approximate measure of the mineral salts and other inorganic matter in the fiber after combustion at a temperature of 575 ± 25°C. The inorganic content can be quite high in plants containing large amounts of silica.

1.4 Proteins

Proteins are polymers of amino acids that are normally high in concentration in young growing cells but can also be found in some plants in high concentration throughout their life cycle. Proteins include enzymes and toxins as well as those

involved in wound responses and pathogen resistance (Iiyama et al., 1993). Pathogen resistance proteins are related to the structural proteins that are thought to provide the framework, in addition to the microfibrillar phase, onto and around which the various non-cellulosic polysaccharides are arranged.

Three classes of structural proteins have been identified and classified on the basis of their repeating amino acid sequences (Iiyama et al., 1993). These three are: hydroxyproline-rich glycoproteins, the glycine-rich proteins, and the proline-rich proteins. The hydroxyproline-rich glycoproteins are usually associated with L-arabinose and D-galactose. The glycine-rich and the proline-rich proteins lack *N*-glycosylation sites in their primary sequence.

In wood, the protein content of the cell is usually less than 1% but can be much higher in grasses. The protein content is often reported as part of the lignin content if the laboratory personnel are not aware of its presence in the plant tissue when doing a lignin determination, since both protein and lignin are isolated in the sulfuric acid procedure.

1.5 Extractives

The extractives area group of cell wall chemicals mainly consisting of fats, fatty acids, fatty alcohols, phenols, terpenes, steroids, resin acids, rosin, waxes, etc. These chemicals exist as monomers, dimers, and polymers. They derive their name as chemicals that are removed by one of several extraction procedures.

2. SAMPLING PROCEDURE

In reporting the chemical content of a plant, it is very important to report as much information about the samples as possible. Since the chemical content of a given species may vary depending upon the growing conditions, harvesting times of the year, etc., it is critical to report these conditions along with the chemical analysis. It is also important to report the exact analytical conditions and procedures used. This way, it may be possible to reproduce the results by other workers in different laboratories. *Without this information, it is not possible to compare data from different laboratories.*

The following information should accompany each chemical analysis:

(1) Source of the plant
   (a) Place of the growth
   (b) Year of the growth
   (c) Age of the plant
   (d) Condition of the soil and fertilizers applied
(2) Sampling
   (a) Different anatomical parts
   (b) Degree of biological deterioration if any
   (c) Sample size
   (d) Drying method applied
   (e) Time of year the sample was taken

(3) Analytical procedure used
(4) Reporting technique

All of the above mentioned criteria could contribute in one way or another toward variations in chemical analyses. Every criterion is as important as the other.

3. ANALYTICAL PROCEDURES

3.1 Extraction

3.1.1 Scope and Summary

Plant materials = Extractives + holocellulose + lignin + inorganic (ash)

This method describes a procedure for extraction of non-wood fiber for further analysis, such as holocellulose, hemicellulose, cellulose, and lignin analysis.

Neutral solvents, water, toluene or ethanol, or combinations of solvents are employed to remove extractives in agro-based fibers. However, other solvents ranging from diethyl ether to 1% NaOH, etc. could be applied according to the nature of extractives.

3.1.2 Sample Preparation

It is highly recommended to have a fresh sample. If not, keep the sample in a refrigerator to avoid fungal attack. Peel off the bark from the stem and separate the sample into component parts. Dry samples are oven dried for 24 hours (usually at 105°C) before milling. Wet samples can be milled while frozen in order to prevent oxidation or other undesirable chemical reactions. Samples are ground to pass 40 mesh (0.40 mm) using a Wiley Mill.

3.1.3 Apparatus

- Buchner funnel
- Extraction thimbles, ASTM 170-220 or Pyrex ™ 33950-MEC E or-MC.
- Extraction apparatus, extraction flask, 500 mL, Soxhlet extraction tube
- Heating device, heating mantle or equivalent
- Boiling chips, glass beads, boilers or any inert granules for taming boiling action
- Chemical fume hood
- Vacuum oven

3.1.4 Reagents and Materials

- Ethanol (ethyl alcohol), 200 proof ethanol
- Toluene, reagent grade
- Toluene–ethanol mixture, mix one volume of ethanol and two volumes of toluene

3.1.5 Procedures

Weigh 2-3 g of sample into several covered (yet ventilated) preweighed extraction thimbles. Place the thimbles in a vacuum oven not hotter than 45°C for 24 h, or to a constant weight. Cool the thimbles in a desiccator for one h and weigh. Then, place the thimbles in Soxhlet extraction units. Place 200 mL of the toluene–ethanol mixture* in a 500 ML round bottom flask with several boiling chips to prevent bumping. Carry out the extraction in a well ventilated chemical fume hood for 24 h, keeping the liquid boiling so that siphoning from the extractor is no less than four times per h. After extraction with the toluene:ethanol mixture, take the thimbles out of the extractors, drain the excess solvent, and wash the samples with ethanol. Place them in the vacuum oven overnight at temperatures not exceeding 45°C for 24 h. When dry, remove them to a desiccator for one h and weigh. Generally, the extraction is complete at this stage; however, the extractability depends upon the matrix of the sample and the nature of extractives. Second and third extractions using a different polarity of solvents may be necessary. Browning (1967) suggests 4 h of successive extraction with 95% alcohol. TAPPI Standard T 264 (TAPPI, 1988) designates two successive extractions, 4 h with ethanol, followed with distilled water for 1 hour. Pettersen et al. (1991) extracted pine samples with acetone/water, followed by the toluene–ethanol mixture.

3.2 Ash Content

3.2.1 Scope

The ash content of fiber is defined as the residue remaining after ignition at 575° ± 25° C (1067° ± 5°F) for 3 h, or longer if necessary to burn off all the carbon. It is a measure of mineral salts in the fiber, but it is not necessarily quantitatively equal to them. Fiber, like wood and pulp, is ashed at a lower temperature than paper (925°C) to minimize the volatilization of inorganic compounds.

3.2.2 Sample Preparation

Obtain a representative sample of the fiber, preferably ground to pass a 40-mesh screen. Weigh, to 5 mg or less, a specimen of about 5 g of moisture-free fiber for ashing, preferably in duplicate. If the moisture in the sample is not known, determine it by drying a corresponding specimen to constant weight in a vacuum oven at 105 ± 3°C.

3.2.3 Apparatus

- Crucible. A platinum crucible or dish with lid or cover is recommended. If platinum is not available, silica may be used.

* OSHA Standard for occupational exposure to Benzene is 29CFR 1910.1028 which became effective as of 12/10/87. Benzene is an OSHA regulated chemical and no longer used due to the health hazard.

- Analytical balance with a sensitivity to 0.l mg.
- Electric muffle furnace adjusted to maintain a temperature of 575 ± 25°C.

3.2.4 Procedure

Carefully clean the empty crucible and cover, and ignite them to constant weight in a muffle furnace at 575 ± 25°C. After ignition, cool slightly and place in a desiccator. When cooled to room temperature, weigh the crucible and cover on the analytical balance.

Place all, or as much as practicable, of the weighed specimen in the crucible. Bum the fiber directly over a low flame of a Bunsen burner (or preferably on the hearth of the furnace) until it is well carbonized, taking care not to blow portions of the ash from the crucible. If a sample tends to flare up or lose ash during charring, the crucible should be covered, or at least partially covered during this step. If the crucible is too small to hold the entire specimen, gently burn the portion added and add more as the flame subsides. Continue heating with the burner only as long as the residue burns with a flame. Place the crucible in the furnace at 575 ± 25°C for a period of at least 3 h, or longer if needed, to burn off all the carbon.

When ignition is complete, as indicated by the absence of black particles, remove the crucible from the furnace, replace the cover and allow the crucible to cool somewhat. Then place in a desiccator and cool to room temperature. Reweigh the ash and calculate the percentage based on the moisture-free weight of the fiber.

3.2.5 Report

Report the ash as a percentage of the moisture-free fiber to two significant figures, or to only one significant figure if the ash is less than 0.1%.

3.2.6 Precision

The results of duplicate determinations should be suspect if they differ by more than 0.5 mg.

Additional Information

1. Since the ignition temperature affects the weight of the ash, only values obtained at 575 ± 25°C should be reported as being in accordance with this method.
2. In this procedure, the temperature of ignition has been specified at 575 ± 25°C, the same as given in TAPPI Standard T 211, “Ash in pulp.”
3. Similar Method: Australia, APPITA, P 3m.
   Related Methods: ASTM D 1102; Canadian, C.P.P.A., G-10.
4. Porcelain crucibles can also be used in most cases for the determination of ash.
5. Special precautions are required in the use of platinum crucibles; a list of rules to follow is given by Pierce and Haenish (1948).
6. If the fiber ash is to be analyzed to determine its various constituents, wet ashing is recommended by Phifer (1957).
7. Data on the volatility of some ash constituents of wood pulp are reported by Bethge

(1960). They report significant losses in sodium, calciums, irons and copper at temperatures of more than 600°C.

3.3 Preparation of Holocellulose (Chlorite Holocellulose)

3.3.1 Scope

Holocellulose is defined as a water-insoluble carbohydrate fraction of plant materials. According to Browning (1967) there are three ways of preparing holocellulose and their modified methods: (1) Chlorination method (also ASTM Standard D1104); (2) Modified chlorination methods; and (3) Chlorine dioxide and chlorite methods. The standard purity of holocellulose is checked following lignin analysis.

3.3.2 Sample Preparation

The sample should be extractive and moisture free and prepared after procedure 3.1. If Procedure 3.1 is skipped for some reason, the weight of the extractives should be accounted for in the calculation of holocellulose.

3.3.3 Apparatus

- Buchner funnel
- 250 mL Erlenmeyer flasks
- 25 mL Erlenmeyer flasks
- Water bath
- Filter paper
- Chemical fume hood

3.3.4 Reagents

- Acetic acid, reagent grade
- Sodium chlorite, $NaClO_2$, technical grade, 80%

3.3.5 Procedure

To 2.5 g of sample, add 80 mL of hot distilled water, 0.5 mL acetic acid, and 1 g of sodium chlorite in a 250 mL Erlenmeyer flask. An optional 25 mL Erlenmeyer flask is inverted in the neck of the reaction flask. The mixture is heated on a water bath at 70°C. After 60 min, 0.5 mL of acetic acid and 1 g of sodium chlorite are added. After each succeeding hour, fresh portions of 0.5 mL acetic acid and 1 g sodium chlorite are added with shaking. The delignification process degrades some of the polysaccharides, and the application of excess chloriting should be avoided. Continued reaction will remove more lignin but hemicellulose will also be lost (Rowell, 1980).

Addition of 0.5 mL acetic acid and 1 g of sodium chlorite is repeated until the fibers are completely separated from lignin. It usually requires 6 h of chloriting, and

the sample can be left without further addition of acetic acid and sodim chlorite in the water bath overnight. At the end of 24 h of reaction, cool the sample and filter the holocellulose on filter paper using a Buchner funnel until the yellow color (the color of holocellulose is white) and the odor of chlorine dioxide are removed. If the weight of the holocellulose is desired, filter the holocellulose on a tarred fritted disc glass thimble, wash with acetone, vacuum-oven dry at 105°C for 24 h, place in a desiccator for an hour and weigh. The holocellulose should not contain any lignin and the lignin content of holocellulose should be determined and subtracted from the weight of the prepared holocellulose.

3.4 Preparation of α -Cellulose (Determination of Hemicellulose)

3.4.1 Scope

The preparation of α -cellulose is a continuous procedure from Procedure 3.3.5 in pursuit of the ultimately pure form of fiber. The terms; α -cellulose, β -cellulose, γ -cellulose, cellulose, cellulose I, cellulose II, cellulose III, cellulose IV, cellulose V are defined in ASTM 1695-77. The term hemicellulose was introduced by Schulze [Schulze, *E. Ber.*, 24, 2274(1891)] and defined as the cell-wall components that are readily hydrolyzed by hot dilute mineral acids, hot dilute alkalies, or cold 5% sodium hydroxide.

3.4.2 Principle of Method

Extractive-free, lignin-free holocellulose is treated with sodium hydroxide and then with acetic acid, with the residue defined as α -cellulose. Thus the last fraction gives the hemicellulose content.

3.4.3 Apparatus

A *thermostat* or other constant-temperature device will be required that will maintain a temperature of 20 ± 0.1°C in a container large enough to hold a row of at least three 250 mL beakers kept in an upright position at all times.

Filtering Crucibles of Alundum™ or fritted glass thimbles of medium porosity.

3.4.4 Reagents

- Sodium hydroxide solution, NaOH, 17.5%, and 8.3%
- Acetic acid, 10%, mix one part by weight of glacial acetic acid with nine parts of distilled water.

3.4.5 Procedure

- Weigh out about 2 g of vacuum-oven dried holocellulose and place into a 250-mL glass beaker provided with a glass cover. Measure 25 mL of 17.5% NaOH solution in a graduated cylinder. and maintain at 20°C.

- Add 10 mL of 17.5% NaOH solution to the holocellulose in the 250-mL beaker, cover with a watch glass, and maintain at 20°C in the water bath. Manipulate the holocellulose lightly with a glass rod with the flat end so that all of the specimen becomes soaked with the NaOH solution.
- After 2 min, manipulate the specimen with the glass rod by pressing and stirring until the particles are separated from one another. After the addition of the first portion of 17.5% NaOH solution to the specimen, at 5 min intervals, add 5 mL more of the NaOH solution and thoroughly stir the mixture with the glass rod, until the NaOH is gone.
- Allow the mixture to stand at 20°C for 30 min, making the total time for NaOH treatment 45 min.
- Add 33 mL of distilled water at 20°C to the mixture. Thoroughly mix the contents of the beaker and allow to stand at 20°C for 1 h before filtering.
- Falter the cellulose with the aid of suction into the tarred, alkali-resistant Alundum or fitted-glass crucible of medium porosity.
- Transfer all the holocellulose residue to the crucible, and wash with 100 mL of 8.3% NaOH solution at 20°C. After the NaOH wash solution has passed through the residue in the crucible, continue the washing at 20°C with distilled water, making certain that all particles have been transferred from the 250-mL beaker to the crucible. Washing the sample in the crucible is facilitated by releasing the suction, filling the crucible to within 6 mm of the top with water, carefully breaking up the cellulose mat with a glass rod to separate any lumps present, and again applying suction. Repeat this step twice. The combined filtrate at this stage of the procedure may be set aside for the determination of β -cellulose.

Pour 15 ML of 10% acetic acid (at room temperature) into the crucible, drawing the acid into the cellulose by suction but, while the cellulose is still covered with acid, release the suction. Subject the cellulose to the acid treatment for 3 min from the time the suction is released, then apply suction to draw off the acetic acid. Without releasing the suction, fill the crucible almost to the top with distilled water at 20°C and allow to drain completely. Repeat the washing until the cellulose residue is free of acid as indicated by litmus paper. Give the cellulose a final washing by drawing, by suction, an additional 250 ML of distilled water through the cellulose in the crucible. Dry the crucible on the bottom and sides with a cloth and then, together with the weighing bottle in which the sample was originally weighed, place it overnight in a vacuum oven to dry at 100-105°C. Cool the crucible and weighing bottle in a desiccator for 1 h before weighing.

3.4.6 Calculation and Report

Calculate the percentage of α -cellulose on the basis of the oven-dry holocellulose sample:

$$\alpha\text{-cellulose, percent} = (W2/WI) \times 100$$

W2 = weight of the oven-dry α -cellulose residue
W1 = weight of the original oven-dry holocellulose sample.

