Chapter 3

Pulping of Non-Woody Biomass

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Additional information is available at the end of the chapter

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Abstract

The use of trees for paper production has contributed to the problem of deforestation with radical negative impact on the environment thereby causing an imbalance in the ecosystem. An increase in the demand and consumption of paper has also induced depletion of woods resources for paper production, thus resulting in limited availability of the raw materials. This work examined the use of non-woody biomasses as alternative raw materials, which are accessible and convertible into pulp and paper of the same quality as those obtained from wood.

Keywords: biomass, pulp, non-wood, cellulose, fibre length, fibre diameter, yield

1. Introduction

Before the industrial revolution, non-woody fibres were the primary raw materials for pulp and paper production [1]. Sources of fibre then included textile rags, cotton, cereal straw, reeds, grasses and sugar cane bagasse. Non-wood materials were in use for papermaking in China almost 2000 years ago until developed countries adopted the process of producing pulp and paper from wood sources. This process was invented in Germany by Friedrich Gottlob Keller in 1840 [2]. Nowadays, about 90–91% of the world's pulp and paper production is produced from wood [1]. It involves the extraction of cellulose from either hardwood or softwood fibres. The cellulose obtained is processed into pulp, used in papermaking. The world consumption of paper has grown to about 400% in the last 40 years and continues to grow about 2.1% yearly since 2009 with North America, Europe and Asia accounting for more than 90% of total paper and paperboard consumption [3]. The steady increase in the use of paper has resulted in the utilisation of about 35% of globally harvested trees in the production of pulp and paper [4]. Statistical data for global consumption and demand for paper and cardboard from 2006 to 2015 presented in **Figure 1** indicated a rise in the use of paper and cardboard until 2009 when there was a decline. There has been further increase from 394.5 million metric tons to 410.7 million metric tons in 2015 globally.

It has been estimated globally that the consumption of paper and paperboard has continued to grow averagely at approximately 2% per annum during the past decade [6]. A projection made indicated that this trend would elongate to the current decade with an increase in the global consumption by 83 million tons from 2010 to 2020. The forecast presumed rise in the use of paper and paperboard in the low-income countries and a reduction in the consumption of paper and cardboard in the high-income countries such as North America and Western Europe in the next decades as shown in **Figure 2** [6]. However, this development has attracted a lot of concerns due to the environmental threat it portends.

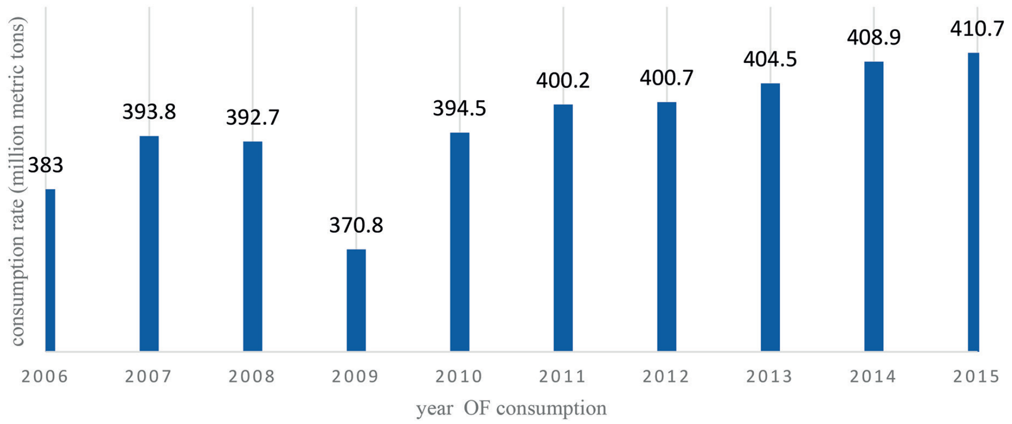

Figure 1. Global consumption of paper and cardboard from 2006 to 2015 (in million metric tons). Source: [5].