3.5 Preparation of Klason Lignin

3.5.1 Scope

Klason lignin gives a quantitative measure of lignin and is not suitable for the study of lignin structures and some other lignins such as cellulolytic enzyme lignin, or Björkman (milled wood lignin) should be prepared (Sjöström, 1981) for the study of lignin structure. About 10-15% of Klason lignin of non-wood sources could be protein, and the protein content should be subtracted from the Klason lignin value applying the Kjeldahl procedure (Procedure 3.6). This procedure is a modified version of TAPPI T222 acid-insoluble lignin in wood and pulp (TAPPI, T-222, 1988). The lignin isolated using this procedure is also called sulfuric acid lignin.

3.5.2 Apparatus

- Autoclave
- Buchner funnel
- 100 mL centrifuge tube, Pyrex™ 8240
- Desiccator
- Glass rods
- Water bath
- 60 mL syringe
- Glass fiber filter paper, Whatman Cat. No. 1827-021, 934-AH
- Glass microfiber filter, 2.1 cm

3.5.3 Reagents

Sulfuric acid, H_2SO_4, 72% and 4% by volume
Fucose, 24.125% in 4% H_2SO_4 [w/w]

3.5.4 Procedure

Prepare samples by Procedure 3.1.5 and dry the sample at 45°C in a vacuum oven overnight. Accurately weigh out approximately 200 mg of ground vacuum-dried sample into a 100 mL centrifuge tube. To the sample in a 100 mL centrifuge tube, add 1 mL of 72% (w/w) H_2SO_4 for each 100 mg of sample. Stir and disperse the mixture thoroughly with a glass rod twice, then incubate the tubes in a water bath at 30°C for 60 min. Add 56 mL of distilled water (use a 60-mL syringe). This results in a 4% solution for the secondary hydrolysis. Add 1 mL fucose internal standard (this procedure is required only if five sugars are to be analyzed by HPLC as a part of the analysis).

Autoclave at 121°C, 15 psi, for 60 min. Remove the samples from the autoclave and filter off the lignin, with glass fiber filters (filters were rinsed into crucibles, dried and tarred) in crucibles using suction, keeping the solution hot. Wash the residue thoroughly with hot water and dry at 105°C overnight. Move to a desiccator,

and let it sit 1 h and weigh to five places. Calculate Kason lignin content from weights.

3.5.5 Interference by Protein in Klason Lignin Determinations

Condensation reactions involving protein can cause artificially high Klason lignin measurements when tissues containing significant protein contents are analyzed, as in the case of non-wood fibers.

The Forest Products Laboratory (FPL) conducted a study (1994) on protein content as a function of growth on kenaf. A trend is apparent: although mature kenaf contains less protein, a greater percentage of this protein is condensed by acid hydrolysis than that of the younger kenaf. As a result, the positive interference from protein remains significant even in the less proteinaceous mature samples. It is reasonable to assume that the same proteins are condensed in samples harvested at either sample time. The ratio of structural protein to total protein increases with increasing maturity. A final note in this regard: hot acid detergent (Goering and Van Soest, 1970) extracted hay gave a protein of 4.3% as compared to 18.5% for raw hay. The initial impression might be that positive interference from. protein is thereby substantially reduced. However, structural proteins are the most likely candidates to be resistant to extraction. Thus, if structural proteins do tend to condense under acid hydrolysis conditions, the outcome for hot acid detergent extracted materials may be similar to that of the more mature kenaf samples.

3.6 Nitrogen Content

3.6.1 Protein Determination by Kjeidahl Method

3.6.1.1 Scope

An FPL study on kenaf showed that by separate Kjeldahl (1883) analysis, 32% of nitrogen was found in Klason lignin and 68% in the hydrolysate of acid hydrolysis. Investigators at the USDA, Dairy Forage Laboratory developed (Goering and Soer, 1970) the acid-detergent lignin procedure where the detergent removed the protein and other acid-soluble materials that would interfere with the lignin determination. Further study is desired in this area.

This Kjeldahl method was modified at FPL (Moore and Johnson, 1967) in 1967, and further modification was achieved in 1993 for use in determination of the amine and amide nitrogen content in nonwood fibers. The organic compound is digested with concentrated sulfuric acid, which converts combined nitrogen into ammonium sulfate. The solution is then made alkaline. The liberated ammonia is then distilled, and the amount determined by titration with standard acid. It is directly applicable to amines and amides but not to nitro-, azo-, and azoxy-compounds. These latter compounds must be reduced (Zn-Hg amalgam and acid or salicylic acid, sodium thiosulfate and acid) before the Kjeldahl treatment. The protein content is then

obtained by multiplying the percent nitrogen in an aliquot of fiber by an empirical factor of 6.25.

3.6.1.2 Sample Preparation

Prepare samples by Procedure 3.1 and place in a vacuum oven at 45°C overnight. Place the sample in a desiccator prior to actual chemical analysis. A quality control sample of DL-Norvaline (%N = 11.96%) and a blank sample should be carried out through this entire procedure.

3.6.1.3 Apparatus

- Burette, 10, 25, or 50 mL
- Desiccator
- Erlenmeyer flask, 250 mL
- Micro–Kjeldahl digestion apparatus
- Micro–Kjeldahl digestion rack, Labconco 7053-S10
- Heating element, Labconco 7053-S10
- Kjeldahl flasks, 30 mL, 100 mL, or 125 mL, Pyrex™ and Kimax
- Micro–Kjeldahl distilling apparatus, Thomas Scientific
- Micro–Kjeldahl distilling unit, 7052-J10
- Distilling unit, 7052-J20
- Steam generator, ASTM, 7052-J30
- Immersion heater, ASTM, 7052-J40

Note: See ASTM E 147 for detailed dimensions of the apparatus.

3.6.1.4 Reagents

- Boric acid, H_3BO_3
- Copper sulfate, $CuSO_4 5H_2O$
- Hydrochloric acid, HCl, 0.01 N
- Mixed indicator (Place 200 mg of bromocresol green and 40 mg of methyl red in 100 mL volumetric flask. Dissolve and fill up to mark with 95% ethanol.)
- DL-Norvaline, 99%, Aldrich 85,162-0
- Potassium sulfate, K_2SO_4
- Sodium carbonate, $NaCO_3$
- Sodium hydroxide, NaOH
- Sulfuric acid, H_2SO_4
- Sodium thiosulfate, anhydrous, $Na_2S_2O_3$
- Mercury (II) oxide, red, HgO

3.6.1.5 Procedure

Digestion: Weigh approximately 100 mg of sample to the nearest 0.1 mg into 30 mL Kjeldahl flask. Add 5 g of K_2SO_4 per gram of sample and 250 mg $CuSO_4 5H_2O$ per gram of sample to each flask. Next, add 10 mL of conc. H_2SO_4 per gram of sample. Place specimens on low heat at first and cook until all black carbon has

disappeared and the solution appears tint in color. Kenaf fiber requires about 2 h for complete digestion, while 10 mg of DL-Norvaline should be fully digested within 1 h.

Note: the weight of sample should be adjusted depending upon the nitrogen content followed by the size of Kjeldahl flask. More sulfuric acid may be needed and distilled water may be added to rinse the sample. For nitro-, azo- or azoxy-compounds: 1 ML 5% salicylic acid in H_2SO_4 and wait 30 min, add 100 mg $Na_2S_2O_3$ wait 10–15 min and proceed with digestion. For amine and amide compounds: skip the step above and start with 650 mg of K_2SO_4, 16 mg of HgO, 1 ML of H_2SO_4 proceed with digestion.

Distillation and Titration: Close the upper stopcock (sample stopcock), open the lower (vacuum) stopcock and pull distilled water, from a large beaker submerged to the condenser tip, by suction and close the lower stopcock. Open the upper stopcock and fill the still with distilled water. Repeat this process until approximately 1–2 liters of water have been washed through the entire system. The lower drain spout is connected to an aspirator via a water trap, and waste water is removed after the rinsing. Add 5 ML of 4% boric acid and 5 drops of the mixed indicator to a 250 ML Erlenmeyer flask. Dilute with 20 mL of distilled water (the solution should be green) and submerge the tip of the condenser in the solution. Open the upper stopcock and quantitatively transfer the digested sample from the Kjeldahl flask to the still. Also rinse the filling cup to insure the complete transfer (Caution: when rinsing, the flask will become hot and sulfuric acid fumes may be emitted). Close the upper stopcock and fill the cup with 28 ML of 40% NaOH. If the filling cup cannot hold the full volume of NaOH, open the stopcock slightly and transfer the remaining NaOH to the cup. Close the stopcock immediately once the NaOH has completely drained. Replace the rubber stopper and plug in the heating coil.

Distill until the volume in the Erlenmeyer flask has doubled. The solution should be blue in color. Lower the flask and rinse the condenser tip. Remove the rubber stopper and turn off the heating coil. Allow the sample to cool. Titrate the distillate from blue to a green endpoint with the standardized 0.01N HCl solution. Calculate the percent of nitrogen in the sample as follows:

$$\%N = \frac{\text{mL HCl (sample} - \text{blank)} \times \text{(normality of HCl)}\ 14.0067 \times 100}{\text{sample weight in mg}}$$

$$\%\ \text{Protein} = 6.25 \times \%N$$

3.7 Determination of Methoxyl Groups

3.7.1 Scope

Methoxyl groups ($-OCH_3$) are present in the lignin and polysaccharide portions of plants. Methoxyl groups occur in lignin and lignin derivatives as side chains of aromatic phenylpropanes and in the polysaccharides mainly as methoxy-uronic acids. Methoxyl content is determined by some modification of the original method

of Zeisel (1886) and an instrument method such as gas chromatography, HPLC or infrared. This is a modified version of ASTM, D1166-84, Standard Test Method for Methoxyl Groups in Wood and Related Materials (ASTM, 1960), TAPPI T 2 wd-72 Methoxyl Group in Wood, and T 209 wd-79 Methoxyl Content of Pulp and Wood (TAPPI, 1988). Related materials can be found in the following references: Friedrich (1927), Clark (1929), Vieböck and Schwappach (1930), Peniston and Hibbert (1939), Bailey (1942), and Samsel (1942).

3.7.2 Principle of Method

In the original method of Zeisel (1886), the methyl iodide was absorbed in an alcoholic solution of silver nitrate. The solution was diluted with water, acidified with nitric acid, and boiled. The silver iodide was removed by filtration, washed, and weighed in the manner usual for halide determinations. A volumetric modification is based on absorption of the methyl iodide in a known volume of standard silver nitrate solution and titration of the unused silver nitrate with standard potassium thiocyanate solution (ferric alum indicator solution). In this procedure, the methyl iodide is collected in an acetic acid solution of potassium acetate containing bromine.

$$CH_3I + Br_2 \rightarrow CH_3Br + IBr$$

$$IBr + 2Br_2 + 3H_2O \rightarrow HIO_3 + 5HBr$$

The excess bromine is destroyed by addition of acid, and the iodate equivalent of the original methoxyl content is determined by titration with sodium thiosulfate of the iodine liberated in the reaction

$$HIO_3 + 5HI \rightarrow 3I_2 + 3H_2O$$

One methoxyl group is equivalent to six atoms of iodine and, consequently, a favorable analytical factor is obtained.

3.7.3 Sample Preparation

The sample is dried, ground, and extracted accordingly prior to the actual analysis taking place.

3.7.4 Apparatus

- Reaction flask
- Heat source-A micro burner
- Vertical air-cooled condenser
- Scrubber
- Absorption vessels

3.7.5 *Reagents*

Bromine, liquid
Cadmium sulfate solution–dissolve 67.2 g of $CdSO_4$—$4H_2O$ in 1 L of water.
Carbon dioxide gas
Formic acid, 90%
Hydroiodic acid
Phenol
Potassium acetate solution in acetic acid—anhydrous potassium acuate (100g) is dissolved in 1 L of glacial acetic acid
Potassium iodide solution-dissolve 100 g of KI in water and dilute to 1 L
Sodium acetate solution—dissolve 415 g of sodium acetate trihydrate in water and dilute to 1 L
Sodium thiosulfate solution (0.1N)—Dissolve 25 g of $Na_2S_2O_3 \cdot H_2O$ in 200 mL of water and dilute to 1 L
Starch indicator solution (10 g/L)
Sulfuric acid—Mix one volume of H_2SO_4 (sp gr 1.84) with nine volumes of water

3.7.6 Procedure

Weigh the sample (about 100 mg of fiber or 50 mg of lignin) accurately in a gelatin capsule and place with the capsule in the reaction flask. Place in the reaction flask 15 ML of HI, 7 g of phenol, and a boiling tube. Place in the scrubber a mixture of equal volumes of $CdSO_4$ solution and $Na_2S_2O_3$. The volume of solution should be adjusted so that the inlet tube of the scrubber is covered to a depth of about 4 mm. Adjust the flow of CO_2 to about 60 bubbles per minute through the scrubber. Bring the contents of the flask to reaction temperature. Adjust the rate of heating so that the vapors of the boiling HI rise about 100 mm into the condenser. Heat the flask at reaction temperature for 30—45 min, or longer if necessary, to remove methoxyl-containing substances or other interfering substances that usually are present in the reagents.

Let the distilling flask cool below 100°C. In the meantime, add to 20 ML of the potassium acetate solution about 0.6 mL of bromine, and mix. Add approximately 15 mL of the mixture to the first receiver and 5 mL to the second, and attach the receiver to the apparatus. Seal the ground-glass joint with a small drop of water from a glass rod.

Remove the distilling flask and introduce the test specimen. Immediately reconnect the flask and seal the ground-glass joint with a drop of molten phenol from a glass rod. Bring the contents of the flask to reaction temperature while passing a uniform stream of CO_2 through the apparatus. Adjust the rate of heating so that the vapors of the boiling HI rise about 100 mL into the condenser. Continue the heating for a time sufficient to complete the reaction and sweep out the apparatus. Usually, not more than 50 min are required.

Wash the contents of both receivers into a 250-ML Erlenmeyer flask that contains 15 mL of sodium acetate solution. Dilute with water to approximately 125 mL, and add 6 drops of formic acid. Rotate the flask until the color of the bromine is discharged, then add 12 more drops of formic acid and allow the solution to stand

for 1 to 2 min. Add 10 mL of KI solution and 10 mL of H_2SO_4, and titrate the liberated iodine with $Na_2S_2O_3$ solution, adding 1 mL of starch indicator solution just before the end point is reached, continuing the titration to the disappearance of the blue color.

3.7.7 Calculation and Report

$$\text{Methoxyl, \%} = (VN \times 31.030 \times 100)/(G \times 1000 \times 6) = (VN/G) \times 0.517$$

V = milliliters of $Na_2S_2O_3$ solution required for the titration,
N = normality of $Na_2S_2O_3$ solution, and
g = grams of moisture-free sample.

3.8 Determination of Acetyl by Gas-Liquid Chromatography (GLC)

3.8.1 Scope

The aliphatic acyl groups in woods and grasses are acetyl and formyl groups which are combined as *0* -acyl groups with the polysaccharide portion. There are basically three ways of determinations: (1) Acid hydrolysis-sample is hydrolyzed to form acetic acid; (2) Saponification—acetyl groups are split from polysaccharides with hot alkaline solution and acidified to form acetic acid; and (3) Transesterification—sample is treated with methanol in acid or alkaline solution to form methyl acetate; acetic acid and methyl acetate are analyzed by gas chromatography.

This procedure is an application of saponification.

$$CH_3COOR + 3NaOH \rightarrow 3CH_3COONa$$

$$CH_3COONa + H^+ \rightarrow CH_3COOH$$

3.8.2 Sample Preparation

Weigh an oven-dried sample in a long handled weighing tube and transfer it to an acetyl digestion flask and add four boiling chips. Pipette 2 mL 1 *N* NaOH solution to wash down the neck of the flask. Connect the reaction flask to a water cooled reflux condenser. Reflux for 1 h, heating the flask in a phosphoric acid bath with a Bunsen burner. Pipette 1 mL of propionic acid (internal standard) into a 10-mL volumetric flask. Quantitatively transfer the liquid from the reaction flask to the volumetric. Wash the reaction flask and the solid residue with several portions of distilled water. Add 0.2 mL of 85% phosphoric acid and make to volume with distilled water. This solution may be filtered through a small plug of glass wool to remove solid particles.

Analyze the sample by GLC and determine the average ratio. Milligrams of acetic acid are determined from the calibration curve.

3.8.3 Reagents

Internal Standard Stock Solution: Weigh 25.18 g of 99+% propionic acid in 500 mL volumetric flask, make to volume with 2% formic acid. Internal Standard Solution: Pipette 10 M-L stock solution into a 200-mL volumetric flask; make to volume with distilled water.

Acetic Acid Standard Solution: Weigh 100 mg 99.7% glacial acetic acid into a 100-ML volumetric flask; make to volume with distilled water.

NaOH Solution 1 ***N:*** Weigh 4 grams NaOH; dissolve in 100 mL distilled water.

3.8.4 Gas Chromatography

Column: Supelco 60/80 Carbopack C/0.3% carbowax 20M/0.1% H_3PO_4 – 3 ft-1/4 inch O. D. and 4 mm I. D.; Oven temperature 120°C; Injection port 150°C; F.I.D. 175°C; Nitrogen 20 mL/min.

The ratio of the area is determined by dividing the peak area of the acetic acid by the area of the propionic acid (internal standard).

The average of the ratios is used to determine mg/mL of acetic acid from the calibration curve.

Preparation of a Calibration Curve: Pipette 1,2,4,6, and 8 mL of standard acetic acid solution into 10-mL volumetric flasks. Pipette 1 mL of propionic acid internal standard into each sample, then add 0.2 mL 85% phosphoric acid. Make to volume with distilled water. Analyze each solution six times by GLC. Calculate the ratios by dividing the peak area of the acetic acid by the peak area of the propionic acid (internal standard). Plot the average ratios against milligrams per milliliter of acetic acid. The results may be reported as acetic acid:

$$\text{mg/mL}\ \frac{\text{Acetic acid found} \times 10\ \text{mL}}{\text{sample weight (mg)}} \times 100 = \%\text{Acetic acid or as Acetyl}$$

$$\text{mg/mL}\ \frac{\text{found} \times 10\ \text{mL} \times 0.7172}{\text{sample weight (mg)}} \times 100 = \%\text{Acetyl}$$

4. CHEMICAL PROPERTIES OF FIBERS

The following table is a compilation of the chemical composition of some non-wood and wood materials. The data include different anatomical parts of the non-wood plants such as bast fibers, cortex, etc. It should be known that this data was collected from different times in different places using a variety of analytical procedures. The lignin contents of non-wood materials are generally lower than those of woods, but the pentosan and extractive contents are higher.

According to an FPL study on kenaf, the lignin content increases whereas the extractive content decreases as a function of growth. Extractive content of cores could be as much as twice of the bast fibers within the given plant. The extractives

content could be twice that of at the top of the plant than at the bottom of the plant in both core and fiber. Details of variations based on growth were seen in Chapter 2. The general sources of variations on chemical compositions can be outlined as follows.

(1) Location–a growing season for an annual plant could be anywhere between 80 to 200 days. The height of kenaf could reach from 1 m to 3 m per year.
(2) Cultivars–different varieties of species. Tainung grows tallest.
(3) Conditions, types of soil, fertilizer applied, moisture, temperature, etc.
(4) Sampling procedure-top of the plant vs. bottom.
(5) Analytical procedure

Table 5.4 Chemical Properties of Agro-based Fibers

[a] Acetyl
[c] Cellulose
[cc] Crude cellulose
[d] Monoethanoamine procedure
[e] Extractives
[h] Holocellulose
[i] Insoluble ash
[k] Pectins
[m] Hemicellulose
[o] Protein
[p] Polyuronide
[s] Silica
[t] Total ash
[u] Uronic acid
[w] Wax

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Monocotyledoneae												
Agavaceae												
Agave sisalana	Sisal	India	55-73	43-56	8-9	21-24	—	—	—	.6-1	<1[s]	[17]
Agave sisalana	Sisal	—	—	63.9	8.6	17.9	—	—	—	0.7	4.6[a]	[25]
Agave sisalana	Sisal	—	73.1[c]	—	11.0	—	—	—	—	—	.9[k], 1.6[e]	[19]
Musa textilis	Abaca or	—	70.1[c]	—	5.7	—	—	—	—	—	.6[k], 1.8[e]	[19]
Musa textilis	Manila hemp	—	78.0	61.0	9.0	17.0	—	—	—	1.0	1.0[s]	[17]
Phormium tenax	Phormium	—	71.3[c]	—	—	—	—	—	—	—	—	[19]
Yucca schidigera (leaves)	—	CA	33.2[d]	22.3	—	—	15.3	—	51.4	—	—	[22]
Bromeliaceae												
Ananas comosus	Pineapple	Leaf	—	69.5	4.4	17.8	—	—	—	0.9	2.7[a]	[25]
Ananas comosus	Pineapple	—	81[c]	—	12.0	—	—	—	—	—	—	[26]
Cyperaceae												
Bulboslylis capilleris	—	MD	26.5[d]	7.8	—	—	5.9	—	43.3	—	—	[22]
Cyperus esculentus	Nut sedge	MD	38.2[d]	23.1	—	—	14.9	—	54.2	—	—	[24]
Cyperus filiculmis	—	MD	39.0[d]	24.9	—	—	12.0	—	52.2	—	—	[24]
Cyperus papyrus	Papyrus	Pith	21.0[h]	39.6	19.7	—	—	—	—	4.6	4.1[a], 10.7[e]	[20]
Cyperus papyrus	Papyrus	India	24.8[h]	40.1	16.1	—	—	—	—	5.2	4.7[a], 9.2[e]	[20]
Scirpus rubricosus	—	MD	44.5[d]	30.4	—	—	7.4	—	43.9	—	—	[22]
Scirpus americanus	—	CA	36.2[d]	22.3	—	—	12.1	—	59.5	—	—	[24]
Scirpus americanus	—	CA	37.2[d]	23.5	—	—	9.6	—	58.6	—	—	[24]
Scirpus paludosus	—	CA	35.3[d]	23.8	—	—	15.3	—	62.7	—	—	[24]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Scirpus sp.	—	NE	40.8[d]	27.0	—	—	9.5	—	47.5	—	—	[24]
Gramineae												
Agropyron elongatum	Wheatgrass	NE	35.4[d]	21.4	—	—	14.3	—	54.2	—	—	[22]
Agropyron intermedium	Wheatgrass	NE	44.1[d]	26.2	—	—	12.2	—	51.2	—	—	[24]
Agrostis sp.	Bent grass	MD	30.4[d]	14.4	—	—	5.7	—	56.0	—	—	[22]
Andropogon barbinodis	Beard grass	TX	46.8[d]	27.7	—	—	5.6	—	52.4	—	—	[22]
Andropogon gerardi	—	KS	52.2[d]	33.4	—	—	5.7	—	39.9	—	—	[23]
Andropogon hallii	—	KS	52.7[d]	33 5	—	—	5.8	—	39.1	—	—	[23]
Andropogon intermedius	—	KS	50.0[d]	31.5	—	—	5.7	—	42.8	—	—	[23]
Andropogon virginicus	—	TX	52.9[d]	33.1	—	—	4.5	—	40.2	—	—	[22]
Aristida wrighii	—	TX	41.3[d]	25.9	—	—	6.3	—	0.9	—	—	[22]
Arundinaria alpina	Bamboo	Ethiopia	43.8[d]	30.4	—	—	3.2	—	25.4	—	—	[22]
Arundinaria longifolia	Bamboo	AZ	60.3[d]	39.3	—	—	3.9	—	27.4	—	—	[22]
Arundinaria tecta	Bamboo	MD	46.1[d]	26.4	—	—	7.9	—	43.0	—	—	[24]
Arundo donax	Addar grass	MD	46.0[d]	29.3	—	—	10.2	—	43.8	—	—	[23]
Avena barbata	Oat	AZ	41.0[d]	27.1	—	—	12.5	—	54.2	—	—	[22]
Avena sativa	Oat	American	71.0[h]	35.9	16.1	26.2	—	14.9	9.7	—	2.4[p]	[20]
Avena sativa	Oat	—	—	39.4	17.5	27.1	4.4	15.3	—	7.2[t]	—	[20]
Avena sativa	Oat	Holland	44-53	31-37	16-19	27-38	—	—	—	6-8	4-7[s]	[17]
Bambusa vulgaris	Bamboo	India	—	37.1	15.5	24.9	—	13.8	—	2.9[i]	1.3[a], 1.1[u]	[20]
Botanical names not given	Bamboo	Brazil	55.2[d]	36.3	—	—	5.0	—	25.8	—	—	[23]
"	Bamboo	—	49-62	32-44	19-24	27-32	—	—	—	1.5-5	.7-3[s]	[17]
"	Bamboo	Dowga	57-66	26-43	21-31	15-26	—	—	—	1.7-5	1.5-3[s]	[17]
"	Bamboo	Medar	68.8[h]	—	24.6	17.2	5.5	6.5	24.9	2.7	1.9[s]	[5]
"	Bamboo	Chiva	67.3[h]	—	26.6	17.7	4.3	5.8	24.0	4.1	2.5[s]	[5]
Bothriochloa intermidia	Bluestem	—	72.0[h]	—	27.5	17.5	2.9	4.9	25.4	3.9	2.3[s]	[5]
Bouteloua curtipendula	Gramagrass	OK	46.7[d]	8.5	—	—	9.9	—	46.5	—	—	[22]
		TX	40.3[d]	23.0	—	—	6.4	—	52.4	—	—	[22]

Bromus rigidus	Bromgrass	MD	40.4[d]	24.8	—	—	5.8	—	49.3	—	—	[22]
Cenchrus myosuroides	—	AZ	45.5[d]	30.4	—	—	9.3	—	43.0	—	—	[22]
Cymbopogon validus	Oilgrass	S. Africa	46.0[d]	29.3	—	—	12.6	—	44.0	—	—	[22]
Cynodon dactylon	Bermuda grass	GA	41.3[d]	24.5	—	—	9. 9	—	51.4	—	—	[22]
Dactylis glomerata	Orchard grass	MD	47.0[d]	31.5	—	—	8.5	—	43.8	—	—	[24]
Digitaria sanguinalis	Crabgrass	MD	34.0[d]	16.7	—	—	8.4	—	46.1	—	—	[22]
Echinochloa crusgalli	Barnyard grass	MD	43.9[d]	27.5	—	—	9.2	—	48.5	—	—	[24]
Echinochloa pyramidalis	—	S. Africa	49.1[d]	30.6	—	—	9.0	—	41.4	—	—	[22]
Eleusine indica	Wiregrass	NC	29.0[d]	8.0	—	—	5.3	—	35.0	—	—	[24]
Elymus canadensis	Wild rye	ND	42.9[d]	27.0	—	—	15.2	—	51.2	—	—	[24]
Elymus giganteus	Wild rye	NE	47.9[d]	32.1	—	—	9.2	—	44.9	—	—	[24]
Elymus sp.	Wild rye	CA	48.3[d]	30.8	—	—	14.2	—	50.0	—	—	[24]
Eragrostis chloromelas	Love grass	AZ	39.9[d]	94.6	—	—	11.5	—	49.0	—	—	[24]
Eragrostis curvula	Love grass	OK	44.7[d]	28.2	—	—	7.5	—	44.3	—	—	[24]
Eragrostis curvula	Love grass	OK	40.8[d]	25.4	—	—	9.3	—	50.2	—	—	[24]
Erianthus ravennae, stalks	Ravenna grass	IL	52.6[d]	35.1	—	—	4.7	—	38.8	—	—	[22]
Guadua amplexifolia, base	—	Mexico	58.2[d]	40.6	—	—	5.8	—	32.2	—	—	[23]
Guadua amplexifolia, middle	—	Mexico	60.9[d]	42.8	—	—	3.7	—	28.5	—	—	[23]
Guadua amplexifolia, top	—	Mexico	61.6[d]	43.0	—	—	4.1	—	29.5	—	—	[23]
Guadua angustifolia	—	Ecuador	52.1[d]	29.8	—	—	3.6	—	37.3	—	—	[23]
Gynerium sagittatum	Wild cane	Honduras	58.4[d]	38.5	—	—	3.2	—	29.9	—	—	[23]
Holcus lanatus	Velvet grass	MD	43.3[d]	29.1	—	—	7.4	—	50.0	—	—	[24]
Hordeum vulgare	Barley	Europe	73.3[h]	36.4	16.6	26.7	—	12.2	—	9.6[t]	2.7[p]	[20]
Hordeum vulgare	Barley	America	47-48	31-34	16-19	24-29	—	—	—	5-7	3-6[s]	[17]
Hordeum vulgare	Barley	whole stalk	—	33.8	14.5	14.7	4.7	16.1	—	6.4[t]	—	[20]
Hyparrhenia hirta	—	S. Africa	54.6[d]	34.1	—	—	8.7	—	37.8	—	—	[22]
Ischaemum arcuatum	—	S. Africa	48.0[d]	30. 8	—	—	11.0	—	42.9	—	—	[22]
Lolium multiflorum	Ryegrass	Spain	49.1[d]	34.5	—	—	7.7	—	42.5	—	—	[23]
Lygeum spartum	—	MD	39.3[d]	24.4	—	—	11.8	—	46.5	—	—	[22]
Melica mulica	Melic grass	MD	52.3[d]	35 5	—	—	6.7	—	39.8	—	—	[23]
Miscanthus sinensis	—	MD	45.5[d]	26.6	—	—	4.0	—	37.8	—	—	[22]
Muhlenbergia rigens	—	CA	39.5[d]	22.8	—	—	5.0	—	47.8	—	—	[22]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Oryza sativa	Rice	Egypti	—	36.2	11.9	24.5	4.6	13.3	—	16.1[f]	—	[20]
Oryza sativa	Rice	Sri Lanka	—	28.1	12.5	26.5	5.1	16.1	—	—	—	[20]
Oryza sativa	Rice	—	—	—	12.0	21.0	2.1	17.7	—	24.8	14.3[s]	[20]
Oryza sativa	Rice	India	43-49	28-36	12-16	23-28	—	—	—	15-20	9-14[s]	[17]
Oryza sativa	Rice	—	53.5[c]	—	25.5	21.0	—	10-14	—	12.0	—	[27]
Oxytenanthera abyssinica	—	Ethiopia	56.7[d]	39.8	—	—	5.4	—	29.5	—	—	[22]
Panicum antidotale	Panic grass	TX	39.3[d]	24.4	—	—	11.8	—	43.3	—	—	[22]
Panicum deustum	Panic grass	S. Africa	39.8[d]	24.3	—	—	11.8	—	50.8	—	—	[22]
Panicum subjunceum	Panic grass	Uruguay	42.0[d]	27.4	—	—	0.4	—	46.1	—	—	[22]
Panicum virgatum	Panic grass	KS	51.6[d]	32.4	—	—	5.9	—	39.4	—	—	[22]
Paspalum arechavaletae	—	Uruguay	45.2[d]	31.1	—	—	5.4	—	47.5	—	—	[22]
Paspalum exaltatum	—	Uruguay	44.8[d]	31.2	—	—	6.4	—	47.7	—	—	[22]
Paspalum haumanii	—	Uruguay	41.9[d]	29.4	—	—	7.4	—	48.8	—	—	[22]
Paspalum quadrifarium	—	Uruguay	46.3[d]	30.5	—	—	4.4	—	43.8	—	—	[22]
Pennisetum macrourum	—	GA	46.2[d]	30.2	—	—	14.1	—	46.1	—	—	[23]
Pennisetum spicatum	—	MI	40.1[d]	26.O	—	—	16.1	—	54.4	—	—	[23]
Pennisetum typhoides	—	S. Africa	48.4[d]	31.4	—	—	6.9	—	43.5	—	—	[22]
Pennisetum typhoides	—	IL	49.2[d]	31.7	—	—	7.3	—	45.5	—	—	[22]
Phleum pratense	—	MD	36.5[d]	18.1	—	—	15.4	—	54.3	—	—	[22]
Phragmites communis	Reeds	China	59.6[c]	—	14.7	18.2	—	—	—	2.1	—	[32]
Phragmites communis	Reeds	Romania	47.2[c]	—	22.9	26.6	—	—	—	2.5	—	[32]
Phragmites communis	Reeds	U.S.S.R.	36.4[c]	—	—	38.8	—	—	—	10.4	—	[32]
Phragmites communis	Reeds	Germany	33.3[c]	—	35.8	16.8	—	—	—	5.7	—	[32]
Phragmites communis	Reeds	Italy	49.1[c]	—	15.7	23.7	—	—	—	6.5	—	[32]
Phragmites communis	Reeds	—	57.0	45.0	22.0	20.0	—	—	—	3.0	2.0[s]	[17]
Phragmites communis	Reeds	NE	46.1[d]	25.1	—	—	8.6	—	46.0	—	—	[22]
Phyllostachys angusta	Bamboo	GA	56.1[d]	35.6	—	—	7.2	—	26.9	—	—	[24]