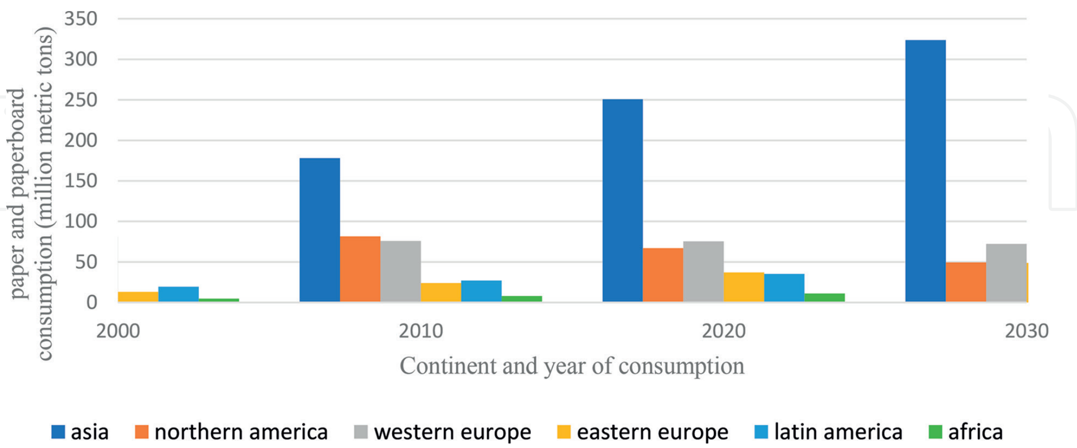

Figure 2. Paper and paperboard consumption in 2000 and 2010 and projections to 2020 and 2030 (in million metric tons). *Source:* [6].

Due to the depletion of wood resources, the use of low-cost raw materials has been introduced to serve as an alternative resource for pulp and paper production [7]. The alternative resources include non-wood fibres, such as agricultural residues and annual plants, considered as valid alternative sources of cellulose for pulp and paper production [8]. Properties that make them suitable include high yielding ability, high pulping quality, good adaptation to prevailing climatic conditions and low-cost [9].

This paper reviews the pulping and paper production from non-wood biomasses, which are mostly annual crops and agricultural residues. These materials are environmentally friendly, cheap and have an unlimited availability that can meet the demand and consumption of paper in an economy.

2. Components of plants

Chemical composition of most plant leaves and grasses have been investigated. They consist of cellulose, lignin, hemicellulose, some terpenes, resins, inorganic element and fatty acids [10]. Research carried out on these plant leaves, and grasses indicate their percentage composition of cellulose ranges from 32.6 to 88% [11]. Cellulose is a polysaccharide consisting of a linear chain of several hundred to over ten thousand linked D-glucose units. Cellulose is the main component of the primary cell wall of green plants. It was first discovered in 1838 by a French chemist Anselme Payen who isolated it from plant matter and determined its chemical formula to be $(C_6H_{12}O_5)n$ [12]. The availability of lignin in plants serves the function of minimising the accessibility of cellulose and hemicellulose to microbial enzymes and also conferring mechanical strength by creating a cross-link with other cell wall components [11]. The application of non-wood raw materials in the pulping process has a lot of advantages such as pulping capability, fine fibres (speciality papers), high-quality bleached pulps [8]. It also allows the production of pulp without an extreme increase in pollution compared to when wood raw materials are used [13].

3. Non-wood fibres and classification

In recent years, the growing interest in alternative sources of raw materials for pulping and paper production other than wood has increased. According to Wisur (1993), in 1989, only 8% of the raw material for pulp and paper production was obtained from non-wood biomass. The use of non-wood raw materials accounts for less than 10% of the total pulp and paper production worldwide [14]. This comprises of 44% straw, 18% bagasse, 14% reeds, 13% bamboo, and 11% others [15]. In developing countries, 60% of cellulose fibres originate from non-wood raw materials, which include annual plants and agricultural residues. Non-wood fibres contain more cellulose and less lignin fraction and can, therefore, digest to produce pulp at low temperatures with lower chemical charges [8]. Non-wood fibres are used to produce pulps and papers with various qualities and strength. Non-wood fibres can be produced within a year compared to the long growth cycles of wood [16]. Fibres obtained from non-wood plants are similar to those of hardwoods. It has been found that their fibres are about 1 mm long, narrow and are usually composed of lignified walls [17].