Phyllostachys aureosuslcata	Bamboo	GA	57.2[d]	36.3	—	—	5.0	—	27.1	—	—	[24]
Phyllostachys bamusoides	Bamboo	GA	56.1[d]	36.3	—	—	6.3	—	26.2	—	—	[24]
Phyllostachys bamusoides cv. castillon	Bamboo	GA	57.6[d]	35.6	—	—	6.1	—	26.8	—	—	[24]
Phyllostachys bamusoides cv. slender crookstem	Bamboo	GA	56.4[d]	35.7	—	—	7.3	—	25.4	—	—	[24]
Phyllostachys bamusoides cv. white crookstem	Bamboo	GA	55.4[d]	34.2	—	—	9.2	—	28.0	—	—	[24]
Phyllostachys bambusoides (base)	Bamboo	GA	58.0[d]	35.5	—	—	5.8	—	23.6	—	—	[24]
Phyllostachys bambusoides (middle)	Bamboo	GA	58.0[d]	35.5	—	—	5.8	—	23.6	—	—	[23]
Phyllostachys bissetii	Bamboo	GA	57.7[d]	36.6	—	—	5.9	—	22.5	—	—	[23]
Phyllostachys congesta	Bamboo	GA	58.0[d]	35.0	—	—	9.4	—	29.1	—	—	[24]
Phyllostachys decora	Bamboo	GA	57.0[d]	35.6	—	—	6.1	—	27.6	—	—	[24]
Phyllostachys dulcis	Bamboo	GA	58.7[d]	35.0	—	—	6.5	—	24.2	—	—	[24]
Phyllostachys flexuosa	Bamboo	GA	52.9[d]	32.9	—	—	12.6	—	32.1	—	—	[24]
Phyllostachys lithophila	Bamboo	GA	57.0[d]	35.5	—	—	6.1	—	26.1	—	—	[24]
Phyllostachys makinoi	Bamboo	Taiwan	61.4[d]	39.0	—	—	4.0	—	22.6	—	—	[22]
Phyllostachys meyeri	Bamboo	Taiwan	59.2[d]	38.7	—	—	2. 9	—	23.6	—	—	[22]
Phyllostachys nidularia cv. smooth sheath	Bamboo	GA	57.8[d]	36.9	—	—	5.8	—	25.5	—	—	[24]
Phyllostachys nigra	Bamboo	GA	53.1[d]	33.0	—	—	13.4	—	31.3	—	—	[24]
Phyllostachys nigra cv. bory	Bamboo	GA	57.2[d]	36.4	—	—	6.0	—	29.5	—	—	[24]
Phyllostachys nuda	Bamboo	GA	58.1[d]	36.7	—	—	6.2	—	26.9	—	—	[24]
Phyllostachys pubescens	Bamboo	GA	56.6[d]	36.1	—	—	5.3	—	25.6	—	—	[22]
Phyllostachys purpurata	Bamboo	GA	57.2[d]	34.1	—	—	6.4	—	28.7	—	—	[24]
Phyllostachys rubromarginata	Bamboo	GA	53.4[d]	35.7	—	—	8.5	—	30.9	—	—	[24]
Phyllostachys viridiglaucescens	Bamboo	GA	56.1[d]	35.6	—	—	8.4	—	27.4	—	—	[24]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Phyllostachys viridis	Bamboo	GA	54.5[d]	34.1	—	—	9.6	—	29.8	—	—	[24]
Phyllostachys vivax	Bamboo	Israel	56.7[d]	36.0	—	—	7.8	—	25.9	—	—	[24]
Saccharum biflorum		S. Africa	48.9[d]	32.3	—	—	6.8	—	43.8	—	—	[22]
Saccharum officinanum	Sugar cane or	FL	47.1[d]	29.9	—	—	10.2	—	41.5	—	—	[22]
Saccharum officinanum	Bagasse	HI	49.4	31.6	17.8	27.6	8.0	12.9	41.0	1.8	—	[3]
Saccharum officinanum	"	LA	53.2	32.4	20.8	30.3	3.1	4.0	32.2	3.3	—	[3]
Saccharum officinanum	"	FL	53.5	—	18.9	30.0	6.0	8.8	35.9	2.4	—	[16]
Saccharum officinanum	"	HI	52.0	—	18.1	27.9	10.8	11.2	39.9	2.2	—	[16]
Saccharum officinanum	"	HI	50.2	—	21.3	27.7	3.2	5.7	33.9	5.4	—	[16]
Saccharum officinanum	"	PR	55.0	—	19.3	31.3	3.6	4.0	31.3	2.6	—	[16]
Saccharum officinanum	"	Mexico	50.9	—	18.1	29.6	5.4	8.0	27.3	3.9	—	[16]
Saccharum officinanum	"	Philippines	46.0	—	22.4	29.9	2.3	7.6	40.1	4.9	—	[16]
Saccharum officinanum	"	India	56.8	—	22.3	31.8	3.0	2.8	31.1	2.3	—	[16]
Saccharum officinanum	"		43[c]	—	23.0	27.5	—	25-30	—	2-4	—	[27]
Saccharum sp.	"	FL	49.0[d]	31.0	—	—	21.8	—	45.5	—	—	[24]
Secale cereale	Rye	America	50-54	33-35	16-19	27-30	—	—	—	2-5	.5-4[s]	[17]
Secale cereale	Rye	Europe	—	37.6	19.0	30.5	3.2	9.4	—	4.3t	—	[20]
Secale cereale	Rye		75.5[h]	39.3	17.8	27.9	—	8.8	—	3.8	3.5[p]	[20]
Secale cereale	Rye	Europe	—	37.2	17.6	25.7	2.9	12.0	—	1.2i	2.1[a], 1.0[u]	[20]
Setaria italica	Foxtail millet	NE	41.0[d]	25.3	—	—	2.6	—	52.6	—	—	[22]
Setaria sphacelata	—	S. Africa	48.1[d]	30.9	—	—	10.4	—	42.4	—	—	[22]
Setaria verticillata	—	MD	39.4[d]	17.5	—	—	8.5	—	43.0	—	—	[22]
Semiarundinaria munielae	Bamboo	Holland	60.7[d]	35.6	—	—	4.5	—	28.6	—	—	[22]
Sorghum almum	Sorghum	(mean)	46.2[cc]	29.1	15.8	23.0	14.3	—	47.5	5.7	—	[9]
Sorghum caffrorum	Sorghum		46.2[cc]	28.8	14.7	27.0	12.2	—	48.3	5.4	—	[9]
Sorghum caudatum	Sorghum		47.2[cc]	29.7	16.0	27.4	8.1	—	47.0	6.2	—	[9]
Sorghum drummondii	Sorghum		44.3[cc]	27.5	—	—	13.7	—	51.0	—	—	[9]
Sorghum nervosum	Sorghum		44.5[cc]	27.9	13.6	26.8	9.6	—	51.0	5.8	—	[9]

Sorghum subglabrecens	Sorghum		47.0[cc]	29.9	15.0	24.7	11.1	—	46.7	5.0	—	[9]
Sorghum technicum	Sorghum		44.9[cc]	28.0	—	—	10.8	—	52.8	—	—	[9]
Sorghum	Sorghum	All others	48.4[cc]	30.1	14.6	27.4	11.2	—	46.9	5.4	—	[9]
Sorghum	Sorghum		43.7[cc]	27.0	—	—	14.4	—	50.0	—	—	[9]
Sorghum durra	Sorghum		46.9[cc]	29.9	15.0	28.0	10.9	—	48.5	5.5	—	[9]
Sorghum helpense	Sorghum		45.8[cc]	29.3	12.1	26.5	9.2	—	46.4	9.6	—	[9]
Sorghum sudanese	Sorghum	Holland	44.5[cc]	28.0	13.8	—	12.2	—	49.2	6.3	—	[9]
Sorghum almum	—	IL	54.9[d]	36.3	—	—	12.7	—	40.8	—	—	[23]
Sorghum vulgare (grain)	—	TX	46.0[d]	29.4	—	—	11.9	—	49.6	—	—	[23]
Sorghum vulgare (broom corn)	—	TX	52.1[d]	32.5	—	—	8.2	—	44.3	—	—	[23]
Sorghum halepense (forage)	—	MD	52.0[d]	33.2	—	—	74	—	41.7	—	—	[23]
Sorghastrum nutans	Wood grass	NE	50.5[d]	31.4	—	—	9.0	—	43.5	—	—	[22]
Spartina cynosuroides	Marsh grass	VA	39.8[d]	25.0	—	—	9.0	—	50.1	—	—	[22]
Spartina pectinata	Marsh grass	NE	42.0[d]	27.3	—	—	13.1	—	50.4	—	—	[22]
Sporobolus cryptandrus	Rush grass	OK	43.6[d]	28.9	—	—	8.6	—	49.8	—	—	[22]
Sporobolus fimbriatus	Rush grass	S. Africa	44.6	26.3	—	—	8.6	—	46.0	—	—	[22]
Stipa coronata	Esparto	CA	44.6[d]	26.4	—	—	8.0	—	48.2	—	—	[23]
Stipa speciosa	Esparto	CA	45.8[d]	27.8	—	—	7.8	—	44.4	—	—	[23]
Stipa splendens	Esparto	NE	42.2[d]	27.2	—	—	10.6	—	46.5	—	—	[23]
Stipa tenacissima	Esparto	Spain	60.5[d]	47.8	—	—	4.2	—	33.1	—	—	[23]
Stipa viridula	Esparto	ND	47.2[d]	29.4	—	—	8.6	—	43.5	—	—	[23]
Stipa sp.	Esparto	—	50-54*	33-38	17-19	27-32	—	—	—	6-8	2-3[s]	[17]
Stipa sp.	Esparto	—	60.0[cc]	48.0	14-16	22-28	4.2	—	33.0	2.8-7.7	—	[10]
Trispeacum dactyloides	—	MD	39.6[d]	25.5	—	—	14.7	—	49.0	—	—	[23]
Triticum sp.	Wheat	America	73.7*	34.7	16.3	26.8	—	12.6	—	9.1	3.1[p]	[20]
Triticum sp.	Wheat	—	—	39.9	16.7	28.2	3.7	7.4	—	6.6[t]	—	[20]
Triticum sp.	Wheat	Holland	49-54	29-35	16-21	16-21	—	—	—	4-9	3—7[s]	[17]
Triticum sp.	Wheat	India	—	33.3	15.6	24.6	7.8	12.5	—	7.8[t]	2.0[a], 1.0[u]	[20]
Triticum sp.	Wheat	—	51.5[c]	—	21.5	23.5	—	14-16.5	—	15-18	—	[27]
Zea mays	Corn	IL	50.4[d]	34.2	—	—	12.1	—	46.7	—	—	[23]
Zea mays, stalk	Corn	Baroni	45.5[c]	—	16.7	27.1	7.0	14.9	47.6	7.0	6.9[s]	[20]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Zea mays	Corn	—	35.4[c]	—	34.0	—	—	—	—	3.6	—	[20]
Zea mays, stalk	Corn	—	50.0[cc]	34.0	5.0	20.0	—	—	—	—	—	[7]
Zea mays, corncobs	Corn	Timell	40.0[cc]	32.0	14.0	41.0	—	—	—	—	—	[7]
Zea mays	Corn	Europe	46.5[c]	—	14.0	—	—	—	—	1.2	—	[20]
Juncaceae												
Juncus acutus	—	CA	36.6[d]	25.4	—	—	16.2	—	54.8	—	—	[24]
Juncus xiphioides	—	CA	43.5[d]	30.0	—	—	11.2	—	48.1	—	—	[24]
Liliaceae												
Asparagus officinalis	—	MD	43.3[d]	25.2	—	—	14.0	—	42.0	—	—	[24]
Musaceae												
Musa sp.	Banana	India	—	61.5	9.7	14.9	—	—	—	4.8	2.8[a]	[25]
Musa sp.	Banana	India	46.7[c]	—	14.0	18.0	—	12-20	—	10.0	—	[27]
Musa sp.	Banana	India	88.7[h]	61.5	9.7	14.9	1.4	28.6	26.0	4.8	1.6[o], 1.6[k]	[15]
Palmae												
Cocos nucifera	Coconut coir	—	60.2	29.8	34.8	19.3	—	10.2	24.4	3.9	0.6[s], 3.4[e]	[11]
Cocos nucifera	Coconut coir	India	43[c]	—	45.0	—	—	—	—	—	—	[26]
Cocos nucifera, pith	Coconut coir	Phillipines	35[c]	—	25.2	7.5	—	3.5-6	—	10.2	—	[27]
Cocos nucifera, husk dust	Coconut coir		44.4[h]	—	29.3	16.9	6.7	16.3	45.2	3.3	0.4[s]	[13]
Cocos nucifera	Coconut coir		51.4[h]	—	39.2	11.0	2.0	2.4	44.4	4.9	0.5[s]	[13]
Cocos nucifera, trunk	Coconut coir		62.3[h]	—	30.9	9.6	1.7	2.4	25.5	2.7	0.9[s]	[13]
Cocos nucifera, petiole	Coconut coir		66.7[h]	—	25.1	22.9	2.6	2.8	22.9	2.8	0.2[s]	[13]
Cocos nucifera, leaves	Coconut coir		64.4[h]	—	16.2	18.6	6.6	8.1	28.6	4.7	2.2[s]	[13]
Cocos nucifera	Coconut coir		47.1[h]	—	27.7	11.6	7.6	9.5	47.2	8.1	4.3[s]	[13]
Sabal texana	Mexican palm	TX	25.1[d]	14.9			12.3		44.6			[22]
Papavearceae												
Papaver sp.	Poppy straw	America	78.0[h]	42.2	20.0	27.6	1.7	19.1	—	—	—	[6]
Restionaceae												

Wildenowia striata	—	S. Africa	44.9[d]	23.1	—	—	8.4	—	44.7	—	—	[22]
Typhaceae												
Typha angustifolia	—	CA	40.7[d]	28.1	—	—	9.4	—	48.4	—	—	[22]
Dicotyledoneae												
Amaranthaceae												
Amaranthus graecizans	Tumbleweed	MD	39.0[d]	25.3	—	—	5.8	—	43.2	—	—	[22]
Amaranthus hybridus	Pigweed	NE	38.4[d]	24.9	—	—	11.4	—	50.0	—	—	[22]
Amaranthus palmeri	—	MD	36.9[d]	24.3	—	—	10.4	—	48.7	—	—	[24]
Amaranthus retroflexus	Redweed	NC	41.2[d]	26.8	—	—	7.0	—	46.4	—	—	[24]
Apcynaceae												
Apocynum cannabinum	Indian hemp	MD	45.3[d]	29.5	—	—	9.9	—	36.8	—	—	[23]
Asclepiadaceae												
Asclepias syriaca	—	NE	46.1[d]	31.2	—	—	8.2	—	39.4	—	—	[23]
Asclepias tuberosa	Butterfly weed	NJ	40.8[d]	27.2	—	—	11.5	—	44.5	—	—	[24]
Asclepias incarnata	—	MD	44.5[d]	29.9	—	—	11.2	—	38.6	—	—	[24]
Caprifoliaceae												
Sambucus canadensis	American elder	NE	44.8[d]	27.9	—	—	9.5	—	31.5	—	—	[23]
Sambucus canadensis	American elder	MD	45.9[d]	28.3	—	—	5.5	—	30.2			[22]
Bombacaceae												
Ceiba petandra	Kapok	—	64.0[c]	—	13.0	—	—	—	—	—	23.0[k]	[19]
Boraginaceae												
Echium vulare	Blueweed	CT	36.6[d]	20.0	—	—	3.2	—	44.2	—	—	[24]
Lithostpermum arvense	—	MD	33.8[d]	21.5	—	—	10.2	—	53.6	—	—	[24]
Campanulaceae												
Lobelia cardinalis	Cardinal flower	VA	44.1[d]	28.3	—	—	11.2	—	49.9	—	—	[22]
Specularia perfoliata	—	MD	37.2[d]	22.6	—	—	10.7	—	18.1	—	—	[22]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Capparidaceae												
Cleome spinosa	—	MD	46.5[d]	29.9	—	—	6.9	—	39.9	—	—	[24]
Cleome serrulata	Stinking clover	NE	53.2[d]	33.2	—	—	4.4	—	30.6	—	—	[24]
Caryophyllaceae												
Agroustemma githago	Corn cockle	MD	44.1[d]	28.3	—	—	7.6	—	41.5	—	—	[24]
Arenaria serpyllifolia	Thyme—eaves	MD	32.0[d]	17.6	—	—	7.8	—	43.7	—	—	[22]
Dianthus ameria	—	MD	38.8[d]	23.8	—	—	11.7	—	47.6	—	—	[24]
Saponaria officinalis	Bouncing bet	CT	53.9[d]	35.3	—	—	12.3	—	52.9	—	—	[22]
Silene antirrhina	Sleepy catchfly	MD	39.2[d]	23.1	—	—	11.0	—	49.2	—	—	[22]
Silene noctiflola	Sticky cockle	CT	41.0[d]	24.3	—	—	3.9	—	42.7	—	—	[22]
Chenopodiaceae												
Atriplex mulleri	Saltbush	GA	45.4[d]	27.2	—	—	6.2	—	29.4	—	—	[24]
Atripex patula var. hastuta	Saltbush	MD	41.3d	25.5	—	—	8.9	—	45.5	—	—	[22]
Chenopodium ambrosioides	Mexican tea	VA	49.5d	31.1	—	—	3.6	—	33.9	—	—	[24]
Chenopodium album	Pigweed	NC	44.1d	27.7	—	—	7.6	—	37.0	—	—	[24]
Kochia scopria	Belvedere	KS	51.8d	32.8	21.4	—	2.2	—	29.9	—	—	[24]
Spinacea oleracea	Spinach	MD	35.3d	21.4	—	—	5.5	—	50.7	—	—	[22]
Cistaceae												
Lechea maritima	Leggett	DE	34.8d	20.0	—	—	6.7	—	38.9	—	—	[22]
Compositae												
Achilea millefolium	Common yarrow	CA	44.2d	28.0	—	—	8.0	—	29.7	—	—	[22]
Agoseris apargiodes	Mountain dandlion	CA	44.2d	28.0	—	—	6.7	—	35.9	—	—	[22]
Ambrosia artemisifolia	Common ragweed	CT	44.9d	28.0	—	—	8.6	—	39.1	—	v	[23]
Ambrosia psilostachya	—	KS	40.8d	25.2	—	—	7.0	—	43.4	—	—	[24]
Ambrosia trifida	Great ragweed	NE	48.4d	30.3	—	—	3.4	—	32.9	—	—	[23]
Ambrosia trifida	Great ragweed	TX	48.9d	30.9	—	—	2.3	—	32.1	—	v	[22]

Anaphalis margaritacea	Pearly everlasting	VA	44.3d	27.6	—	—	9.7	—	38.1	—	v	[24]
Arctium nemorosum	Petiole hollow	MD	41.7d	27.0	—	—	11.7	—	43.5	v	—	[24]
Artemisia vulgaris	Common mugwort	KS	42.2d	26.1	—	v	9.9	—	40.7	—	—	[24]
Artemisia sp.	Wormwood	VA	48.3d	31.1	—	—	10.7	—	34.7	—	—	[24]
Aster sp.	Starwort	DE	47.0d	30.2	—	—	5.6	—	37.3	—	—	[24]
Athemis colula	Mayweed	MD	44.6d	27.6	—	—	13.4	—	41.1	—	v	[[22]
Baccharis glutinosa	Seep willow	TX	40.7d	25.9	—	—	8.3	—	30.9	v	—	[22]
Baccharis sarothroides	—	AZ	39.2d	22.9	—	—	12.8	—	43.7	—	v	[22]
Isamorhiza annus seed nuts	Sunflower	—	32.0cc	30.0	27.0	27.0	—	v	—	—	—	[7]
Bidens frondosa	Beggar-ticks	CT	40.6d	26.3	—	—	18.9	—	44.9	—	—	[24]
Centaurea cyanus	Blue bottle	DE	44.2d	27.7	—	v	7.4	—	42.3	—	—	[22]
Centaurea cyanus	—	MD	46.4d	27.7	—	—	8.6	—	35.2	—	—	[24]
Cichorium intybus	Common chicory	MD	45.0d	29.6	—	—	6.3	—	40.7	—	—	[22]
Cirsium discolor	—	MD	42.1d	27.2	—	—	7.5	v	44.7	v	v	[23]
Chrysanthemum leucanthemum	Oxeye daisy	CT	40.3d	25.0	—	v	12.1	—	45.0	—	—	[24]
Erigeron annuus	White-top	MD	47.4d	29.6	—	v	8.2	—	38.3	—	—	[24]
Erigeron canadensis	Horse weed	VA	31.3d	31.9	—	—	5.5	—	32.0	—	—	[24]
Erigeron tweedya	—	Uruguay	44.0d	28.4	—	—	4.4	—	43.6	—	v	[22]
Eupatorum dubium or puroureum	Joe-Pye weed	MD	49.2d	33.0	—	v	7.8	—	31.9	—	—	[24]
Eupatorium hyssopifolium	—	ND	48.2d	31.8	—	—	6.2	—	28.0	—	v	[24]
Eupatorium laevigatum	—	Uruguay	53.4d	36.1	—	—	2.3	—	23.8	—	—	[22]
Eupatorium perfoliatum	Thoroughwort	Uruguay	50.6d	33.6	—	—	6.9	—	31.2	v	—	[22]
Eupatorium perfoliatum	Thoroughwort	MD	50.0d	32.0	—	v	4.2	v	31.4	v	v	[24]
Eupatorium serotinum	—	MD	45.8d	28.8	—	—	9.1	—	42.2	—	v	[24]
Eupatorium urticasfolium	—	CT	46.5d	28.8	—	—	10.6	—	42.6	—	—	[24]
Grindelia stricta ssp. Venulosa	Gumweed	CA	33.7d	20.8	—	v	19.3	—	54.6	—	—	[22]
Gutierrezia sarothrae	—	TX	24.5d	14.4	—	—	27.3	—	61.3	—	—	[22]
Heliopsis Laevis	—	MD	45.9d	29.3	—	—	9.0	—	38.8	—	v	[24]
Heterotheca subaxillaris	Camphorweed	DE	35.1d	22.0	—	—	22.7	—	55.1	—	v	[24]
Haplopappus ciliatus	—	KS	50.5d	32.4	—	—	6.4	v	30.1	v	v	[22]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Helenium tenuifolium	Sneezweed	VA	40.1d	22.8	—	—	8.3	—	37.1	—	—	[22]
Helianthus annuus	Common sunflower	NE	46.9d	3n.s	—	—	7.2	—	36.9	—	—	[23]
Helianthus grosserratus	Sunflower	KS	46.2d	29.4	—	—	6.5	—	39.2	—	—	[23]
Helianthus maximiliani	Sunflower	KS	42.4d	26.8	—	—	10.1	—	40.9	—	—	[23]
Helianthus rigidis	Sunflower	KS	37.3d	23.3	—	—	13.9	—	51.3	—	—	[23]
Helianthus salicifolius	Sunflower	KS	37.2	29.9	—	—	17.4	—	49.3	—	—	[23]
Helianthus scaberrimus	Sunflower	NE	44.4d	28.1	—	—	11.0	—	40.7	—	—	[22]
Helianthus tuberosus	Sunflower	NE	48.5d	31.1	—	—	6.4	—	38.7	—	v	[23]
Helianthus tuberosus	Sunflower	IA	34.0d	22.1	—	—	21.6	—	55.1	—	—	[22]
Hulsea heterochroma	—	CA	32.6d	19.7	—	—	23.8	—	57.1	—	v	[22]
Hymenopappus sp.	Old-plainsman	KS	40.0d	23.9	—	—	9.2	—	44.2	—	—	[22]
Iva zanthifolia	—	NE	47.3d	30.0	—	—	5.5	—	36.9	—	—	[22]
Lactuca scaroila	—	MD	45.8d	30.0	—	—	11.8	—	41.4	—	—	[24]
Liatris punctata	—	KS	41.6d	24.1	—	—	6.9	—	43.0	—	—	[24]
Lactuca canadensis	Milkweed	MS	42.3d	29.4	—	—	11.3	—	47.1	—	—	[23]
Pluchea foetida	Stinking Fleabane	DE	47.2d	29.6	—	—	6.1	—	35.9	—	—	[22]
Ratibida columnifera	—	TX	48.0d	31.5	—	—	4.2	—	29.7	—	—	[22]
Rudbeckia serotina	—	MDS	39.1d	23.9	—	—	10.2	—	39.2	—	—	[22]
Senecio braisliensis	—	Uruguay	47.3d	30.6	—	—	3.2	—	36.3	—	—	[22]
Silphium intgrifolium	—	KS	43.3d	27.0	—	—	8.3	—	39.3	—	—	[23]
Silphium laciniatum	Rosinweed	KS	39.7d	25.1	—	—	10.1	—	45.6	—	—	[23]
Solidago gigantea	Goldenrod	CT	48.7d	31.5	—	—	7.9	—	34.3	—	—	[23]
Solidago graminifolia	Goldenrod	CT	38.2d	20.6	—	—	7.0	—	34.0	—	—	[22]
Solidago rugosa	Goldenrod	CT	53.7d	34.2	—	—	4.2	—	30.0	—	—	[22]
Solidago sempervirens	Goldenrod	MD	44.3d	27.1	—	—	7.9	—	39.3	—	—	[23]
Sonchus oleraceus	Sow-thistle	MD	38.9d	26.0	—	—	13.6	—	51.7	—	—	[22]