Non-wood fibres are classified into three main categories according to their origin namely; agricultural by-products, industrial crops and naturally growing crops [18]. Agricultural by-products are the secondary products of principal crops such as cereals and grains and are usually characterised by the low raw material prices and moderate quality. They include rice straws and wheat straws. The industrial crops are high in cost. They include hemp, sugarcane and kenaf and they are used in producing high-quality pulps. The naturally growing plants are bamboo, and some grass fibres such as reeds, elephant grass, and Sabai grass [19]. Based on the position of the fibre in plants, non-wood plant fibres can be classified into four types namely; grass fibres (stalk/culm fibres), bast fibres, leaf fibres, and fruit fibres [20].

3.1. Grass fibres

Grass fibres are mainly obtained from the vascular bundles in monocotyledonous stems and leaves. They can also be obtained from separate fibre strands situated on the outer sides of the vascular bundles [21]. Grass fibres for pulping and paper production are largely obtained from cereal straws, sugarcane, reeds and bamboo. The vascular tissues can be distributed in two circles as in the cereal straw and in most temperate grasses, with a continuous cylinder of sclerenchyma close to the periphery. These tissues can also be scattered throughout the stem section as in corn (*Zea mays*), bamboo, and sugar cane [22, 23]. According to Hurter [24], the average length of grass fibres is 1-3 mm, and the ratio of fibre length to width varies from 75:1 and 230:1. Wheat straw fibres (*Triticum aestivum* L.) have an average length of 1.4 mm (0.4–3.2 mm) and a width of 0.015 mm (0.08–0.034 mm) [25]. It is the most commonly used monocotyledon in commercial pulping. Fibres obtained from cereal straws such as; rye *(Secale cereal* L.), barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.) are similar to those of wheat [23]. In countries of southern and eastern Asia, rice straw (*Oryza sativa* L.) is a major resource in paper production. The major challenges in the application of rice straw are the high cost of collection and storage. Also, rice straw contains a high amount of silica. However, these drawbacks notwithstanding, rice straw is a favoured fibre source in countries with a limited supply of wood due to its availability [20, 25].

Two other important agricultural residues in this category used for pulping are bamboo and bagasse. According to Atchison [26], Bagasse is used in the production of all grades of paper. While bagasse pulp is obtained from sugarcane waste, bamboo pulp, on the other hand, is commonly made from pruned stem [23]. Bamboo appears prominently in the natural vegetation of many parts of the world. Its growth is favoured mostly in warm tropical climates, and it grows from sea level to the snow line. It possesses two distinct growth forms in which it could be single stemmed or densely clumped. From research, bamboo has been proven to be the fasted growing plants available for pulp and attain their full height of 15–30 m in 2–4 months by diurnal growth rates of 20–100 cm. Its maturity stage is reached when the culm is about 3–4 years old [20]. It has an average fibre length of 2.7–4.0 mm with an average fibre diameter of 0.015 mm. It has got vast applications in the production of printing and writing paper, Bristol board, duplex and triplex paper, wrapping paper, bag paper, multiwall and newsprint substitute [25].

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In the case of esparto grass (*Stipa tenecissima* L.), it is mostly found growing wild in the northern part of Africa and also the Mediterranean steppe areas of southern Spain. The location of fibre in this non-wood plant is the leaves. This is the region where the fibre is obtained. It occurs as long rolled up leaves with a length of about 1 m. It has a greyish green colour with a coarse and strong texture. The fibres obtained from this plant leaves are thin and round, approximately 0.01 mm in diameter and a little over 1 mm long. The lumen or canal is very tiny which makes it very springy. They are mostly used in the production of bulky, smooth and well-formed paper for fine printing and lithographic paper [25, 27].