Tagetes patula	Marigold	MD	40.8d	26.0	—	—	7.3	—	42.4	—	—	[22]
Tragopogon pratensis •	Goat's-beard	MD	39.8d	24.3	—	—	9.9	—	45.6	—	—	[22]
Verbesina occidenalis	Crown-beard	MD	42.2d	27.0	—	—	10.7	—	42.4	—	—	[22]
Veronia baldwini	Ironweed	NE	42.0d	26.3	—	—	11.7	—	37.8	—	—	[22]
Vernonia novelboracensis	Ironweed	MD	44.2d	27.7	—	—	8.7	—	36.7	—	—	[22]
Wyethia angustifolea	—	CA	42.0d	25.8	—	—	9.5	—	46.4	—	—	[22]
Wyethia helenioides	—	CA	34.4d	21.2	—	—	13.2	—	55.4	—	—	[22]
Xanthium pensylvanicum	—	MD	42.2d	26.9	—	—	5.7	—	39.6	—	—	[22]
Zinnia elegans	Zinnia	MD	43.8d	24.8	—	—	3.3	—	33.0	—	—	[22]
Cruciferae												
Berteroa incana	—	CT	46.0d	27.1	—	—	5.5	—	38.8	—	—	[24]
Brassica nigra	—	MD	37.7d	22.9	—	—	10.4	—	50.7	—	—	[24]
Brassica cf. nigra	—	CA	49.9d	30.3	—	—	4.5	—	33.2	—	—	[24]
Brassica rapa	—	MD	50.8d	31.8	—	—	3.5	—	30.6	—	—	[24]
Cakile edentula	—	MD	28.5d	17.5	—	—	15.4	—	57.9	—	—	[24]
Erysimum officinale	—	MD	40.3d	24.7	—	—	6.9	—	46.6	—	—	[24]
Lepidium virginiacum	—	MD	47.1d	28.0	—	—	3.8	—	32.8	—	—	[24]
Raphaus raphanistrum	—	MD	41.4d	25.9	—	—	7.6	—	46.0	—	—	[24]
Sisyembrium irio	—	TX	36.2d	22.2	—	—	7.9	—	52.7	—	—	[22]
Dipsacaceae												
Dipsacus sylvestri	—	MD	43.7d	28.5	—	—	8.8	—	41.1	—	—	[24]
Euphorbiaceae												
Acalypha viginica	—	MD	44.0d	27.8	—	—	15.4	—	47.4	—	—	[23]
Croton glandulosus	—	ND	47.0d	30.3	—	—	7.2	—	38.4	—	—	[24]
Croton texensis	—	KS	42.6d	27.8	—	—	10.6	—	43.2	—	—	[24]
Euphorbia maculanta	—	MD	42.0d	25.2	—	—	13.1	—	40.9	—	—	[24]
Euphorbia maginata	—	NE	49.9[d]	32. 5	—	—	4.6	—	36.2	—	—	[24]
Ricinus communis	—	NE	49.7[d]	34.0	—	—	2.5	—	32.7	—	—	[23]
Guttiferae												
Ascyrum hypericodes	—	VA	44.0[d]	26.7	—	—	9.7	—	36.6	—	—	[24]
Hypericum perforatum	—	KS	44.9[d]	27.1	—	—	9.2	—	35.0	—	—	[24]
Hypericum punctatum	—	MD	44.1[d]	27.2	—	—	10.3	—	39.7	—	—	[24]
Hydrophyllaceae												
Phacelia californica	—	CA	38.5[d]	23.7	—	—	8.7	—	50.1	—	—	[22]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Labiatae												
Monarda citriodora	—	TX	50.1[d]	32.0	—	—	2.2	—	30.8	—	—	[22]
Monarda fistutulosa	—	MD	41.9[d]	26.8	—	—	11.3	—	43.0	—	—	[22]
Nepeta cataria	—	DE	45.0[d]	25.7	—	—	9.6	—	39.8	—	—	[22]
Salvia azure	—	KS	45.8[d]	28.0	—	—	6.4	—	38.6	—	—	[22]
Trichostema dichotomumt	—	MD	47.0[d]	28.5	—	—	10.9	—	39.0	—	—	[22]
Leguminosae												
Aeschynomene scabra	—	Mexico	48.2[d]	33.5	—	—	5.7	—	29.7	—	—	[22]
Alysicarpus rugosus	—	GA	40.5[d]	27.1	—	—	7.3	—	42.9	—	—	[24]
Alysicarpus vaginalis	—	GA	37.8[d]	25.3	—	—	9.8	—	44.7	—	—	[24]
Arachis hypogaea, hulls	Peanut	—	46.0[cc]	36.0	33.0	19.0	—	—	—	—	—	[7]
Astragalus cicer	—	KS	41.6[d]	28.2	—	—	11.8	—	47.9	—	—	[24]
Astragalus sp.	—	KS	38.8[d]	24.9	—	—	10.3	—	46.7	—	—	[24]
Astragalus sp.	—	NE	48.7[d]	32.4	—	—	7.0	—	36.0	—	—	[22]
Baptisia leucophaea	—	KS	44.0[d]	28.9	—	—	10.2	—	41.3	—	—	[22]
Baptisia minor	—	KS	49.7[d]	31.7	—	—	5.3	—	31.9	—	—	[24]
Baptisia tinctoria	—	MD	46.1[d]	29.6	—	—	13.1	—	38.8	—	—	[24]
Cassia fasciculata	—	IA	40.9[d]	20.5	—	—	12.1	—	44.3	—	—	[24]
Cassia marilandica	—	KS	49.5[d]	31.3	—	—	4.7	—	31.8	—	—	[22]
Cassia tora	—	NC	45.0[d]	28.0	—	—	14.5	—	44.5	—	—	[24]
Crotalaria eriocarpa	—	Mexico	52.9[d]	36.1	—	—	6.0	—	28.1	—	—	[24]
Crotalaria intermedia	—	GA	54.8[d]	38.1	—	—	3.5	—	32.0	—	—	[24]
Crotalaria incana	Sunn hemp	FL	51.0[d]	34.8	—	—	4.6	—	31.0	—	—	[22]
Crotalaria juncea	Sunn hemp	IL	54.1[d]	37.9	—	—	3.3	—	31.2	—	—	[23]
Crotalaria juncea (Brazilian)	Sunn hemp	IL	55.4[d]	39.2	—	—	3.3	—	28.7	—	—	[23]
Crotalaria juncea (ridged stem)	Sunn hemp	TX	54 .6[d]	36.3	—	—	5.1	—	29.3	—	—	[23]

Crotalaria juncea (smooth stem)	Sunn hemp	TX	53.7[d]	35.6	—	—	4.3	—	30.5	—	—	[24]
Crotalaria juncea	Sunn hemp	FL	—	78.3	—	—	—	—	—	0.3	1.5[a]	[25]
Crotalaria juncea	Sunn hemp	GA	54.9[cc]	38.7	—	3.6	4.5	—	29.5	—	—	[10]
Crotalaria juncea	Sunn hemp	IL	51.9[cc]	36.3	4.0	—	6.8	—	33.5	—	—	[10]
Crotalaria juncea	Sunn hemp	IN	53.3[cc]	36.9	—	—	3.3	—	31.4	—	—	[10]
Crotalaria juncea	Sunn hemp	LA	54.9[cc]	36.3	—	—	5.2	—	28.7	—	—	[10]
Crotalaria juncea	Sunn hemp	MI	60.5[cc]	41.5	—	—	1.9	—	23.2	—	—	[10]
Crotalaria juncea	Sunn hemp	MO	55.1[cc]	38.9	—	—	3.8	—	30.1	—	—	[10]
Crotalaria juncea	Sunn hemp	TX	54.6[cc]	37.6	—	—	4.7	—	29.3	—	—	[10]
Crotalaria juncea	Sunn hemp	—	53.7[cc]	35.6	—	—	3.6	—	29.1	—	—	[10]
Crotalaria mucronata	—	FL	55.3[d]	38.0	—	—	3.2	—	29.8	—	—	[22]
Crotalaria spectabilis	—	FL	40.6[d]	29.0	—	—	8.5	—	48.8	—	—	[22]
Crotalaria sp.	—	GA	49.6[d]	34.1	—	—	8.4	—	36.4	—	—	[24]
Crotalarta striata	—	FL	48.9[d]	34.2	—	—	5.4	—	38.4	—	—	[22]
Cyamopsis tetragonoloba	—	NE	49.6[d]	34.8	—	—	4.5	—	40.8	—	—	[24]
Dalea alopecuroides	Foxtail dalea	IA	47.2[d]	32.5	—	—	9.0	—	37.2	—	—	[22]
Dalea enneandra	—	KS	52.2[d]	35.9	—	—	7.2	—	32.0	—	—	[24]
Dalea deffusa	—	Mexico	52.2[d]	35.2	—	—	4.0	—	31.6	—	—	[22]
Dalea leporina	—	Mexico	50.8[d]	34.9	—	—	5.2	—	25.6	—	—	[22]
Dalea mutabies	—	Mexico	48.3[d]	33.3	—	—	7.0	—	34.6	—	—	[22]
Dalea vernicia	—	Mexico	45.7[d]	30.7	—	—	11.8	—	33.1	—	—	[22]
Desmanthus sp.	—	KS	46.8[d]	31.0	—	—	5.6	—	34.5	—	—	[23]
Desmanthus illinoensis	—	NE	49.0[d]	31.7	—	—	5.6	—	33.6	—	—	[23]
Desmanthus interior	—	Mexico	48.6[d]	31.8	—	—	4.9	—	33.6	—	—	[22]
Desmodium distortum	—	GA	46.5[d]	31.9	—	—	6.9	—	37.2	—	—	[24]
Desmodium gyrans	—	KS	43.9[d]	29.7	—	—	7.6	—	40.5	—	—	[22]
Desmodium illinoensis	—	KS	45.9[d]	31.1	—	—	8.0	—	40.8	—	—	[22]
Desmodium nicaraguense	—	Mexico	55.7[d]	40.2	—	—	3.2	—	28.5	—	—	[22]
Desmodium virgatum	—	GA	46.8[d]	30.1	—	—	9.3	—	36.0	—	—	[24]
Glycine max	Soy bean	IL	53.3[d]	34.8	—	—	3.1	—	31.1	—	—	[24]
Glycyrrhiza lepidota	Wild licorice	NE	42.1[d]	28.3	—	—	6.6	—	42.2	—	—	[24]
Indigofera hiruta	—	FL	52.8[d]	36.3	—	—	5.6	—	34.2	—	—	[24]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Indigofera sp.	Indigo	GA	37.6[d]	24.3	—	—	6.2	—	41.6	—	—	[22]
Lespedeza capitata	—	NE	48.5[d]	31.5	—	—	4.4	—	29.3	—	—	[24]
Lespedeza hedysarioides	—	KS	42.8[d]	27.3	—	—	7.4	—	39.9	—	—	[24]
Lespedeza inschanica	—	KS	41.5[d]	26.9	—	—	8.4	—	42.9	—	—	[24]
Lespedeza sp.	Bush clover	GA	49.6[d]	34.6	—	—	6.4	—	32.3	—	—	[22]
Lotus scoparius	—	CA	34.8[d]	22.8	—	—	11.0	—	47.4	—	—	[22]
Lupinus formosus	—	CA	48.4[d]	32.6	—	—	9.6	—	35.6	—	—	[22]
Lupinus latifolius	—	CA	40.9[d]	25.9	—	—	8.7	—	47.0	—	—	[22]
Lupinus micranthus	—	CA	28.9[d]	18.3	—	—	12.0	—	59.8	—	—	[22]
Melilotus albus	—	IL	40.8[d]	26.4	—	—	12.2	—	44.7	—	—	[22]
Melilotus officinalis	Yellow melilot	MD	42.6[d]	27.0	—	—	10.1	—	42.8	—	—	[22]
Petalostemon mutiflorum	Prairie clover	KS	36.1[d]	23.3	—	—	9.9	—	47.9	—	—	[22]
Petalostemon purpureum	Prairie clover	KS	36.1[d]	23.3	—	—	9.9	—	47.9	—	—	[22]
Sesbania arabica	—	OK	51.8[d]	35.3	—	—	3.6	—	27.4	—	—	[22]
Sesbania cannabina	—	OK	50.7[d]	33.9	—	—	5.0	—	28.8	—	—	[22]
Sesbania cinerescens	—	GA	44.8[d]	30.3	—	—	6.4	—	38.8	—	—	[23]
Sesbania drummondii	—	TX	46.7[d]	31.6	—	—	5.3	—	31.8	—	—	[22]
Sesbania exaltata	Colorado River hemp	TX	51.3[d]	34.5	—	—	3.4	—	28.9	—	—	[22]
Sesbania sonorae	—	AZ	54.1[d]	36.3	—	—	3.3	—	27.8	—	—	[23]
Sesbania vesicaria	—	TX	50.2[d]	33.1	—	—	2.4	—	27.1	—	—	[22]
Sesbania sp.	—	TX	55.6[d]	40.2	—	—	2.1	—	23.9	—	—	[22]
Tephrosia virginiana	—	MD	45.1[d]	30.0	—	—	7.8	—	34.4	—	—	[22]
Tephrosia sp.	Horay pea	GA	42.8[d]	28.6	—	—	13.8	—	40.6	—	—	[22]
Swainsona salsula	—	CO	41.3[d]	27.3	—	—	8.4	—	36.4	—	—	[22]
Linaceae								—				
Linum usitatissimum	Flax	—	76-79	45-68	10-15	6-17	—	—	—	2-5	—	[17]
Linum usitatissimum	Flax	—	71.2[c]	—	2.2	—	—	—	—	—	2.0[k], 6.0[e]	[19]

Linum usitatissimum	Flax	IL	40.4[d]	27.2	—	—	8.9	—	39.6	—	—	[22]
Lythraceae												
Heimia salicifolia	—	Uruguay	46.4[d]	28.9	—	—	5.9	—	32.8	—	—	[22]
Malvaceae												
Abutilon americanum	—	Mexico	45.6[d]	28.8	—	—	4.6	—	31.6	—	—	[22]
Abutilon crispum	—	Mexico	48.0[d]	31.3	—	—	5.0	—	33.6	—	—	[22]
Abutilon theophrasti	—	MD	42.8[d]	27.6	—	—	9.4	—	43.6	—	—	[23]
Abutilon trisulcatum	—	Mexico	48.0[d]	32.1	—	—	4.8	—	30.0	—	—	[22]
Altaea rosea	—	MD	47.9[d]	30.5	—	—	6.5	—	36.8	—	—	[23]
Althaea cannabina	Hollyhock of gardens	Spain	44.3[d]	27.5	—	—	6.9	—	39.4	—	—	[22]
Althaea setosa	—	Israel	45.8[d]	28.8	—	—	4.3	—	38.5	—	—	[22]
Anoda pentaschista	—	Mexico	47.9[d]	30.7	—	—	5.2	—	36.8	—	—	[22]
Gossypium spp.	Cotton, staple	—	—	85-90	3-3.3	21-23	—	—	—	1-1.5	<1[s]	[17]
Gossypium spp.	Cotton, linters	Indonesia	—	80-85	3-3.5	—	—	—	—	1-2	<1[s]	[17]
Hibiscus cannabinus	Kenaf, hurds	IL	53.8[d]	34.7	15-18	—	3.7	—	30.9	—	—	[23]
Hibiscus cannabinus	Kenaf	FL	52.2[d]	34.0	10.5	21-23	3.4	—	29.4	—	—	[23]
Hibiscus cannabinus	Kenaf	—	47-57	31-39	12.1	18.3	—	—	—	2-5	—	[17]
Hibiscus cannabinus	Kenaf, stem	MD	53.1[cc]	36.5	13.2	22.7	4.3	11.2	33.0	—	—	[4]
Hibiscus cannabinus	Kenaf, stem	GA	58.0[cc]	40.2	7.7	19.7	3.3	7.4	28.4	—	—	[4]
Hibiscus cannabinus	Kenaf, whole	—	54.4[cc]	37.4	8.0	16.1	—	—	—	4.1	—	[28]
Hibiscus cannabinus	Kenaf, bast	—	57.2[cc]	42.2	17.4	16.0	—	—	—	5.5	—	[28]
Hibiscus cannabinus	Kenaf, core	—	51.2[cc]	33.7	13.4	19.0	—	—	—	2.9	—	[28]
Hibiscus cannabinus	Kenaf, bottom	—	53.9[d]	35.3	—	20.1	3.4	9.7	32.4	—	6[o]	[8]
Hibiscus cannabinus	Kenaf, top	—	46.4[d]	29.8	—	—	5.5	12.8	39.6	—	11.1[o]	[8]
Hibiscus cisplantinus	Kenaf	NC	46.1[d]	30.5	—	—	2.5	—	33.2	—	—	[22]
Hibiscus eelveldeanus	Kenaf	FL	51.9[d]	36.3	—	—	7.5	—	31.0	—	—	[22]
Hibiscus esculentus	Okra	NE	35.4[d]	23.3	—	—	5.0	—	45.6	—	—	[23]
Hibiscus esculentus (pods only	Okra	SC	52.8[d]	34.7	—	—	5.3	—	36.8	—	—	[23]
Hibiscus grandiflorus		FL	45.3[d]	31.6	—	—	5.2	—	29.1	—	—	[22]
Hibiscus militaris	Halberd-leaved rose mallow	Mexico	43.9[d]	28.9	—	—	8.3	—	38.0	—	—	[22]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Hibiscus lasiocarpus	—	Mexico	50.1[d]	33.2	—	—	2.8	—	30.1	—	—	[22]
Hibiscus rosa—inensis	Chinese rose	FL	44.2[d]	29.4	—	—	9.2	—	36.9	—	—	[22]
Hibiscus sabdariffa	Roselle	CA	48.6[d]	32.3	—	—	9.1	—	37.8	—	—	[23]
Hibiscus syriacus	Rose of Sharon	MD	36.8[d]	22.9	—	—	5.7	—	41.0	—	—	[22]
Hibiscus trionum	Flower of an Hour	MD	38.1[d]	23.1	—	—	6.8	—	39.8	—	—	[22]
Hibiscus sp.	Rose mallow	Uruguay	46.5[d]	32.2	—	—	4.6	—	38.8	—	—	[22]
Horsfordia newberryi	—	Mexico	50.3[d]	34.0	—	—	5.9	—	27.6	—	—	[22]
Kosteletzkya althacifolia	—	FL	46.7[d]	31.4	—	—	4.4	—	31.8	—	—	[22]
Kosteletzkya sagittata	—	Mexico	42.8[d]	28.5	—	—	7.0	—	42.6	—	—	[22]
Lavatera arborea	Tree mallow	CA	48.1[d]	28.9	—	—	4.3	—	38.2	—	—	[22]
Lavatera punctata	—	Israel	38.7[d]	25.0	—	—	9.4	—	48.8	—	—	[22]
Lavatera rotundata	—	Spain	42.3[d]	25.5	—	—	7.9	—	41.5	—	—	[22]
Malachra alceaefolia	—	Mexico	45.9[d]	30.4	—	—	3.8	—	35.3	—	—	[22]
Malva rotundifolia	—	MD	42.7[d]	27.2	—	—	9.0	—	55.4	—	—	[22]
Malva sylvestris	—	Israel	29.6[d]	18.4	—	—	22.7	—	59.6	—	—	[22]
Malva tournefortiana	—	Spain	44.2[d]	27.5	—	—	7.5	—	43.7	—	—	[22]
Malvastrum sp.	—	S. Africa	49.8[d]	33.0	—	—	4.9	—	29.0	—	—	[22]
Pavonia xanthogloca	—	Urguay	45.0[d]	29.0	—	—	5.1	—	41.6	—	—	[22]
Sida acuta	—	Mexico	44.8[d]	28.6	—	—	5.0	—	33.6	—	—	[22]
Sida carpinifolia	—	GA	40.5[d]	24.5	—	—	7.8	—	40.4	—	—	[22]
Sida inflexa	—	NC	38.2[d]	23.3	—	—	5.1	—	40.2	—	—	[22]
Sida rhombifolia	—	Mexico	50.6[d]	32.6	—	—	2.4	—	25.3	—	—	[22]
Sida sp.	—	FL	51.2[d]	34.1	—	—	4.0	—	28.3	—	—	[22]
Sphaeralcea angustifolia	—	Mexico	48.6[d]	30.3	—	—	3.0	—	34.2	—	—	[22]
Sphaeralcea bonariensis	—	Uruguay	47.0[d]	29.9	—	—	4.3	—	30.9	—	—	[22]
Sphaeralcea coccinea	Prairie mallow	NM	29.0[d]	16.4	—	—	8.6	—	53.8	—	—	[22]
Sphaeralcea emoryi	—	—	42.6[d]	26.3	—	—	6.0	—	40.7	—	—	[22]