3.2. Bast fibres

Bast fibres refer to fibres obtained from the phloem of the vascular tissues of dicotyledons [23]. Fibres obtained from hemp, kenaf, ramie (*Boehmeria nivea* L.) and jute (*Corchorus capsularis* L.) are derived from the secondary phloem located in the outer part of the cambium. In the case of flax, the fibres are mainly cortical fibres in the inner bark, on the outer periphery of the vascular cylinder of the stem [20, 22]. Flax is an annual plant cultivated in temperate climate for purposes of obtaining linseed oil and fibres. It has an average fibre length of 30 mm and an average diameter of 0.02 mm. Raw materials for flax pulp are derived from three sources namely:

- Textile wastes (old rags and new cuttings).
- Fibre waste remaining when bast fibres are removed from textile flax
- The entire plant after the removal of the seeds from seed flax.

The raw material obtained from the textile waste is of the purest form while that obtained from the entire plant after the seeds are being removed is of low quality and is known as seed flax tow [25]. Blended flaxes in various proportion serve important purposes in the production of speciality papers like book paper, lightweight printing and writing paper, condenser paper, currency and security paper, and cigarette paper.

Jute is characterised by high cellulose content with long fibres. It is primarily grown in Asian countries such as China, India, Thailand, Bangladesh and it attains a height of 2.5–3.5 m when fully grown. It possesses an outer bark comprising of about 40% of the stem by weight, and it is mainly used in the production of low value-added products such as ropes, cordage and gunny sacks [28]. Jute fibres have an average fibre length of 2–5 mm and an average fibre diameter of 0.02 mm. When blended into various proportions, it is used in printing and writing paper, tag, and wrapping and bag paper [20].

Hemp (*Cannabis sativa*) is an annual plant, which grows up to a height of 4.5 m. The fibre consists of 35% long bast fibres and 65% short core fibres [29]. The male plant of hemp produces more fibres compared to the female, which is known to produce more of seeds. This is due to the rapid lignification process which occurs in the female plants. Hemp plant attains maturity within 80–150 days and must be harvested at the proper time in other to be able to maximise its fibre quality. Early harvesting results in reduced yield and weak fibres, whereas delayed harvesting can produce stems that are difficult to separate during the process of retting. Fibres obtained from hemp have a length ranging from 15 to 55 mm and an average length of 20 mm.

The fibres are distinguished by having forked ends with a varying diameter between 0.016 and 0.22 mm [25]. It has found application in the manufacturing of speciality papers.

Kenaf (*Hibiscus cannabinus*) is a tropical crop native to Africa. It consists of an outer fibrous bark and an inner woody core. It is composed of approximately 65.7% cellulose, 21.6% lignin and pectin [30]. Pulp obtained from kenaf through Kraft, soda, or neutral sulphite is of more quality and superior to pulps obtained from commercial hardwood. Except for tear, it is comparable to softwood Kraft pulps and superior to softwood pulps [31]. The fibres obtained from bast (outer bark) are 3–4 mm long while those from the core are 0.6 mm long [32]. They are applicable in the production of newsprint, multi-sack, tissue paper, bleached paperboard, and other lightweight speciality papers.

3.3. Leaf fibres

Several plants have leaves containing fibres that are suitable for papermaking. Fibres obtained from leaves and leaf sheaths of several monocots, tropical and sub-tropical species are referred to as leaf fibres [33]. Some of these fibres produce papers with excellent qualities. The common plants in this category include abaca (Manila hemp) (*Musa textilis*) and sisal (*Agave sisalana*).

Strong Manila hemp or Abaca is plant grown mainly in the Philippines, and its fibre is obtained from leaf sheath of a banana-like-plant. The propagation of this plant is done through suckering or growing of shoots from roots. It attains maturity after 18–24 months after planting and can be harvested, and the fibres can be obtained and isolated to produce pulp.

The quality of abaca pulp is affected by the type of cleaning, which determines the grade of fibres [25]. Pulp isolated from the highly graded fibres are used in the production of high strength speciality tissues, such as tea bags and meat casings while fair to residual grades of fibres obtained are made into pulp for making speciality papers with high tear and tensile strengths such as vacuum bags and wrapping papers [34].

Sisal is a non-wood leaf native to Mexico. It has successfully thrived in semiarid regions of Brazil, Tanzania and Kenya. Sisal leaves have a width of about 10 cm, length of about 1–1.5 m and weight of 500–700 g. Sisal leaves are harvested manually and are transversely cut to 50 mm length before being hammer milled. The juice and pitch are removed through vertical screens and chaffed sisal fibres are transported by conveyors to the drying process. When the sisal fibre is thoroughly dried, it is then pressed into bales for pulping [25].