Sphaeralcea sp.	Flase mallow	CA	47.8[d]	30.2	—	—	7.4	—	32.0	—	—	[22]
Urena lobata	—	FL	52.4[d]	34.4	—	—	5.6	—	35.2	—	—	[22]
Wissadula amplissima	—	Mexico	49.5[d]	33.3	—	—	4.7	—	29.9	—	—	[22]
Wissadula cineta	—	Mexico	50.0[d]	34.5	—	—	5.1	—	25.0	—	—	[22]
Moraceae												
Cannabis sativa	Hemp	—	74.9[c]	—	3.7	—	—	—	—	—	.9[k], 3.1[e]	[19]
Cannabis sativa	Hemp	IL	56.2[d]	37.6	—	—	4.0	—	30.1	—	—	[23]
Onagraceae												
Gaura parviflora	—	NE	42.6[d]	26.9	—	—	12.8	—	46.1	—	—	[24]
Oenothera affinis	—	Uruguay	53.0[d]	38.7	—	—	4.1	—	31.3	—	—	[22]
Oenothera biennis	Evening primrose	CT	47.2[d]	31.4	—	—	3.0	—	41.6	—	—	[24]
Oenothera humifusa	—	MD	37.4[d]	23.5	—	—	10.0	—	46.4	—	—	[24]
Oenothera laciniata	—	MD	35.7[d]	23.2	—	—	8.0	—	44.8	—	—	[24]
Phytolaccaceae								—		—	—	
Phytolacca americana	Virginian Pokeweed	MD	42.4[d]	28.4	—	—	11.0	—	47.9	—	—	[22]
Polemonuaceae								—		—	—	
Phlox paniculata	—	MD	53.0[d]	35.4	—	—	2.9	—	28.6	—	—	[22]
Polygonaceae								—		—	—	
Eriogonum annuum	—	KS	43.2[d]	25.6	—	—	10.6	—	46.3	—	—	[22]
Eriogonum fasciculatum	California buckwheat	CA	51.8[d]	30.4	—	—	3.7	—	21.1	—	—	[22]
Polygonoceae								—		—	—	
Polygonum persicaria	—	CT	43.0[d]	29.0	—	—	7.7	—	34 .7	—	—	[23]
Polygonum orientale	Prince's feather	NE	46.6[d]	30.4	—	—	7.4	—	40.4	—	—	[22]
Rumex crispus	—	MD	47.1[d]	30.9	—	—	7.7	—	43.9	—	—	[22]
Ranunculaceae												
Thalictrum polycarpum	—	CA	49.5[d]	30.6	—	—	4.6	—	29.5	—	—	[22]
Rosaceae								—		—	—	
Potentilla fruiticosa	Golden hardhack	CT	43.6[d]	27.1	—	—	9.1	—	31.3	—	—	[24]
Petentilla norvegica	—	MD	39.1[d]	23.9	—	—	6.6	—	44.1	—	—	[22]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Rubiaceae												
Diodia teres	—	VA	38.6[d]	22.8	—	—	7.3	—	43.2	—	—	[24]
Scrophulariceae												
Gerardia flava	—	NJ	42.4[d]	27.0	—	—	4.9	—	40.1	—	—	[24]
Linaria canadensis	Toadflax	MD	41.0[d]	24.9	—	—	16.0	—	46.6	—	—	[24]
Mimulus guttatus	Common monkey flower	CA	32.5[d]	20.1	—	—	19.5	—	63.5	—	—	[24]
Mimulus ringens	Allegheny monkey flower	CT	30.4[d]	16.2	—	—	17.4	—	55.1	—	—	[24]
Penstemon digitalis	—	MD	41.2[d]	23.6	—	—	14.1	—	47.0	—	—	[24]
Penstemon palmeri	—	CA	38.8[d]	21.1	—	—	16.4	—	50.5	—	—	[24]
Scrophularia californica	—	CA	42.8[d]	26.4	—	—	11.2	—	45.8	—	—	[24]
Scrophularia marilandica	Carpenter's square	MD	47.5[d]	30.6	—	—	8.3	—	37.5	—	—	[24]
Veronica peregrinia	—	MD	33.5[d]	17.7	—	—	5.8	—	49.7	—	—	[24]
Verbascum blattaria	Moth mullein	MD	43.8[d]	26.5	—	—	13.6	—	43.3	—	—	[22]
Vervascum sinuatum	—	MD	49.0[d]	29.8	—	—	7.7	—	35.0	—	—	[22]
Solanaceae												
Datura stramonium	Stramonium	NE	49.9[d]	33.1	—	—	9.4	—	34.2	—	—	[24]
Thymelaeaceae												
Gnidia oppositifolia	—	S. Africa	52.5[d]	34.9	—	—	4.3	—	30.0	—	—	[22]
Tiliaceae												
Corchorus capsularis	Jute	FL	56.3[d]	39.1	—	—	3.5	—	28.6	—	—	[22]
Corchorus capsularis	Jute	—	57-58	—	21-26	18-21	—	—	—	.5-1	<1[s]	[17]

Corchorus capsularis	Jute	—	58.0	—	26.8	—	0.6	1.4	25.9	1.9	—	[20]
Corchorus capsularis	Jute	—	71.5[c]	—	8.1	21.6	—	—	—	—	.2[k], 1.8	[19]
Corchorus capsularis	Jute	India	—	60.7	12.5	—	0.9	—	—	0.8	3.5[a], 4.8[p]	[25]
Corchorus olitorius	Jute	India	—	61.0	13.2	15.6	—	—	—	0.5	2.9[a], 5.2[p]	[25]
Corchorus capsularis	Jute	India	—	58.9	13.5	15.9	—	—	—	0.5	2.8[a], 4.9[p]	[25]
Corchorus capsularis	Jute	India	57.6[c]	—	21.3	17.0	—	1.1-1.8	—	0.3-5	—	[27]
Corchorus capsularis	Jute	Bangladesh	21-24[m]	58-63	12-14	18.8	—	—	—	—	—	[21]
Umbelliferae												
Cicuta maculata	Water hemlock	MD	48.9[d]	31.6	—	—	4.3	—	34.4	—	—	[23]
Daucus carata	Wild carrot	MD	42.8[d]	28.0	—	—	9.7	—	45.9	—	—	[24]
Heracleum lanatum	—	MD	45.6[d]	30.4	—	—	5.9	—	36.2	—	—	[23]
Pastinaca sativa	Parsnip	MD	46.0[d]	29.8	—	—	7.0	—	40.2	—	—	[22]
Pituranthos tortuosa	—	Israel	42.6[d]	28.0	—	—	6.4	—	37.7	—	—	[22]
Urticaceae												
Boehmeria cylindrica	Bog hemp	NC	42.5[d]	28.8	—	—	9.0	—	42.0	—	—	[22]
Boehmeria nivea	Ramie	LA	53.5[d]	37.7	—	—	7.1	—	33.2	—	—	[22]
Boehmeria nivea	Ramie	India	—	86.9	0.5	—	—	—	—	1.1	0.6[a]	[25]
Boehmeria nivea	Ramie	—	76.2[c]	—	0.7	3.9	—	—	—	—	2.1[k], 6.4[e]	[19]
Laportea canadensis	—	NC	40.3[d]	28.6	—	—	12.9	—	47.0	—	—	[22]
Verbenceae												
Verbena hastata	—	CT	43.2[d]	25.5	—	—	4.6	—	40.1	—	—	[22]
Verbena urticifolia	White vervain	MD	47.3[d]	29.4	—	—	6.5	—	36.8	—	—	[22]
Other fibers												
Botanical name not given	Seed flax tow	India	47.0	34.0	23.0	25.0	—	—	—	2-5	—	[17]
Botanical name not given	Sabai	—	54.5	—	22.0	23.9	4.1	9.5	39.7	6.0	—	[11]
Botanical name not given	Sabai	—	54-57	—	17-22	18-24	—	—	—	5-7	3-4[s]	[17]
Botanical name not given	Mesta	India	—	60.0	10.1	14.8	—	—	—	0.7	4.8[a]	[25]
Botanical name not given	Roselle	India	—	59.7	9.9	15.0	—	—	—	0.5	4.8[a]	[25]
Botanical name not given	Dhaincha	India	—	63.6	16.3	9.8	—	—	—	0.7	1.2[a]	[25]
Botanical name not given	Bhindi	—	—	53.5	10.4	21.0	—	—	—	1.3	4.9[a]	[25]
Botanical name not given	Palmyrah	—	40-52[c]	—	42-43	—	—	—	—	—	—	[26]
Botanical name not given	Talipot	India	67-68[c]	—	28-29	—	—	—	—	—	—	[26]
Botanical name not given	Bhabar	India	53.8[c]	—	22.2	24.0	—	15-33	—	4.8-5.0	—	[27]

Table 5.4 Chemical Properties of Agro-based Fibers

Fibers		Variety/or Place of growth	Cross & Bevan Cellulose	α-Cellulose	Lignin	Pento-sans	Solubility			Ash	Others	Ref.
Botanical name	Common name						Alcohol Benzene	Hot Water	1% NaOH			
Botanical name not given	Groundnut husk	India	50.6[c]	—	30.6	11.1	—	5-11	—	2-5	—	[27]
Botanical name not given	Munj	Pakistan	58.2[c]	—	20.5	23.7	—	6-10	—	2-3	—	[27]
Botanical name not given	Bindi	—	81.0[c]	—	9.4	—	—	—	—	0.6	0.3[w]	[31]

[a] Acetyl
[c] Cellulose
[cc] Crude cellulose
[d] Monoethanoamine procedure
[e] Extractives
[h] Holocellulose
[i] Insoluble ash
[k] Pectins
[m] Hemicellulose
[o] Protein
[p] Polyuronide
[s] Silica
[t] Total ash
[u] Uronic acid
[w] Wax

Table 5.4 Chemical Properties of Agro-based Fibers

Botanical Name	Common Name	Holo-cellulose	Cross & Bevan Cellulose	α-cellulose	Pento-sans	Klason Lignin	Solubility 1% NaOH	Solubility Hot Water	Solubility EtOH/ Benzene	Ether	Ash	Ref
Hardwoods												
Acer macrophyllum	Bigleaf maple	—	—	46.0	22.0	25.0	18.0	2.0	3.0	0.7	0.5	[33]
Acer negundo	Boxelder	—	—	45.0	20.0	30.0	10.0	—	—	0.4	—	[33]
Acer rubrum	Red maple	77.0	61.0	47.0	18.0	21.0	16.0	3.0	2.0	0.7	0.4	[33]
Acer saccharinum	Silver maple	—	56.0	42.0	19.0	21.0	21.0	4.0	3.0	0.6	—	[33]
Acer saccharum	Sugar maple	—	60.0	45.0	17.0	22.0	15.0	3.0	3.0	0.5	0.2	[33]
Alnus rubra	Red alder	74.0	—	44.0	20.0	24.0	16.0	3.0	2.0	0.5	0.3	[33]
Arbutus menziesii	Pacific madrone	—	—	44.0	23.0	21.0	23.0	5.0	7.0	0.4	0.7	[33]
Betula alleghaniensis	Yellow birch	73.0	64.0	47.0	23.0	21.0	16.0	2.0	2.0	1.2	0.7	[33]
Betula nigra	River birch	—	57.0	41.0	23.0	21.0	21.0	4.0	2.0	0.5	—	[33]
Betula papyrifera	Paper birch	78.0	63.0	45.0	23.0	18.0	17.0	2.0	3.0	1.4	0.3	[33]
Carya cordiformus	Bitternut hickory	—	56.0	44.0	19.0	25.0	16.0	5.0	4.0	0.5	—	[33]
Carya glaubra	Sweet Pignut hickory	71.0	—	49.0	17.0	24.0	17.0	5.0	4.0	0.4	0.8	[33]
Carya ovata	Shagbark hickory	71.0	—	48.0	18.0	21.0	18.0	5.0	3.0	0.4	0.6	[33]
Carya pallida	Sand hickory	69.0	—	50.0	17.0	23.0	18.0	7.0	4.0	0.4	1.0	[33]
Carya tomentosa	Mockernut hickory	71.0	—	48.0	18.0	21.0	17.0	5.0	4.0	0.4	0.6	[33]
Celtis laeoigata	Sugarberry	—	54.0	40.0	22.0	21.0	23.0	6.0	3.0	0.3	—	[33]
Eucalyptus gigantea	—	72.0	—	49.0	14.0	22.0	16.0	7.0	4.0	0.3	0.2	[33]
Fagus grandifolia	American beech	77.0	61.0	49.0	20.0	22.0	14.0	2.0	2.0	0.8	0.4	[33]
Fraxinus americana	White ash	—	51.0	41.0	15.0	26.0	16.0	7.0	5.0	0.5	—	[33]
Fraxinus pennsyloanica	Green ash	—	53.0	40.0	18.0	26.0	19.0	7.0	5.0	0.4	—	[33]
Gleditsia triacanthos	Honey locust	—	—	52.0	22.0	21.0	19.0	—	—	0.4	—	[33]
Laguncularia racemosa	White mangrove	—	52.0	40.0	19.0	23.0	29.0	15.0	6.0	2.1	—	[33]
Liquidambar styraciflua	Sweetgum	—	60.0	46.0	20.0	21.0	15.0	3.0	2.0	0.7	0.3	[33]
Liriodendron tulipifera	Yellow poplar	—	62.0	45.0	19.0	20.0	17.0	2.0	1.0	0.2	1.0	[33]

Table 5.4 Chemical Properties of Agro-based Fibers

Botanical Name	Common Name	Holo-cellulose	Cross & Bevan Cellulose	α-cellulose	Pento-sans	Klason Lignin	Solubility			Ether	Ash	Ref
							1% NaOH	Hot Water	EtOH/ Benzene			
Lithocarpus densiflorus	Tanoak	71.0	—	46.0	20.0	19.0	20.0	5.0	3.0	0.4	0.7	[33]
Milalenca quinqueneroi	Cajeput	—	56.0	43.0	19.0	27.0	21.0	4.0	2.0	0.5	—	[33]
Nyssa aquatica	Water tupelo	59.0	45.0	—	16.0	24.0	16.0	4.0	3.0	0.6	0.6	[33]
Nyssa syloatica	Black tupelo	72.0	57.0	45.0	17.0	27.0	15.0	3.0	2.0	0.4	0.5	[33]
Populus alba	White poplar	67.0	52.0	—	23.0	16.0	20.0	4.0	5.0	0.9	—	[33]
Populus deletoides	Eastern cottonwood	—	64.0	47.0	18.0	23.0	15.0	2.0	2.0	0.8	0.4	[33]
Populus tremoides	Quaking aspen	78.0	65.0	49.0	19.0	19.0	18.0	3.0	3.0	1.2	0.4	[33]
Populus trichocarpa	Black cottonwood	—	—	49.0	19.0	21.0	18.0	3.0	3.0	0.7	0.5	[33]
Prunus serotina	Black cherry	85.0	60.0	45.0	20.0	21.0	18.0	4.0	5.0	0.9	0.1	[33]
Quercus alba	White oak	67.0	—	47.0	20.0	27.0	19.0	6.0	3.0	0.5	0.4	[33]
Quercus coccinea	Scarlet oak	63.0	—	46.0	18.0	28.0	20.0	6.0	3.0	0.4	—	[33]
Quercus douglasii	Blue oak	59.0	—	40.0	22.1	27.0	23.0	11.0	5.0	1.4	1.4	[33]
Quercus falcata	Southern red oak	69.0	—	42.0	20.0	25.0	17.0	6.0	4.0	0.3	0.4	[33]
Quercus kelloggii	California black oak	60.0	—	37.0	23.0	26.0	26.0	10.0	5.0	1.5	0.4	[33]
Quercus lobata	Valley oak	70.0	—	43.0	19.0	19.0	23.0	5.0	7.0	1.0	0.9	[33]
Quercus lyrata	Overcup oak	—	—	40.0	18.0	28.0	24.0	9.0	5.0	1.2	0.3	[33]
Quercus marylandica	Blackjack oak	—	57.0	44.0	20.0	26.0	15.0	5.0	4.0	0.6	—	[33]
Quercus prinus	Chestnut oak	76.0	—	47.0	19.0	24.0	21.0	7.0	5.0	0.6	0.4	[33]
Quercus rubra	Northern red oak	69.0	—	46.0	22.0	24.0	22.0	6.0	5.0	1.2	0.4	[33]
Quercus stellata	Post oak	—	55.0	41.0	18.0	24.0	21.0	8.0	4.0	0.5	1.2	[33]
Quercus velutina	Black oak	71.0	—	48.0	20.0	24.0	18.0	6.0	5.0	0.2	0.2	[33]
Salix nigra	Black willow	—	61.0	46.0	19.0	21.0	19.0	4.0	2.0	0.6	—	[33]
Tilia heterophylla	Basswood	77.0	65.0	48.0	17.0	20.0	20.0	2.0	4.0	2.1	0.7	[33]
Ulmus americana	American elm	73.0	61.0	50.0	17.0	22.0	16.0	3.0	2.0	0.5	0.4	[33]
Ulmus crassifolia	Cedar elm	—	—	50.0	19.0	27.0	14.0	—	—	0.3	—	[33]

Softwoods

Abies amabilis	Forbes/Pacific silver fir	—	61.0	44.0	10.0	29.0	11.0	3.0	3.0	0.7	0.4	[33]
Abies balsamea	Balsam fir	—	58.0	42.0	11.0	29.0	11.0	4.0	3.0	1.0	0.4	[33]
Abies concolor	White fir	66.0	—	49.0	6.0	28.0	13.0	5.0	2.0	0.3	0.4	[33]
Abies lasiocarpa	Subalpine fir	67.0	—	46.0	9.0	29.0	12.0	3.0	3.0	0.6	0.5	[33]
Abies procera	Noble fir	61.0	—	43.0	9.0	29.0	10.0	2.0	3.0	0.6	0.4	[33]
Chamaecyparis thyoides	Atlantic white cedar	—	53.0	41.0	9.0	33.0	16.0	3.0	6.0	2.4	—	[33]
Juniperus deppeana	Alligator juniper	57.0	—	40.0	5.0	34.0	16.0	3.0	7.0	2.4	0.3	[33]
Larix larcina	Tamarack	64.0	—	44.0	8.0	26.0	14.0	7.0	3.0	0.9	0.3	[33]
Larix occidentalis	Western larch	65.0	56.0	48.0	9.0	27.0	16.0	6.0	2.0	0.8	0.4	[33]
Libocedrus decurrens	Incense cedar	56.0	—	37.0	12.0	34.0	9.0	3.0	3.0	0.8	0.3	[33]
Picea enlgellmanni	Engelman spruce	69.0	60.0	45.0	10.0	28.0	11.0	2.0	2.0	1.1	0.2	[33]
Picea glauca	White spruce	—	61.0	43.0	13.0	29.0	12.0	3.0	2.0	1.1	0.3	[33]

REFERENCES

Amin, M. B., Maadhah, A. G., and Usmani, A. M., Natural vegetable fibers: A Status Report, *Renewable-Resource Materials New Polymer Sources*, Carraher, C. E. Jr. and Sperling, L.H., Eds., Plenum Press, New York, 29, 1985.

Atchison, J. E., Data on non-wood plant fibers, *Pulp and Paper Manufacture, Volume 1, Properties of Fibrous Raw Materials and their Preparation for Pulping*, M. J. Kocurek, Series Editor, TAPPI Press, Atlanta, GA, XVII, 1983.

Atchison, J. E., IV, Bagasse, *Pulp and Paper Manufacture, Volume 3, Secondary Fibers and Non-wood Pulping*, M. J. Kocurek, Series Editor, TAPPI Press, Atlanta, GA, Chap. IV, 1987.

Bagby, M. O., Adamson, W. C., Clark, T. F., and White, G. A., Kenaf stem yield and composition: Influence of maturity and field storage, Report No. 58, Non-Wood Plant Fiber Pulping Progress, TAPPI CA, Report No. 6, 1975.

Bhargava, R. L. V, Bamboo, *Pulp and Paper Manufacture, Volume 3, Secondary Fibers and Non-wood Pulping*, M. J. Kocurek, Series Editor, The Joint Textbook Committee of the Paper Industry, 71, 1987.

Chawla, J. S., Poppy straw, A new source for fibre boards, *Indian Pulp & Paper*, December, 1977–January, 1978.

Chow, P., *Dry Formed Composite Board From Selected Agricultural Fiber Residues*, Food and Agriculture Organization of the United Nations, FO/WCWP/75 Doc. No. 110, 14, 1974.

Clark, T. F. and Wolff, I. A., A search for new fiber crops, XI, Compositional characteristics of Illinois kenaf at several population densities and maturities, *TAPPI*, 52(11), 1969.

Clark, T. F., Nelson, G. H., Cunningham, R. L., Kwolek, W. F., and Wolff, I. A., A search for new fiber crops; Potential of sorghums for pulp and paper, *TAPPI*, 56, 3, 1973.

Cunningham, R. L., Carr, M. E., and Bagby, M. O., Hemicellulose isolation from annual plants, *Biotechnology and Bioengineering Symp.*, No. 17, 159, 1987.

Cunningham, R. L., Clark, T. F., and Bagby, M. O., Crotalria juncea–annual source of papermaking fiber, *TAPPI*, 61, 2, 1978.

Duckart, L., Byers, E., and Thompson, N. S., The structure of a "xylan" from kenaf, *Cellulose Chem. Technol.*, 22, 29, 1988.

Eddi, M. and Shinagawa, S., Chemical compositions of coconut coir and its pulp properties, *Berita Selulosa*, XVII, TAPPI Press, 4, 1982.

Eroglu, H. and Usta, M., Oxygen bleaching of soda oxygen wheat straw pulp, *Nonwood Plant Fiber Pulping*, Progress Report No. 19, 1988.

Francia, P. C., Escolano, E. U., and Semana, J. A., Proximate chemical composition of the various parts of the coconut palm, *The Philippine Lumber*, 19(7), 1973.

Goyal, S. K. and Ray, A. K., Economic comparison of soda and soda–AQ pulping processes for cereal straw, *Non-wood Plant Fiber Pulping*, Progress Report No. 19, TAPPI Press, 1988.

Gupta, P. C., Day, A., and Mazumdar, A. K., Chemical characterization of banana (*Musa sapientum* Linn) fibre, *Research and Industries*, 17, 1972.

Hamid, S. H., Maadhah, A. G., and Usmani, A. M., Bagasse-based building materials, *Polym.-Plast. Technol. Eng.*, 21(2), 173, 1983.

Hurter, A. M., Utilization of annual plants and agricultural residues for the production of pulp and paper, *Non-wood Plant Fiber Pulping*, Progress Report No. 19, TAPPI Press, 1988.

Iiyama, K., Lam, T. B. T., Meikle, P. J., Ng, K., Rhodies, D. I., and Stone, B. A., Cell wall biosynthesis and its regulation, *Forage Cell Wall Structure and Digestibility*, Jung, H. G., Buxton, D. R., Hatfield, R. D., and Ralph, J. Eds., American Soc of Agronomy, Inc., Madison, WI, 621, 1993.

Jones, R. W., Krull, J. H., Blessin, C. W., and Inglett, G. E., Neutral sugars of hemicellulose fractions of pith from stalks of selected plants, *Cereal Chem.*, 56(5), 441, 1979.

Lewin, M. and Pearce, E. M., Volume IV: Fiber Chemistry, *Handbook of Fiber Science and Technology*, Marcel Dekker, Inc., New York, 1985.

Misra, D. K., VI, Part VI. Cereal straw, *Pulp and Paper Manufacture, Volume 3, Secondary Fibers and Non-wood Pulping*, M. J. Kocurek, Series Editor, The Joint Textbook Committee of the Paper Industry, 82, 1987.

McGovern, J. N., Fibers, Vegetable, in *Encyclopedia of Polymer Science and Engineering*, Vol. 7, John Wiley & Sons, Inc., New York, 1986.

McGovern, J. N., Coffelt, D. E. , Hurter, A. M., Ahuja, N.K., and Wiedermann, A., IX Other Fibers, in *Pulp and Paper Manufacture, Volume 3, Secondary Fibers and Non-wood Pulping*, M. J. Kocurek, Series Editor, The Joint Textbook Committee of the Paper Industry, 1987.

Nelson, G. H., Clark, T., Wolff, F., I. A., and Jones, Q., A search for new fiber crops: Analytical Evaluations, *TAPPI*, 49(1), 1966.

Nieschlag, H. J. , Nelson, G. H., Wolff, I. A., and Perdue, Jr., R.E., A Search For New Fiber Crops, *TAPPI*, 43(3), 1960. a&b

Nieschlag, H. J., Earle, F. R. , Nelson, G. H., and Perdue, Jr., R. E., A search for new fiber crops II. Analytical Evaluations, Continued, *TAPPI*, 43(12), 1960.

Obst, J., Analysis of plant cell walls, *Forage Cell Wall Structure and Digestibility*, Jung, H. G., Buxton, D. R., Hatfield, R. D., and Ralph, J. Eds., American Soc of Agronomy, Inc., Madison, WI, Chapter 7, 167, 1993.

Pandey, S. N., Anantha Krishnan, S. R., Fifty years of research 1939–89, Jute Technological Research Laboratories publication, 1990. Calcutta, India

Pettersen, R. C., The chemical composition of wood, *The Chemistry of Solid Wood*, Rowell, R. M., Ed., Advances in Chemistry Series, 20, American Chemical Society, Washington, D.C., (ACS), 1984.

Ralph, J., Hatfield, R. D., Lu, F., Grabber, J. H., Jung, H. G., Han, J. S., and Ralph, S. A., Kenaf's amazing lignin, *Proceedings of the 8th International Symposium on Wood and Pulping Chemistry*, Helsinki, Finland, Vol. 2, 125, 1995.

Sarkanen, K. V. and Ludwig, C. H. (Eds.), *Lignins: Occurrence, Formation, Structure and Reactions*, Wiley-Interscience, New York, 1971.

Satyanarayana, K. G., Pai, B. C., Sukumaran, K., and Pillai, S. G. K., Fabrication and properties of lignoncellulosic fiber-incorporated polyester composites, *Handbook of Ceramic and Composites*, Marcel Dekker, New York, 1989.

Singh, S. M., Physico-chemical properties of agricultural residues and strength of portland cement-bound wood products, *Research and Industry*, 24, 1979.

Sjöström, E., Wood polysaccharides, *Wood Chemistry, Fundamentals and Applications*, Academic Press, New York, 51, 1981.

Stamm, A.J., *Wood and Cellulose Science*, The Ronald Press Co., New York, 1964.

Touzinsky, G. F., VIII, Kenaf, *Pulp and Paper Manufacture, Volume 3, Secondary Fibers and Non-wood Pulping*, M. J. Kocurek, Series Editor, The Joint Textbook Committee of the Paper Industry, 1987, p. 106.

Upadhyaya, J. S. and Singh, S. P., Studies on neutral sulphite pulping of *Cajanus cajan, Nonwood Plant Fiber Pulping*, Progress Report No. 19, TAPPI Press, 1988a.

Upadhyaya, J. S. and Singh, S. P., Studies on soda and soda-anthraquinone pulping of *Sesbania aculeata*–The over-all reaction pattern, *Nonwood Plant Fiber Pulping*, Progress Report No. 19, TAPPI Press, 1988b.

Wakil, A. A., Jamil, N., and Younis, M. T., The characteristics of *Hibiscus esculentus* okra (Bindi) fibers, *Pakistan Journal of Science & Industrial Research*, 16(3/4), 1973.

Wiedermann, A., VII, Reeds, *Pulp and Paper Manufacture, Volume 3, Secondary Fibers and Non-wood Pulping*, M. J. Kocurek, Series Editor, The Joint Textbook Committee of the Paper Industry, 1987, 94.