3.4. Fruit fibre

Fruit fibres are obtained from unicellular seed or fruit hairs. They are also referred to as the seed hair fibres. The most important is cotton fibre which is formed by the elongation of individual epidermal hair cells in seeds of various *Gossypium* species [33]. Cotton fibres come from the seedpod of cotton plants. Regular cotton fibres are too long and too expensive for conventional papermaking. The average fibre length of cotton fibres is 25 mm, and the average fibre diameter is 0.02 mm. It is used in the production of high-grade bond ledger book and writing paper [25].

Borassus (Palmyra palm) is another example of fruit fibre. It is native to tropical African and part of southern Asia. The mesocarp of Palmyra palm fruits is the fibrous material that can serve as a raw material for pulp and papermaking. Palmyra palm fruit fibres possess adequate properties that make it suitable as an alternative raw material of cellulosic pulps for papermaking [35].

3.5. Characteristics of non-wood fibre

Most non-wood fibre commonly used in pulp and paper production is obtained from annual plants, which attain pulp size (growth) within a short period. This makes their availability sufficient for papermaking in contrast to wood fibres, which takes years to grow to pulpable size [36]. Some exceptions in this category of non-wood fibres that do not grow within a short period include bamboo, sisal, hesperaloe etc. These fibres take a longer period to grow to size required for pulping. Various non-wood pulp can be grouped into two main categories:

- the common non-wood or hardwood substitutes and
- the speciality non-wood fibres or softwood substitutes

Major examples of the common non-wood fibres pulp include cereal straws, sugarcane bagasse (*Saccharum officinarum*) bamboo, reeds and grasses, kenaf, corn stalks (*Zea mays*), sorghum stalks etc. There are several types of cereal straws used in pulping and papermaking processes. They include straws from rye (*Secale cereale*), oat (*Avena sativa*) and barley (*Hordeum vulgare*). Of all these straws, rye is the most suitable for pulping. It is generally available and used to produce paper with high strength properties [9]. Speciality non-wood fibres include cotton stalk (*Gossypium*) and linters (flax, hemp) and kenaf bast fibres, abaca, bamboo, hesperaloe etc. [36]. The presence of lower lignin content and higher cellulose content in some of these non-wood plants, which include kenaf [31, 37], hemp [29, 38], jute [28], reed, bamboo [39] has been subject of many research works.

Non-wood plants like kenaf (*Hibiscus cannabinus* L.) and giant reed (*Arundo donax* L.) internodes give very good values in properties, which are comparable to some softwood and most hardwood species. Limitation in the use of some non-wood plants such as; cotton, miscanthus, switchgrass etc. is occasioned by their short fibres. Nevertheless, they possess other complementary qualities such as satisfactory slenderness ratio. Fibres obtained from reed internode (70.5 mm) are shorter compared to those obtained from kenaf bark (105.9 mm). These fibres have good slenderness ratio, close to those of some hardwoods (55–75 mm). They also have acceptable Runkle ratio. Owing to their low flexibilities, their properties such as tensile, bursting strengths as well as folding endurance are negatively affected. Node fibres show, less advantages in its use for pulp and paper production due to their shorter and thicker fibre production [40].

These non-wood plants have varying physical and chemical characteristics. Some monocots such as cereal straws, sugarcane bagasse and corn stalks have been compared to the hardwoods and are found to have similar fibre fractions as contained in the hardwoods [36]. The monocots have been investigated to contain a significant proportion of very thin-walled cells, barrel-shaped parenchyma cells, and vessel with fine epidermal cells in a wide range of dimensions [36]. On the other hand, dicots such as flax straw, kenaf and hemp contain two distinct fibre types. These include; an inner core of short fibres surrounded by a layer bast fibres in which the core fibres are mainly composed. Pulping process is so tedious in these samples due to high lignin content attributed to core fibres.

3.6. Morphological and chemical properties of non-wood fibres

Morphological and chemical characteristics of non-wood fibres have an essential role in the technical aspects involved in paper production. Rousu and Rousu [41] stated that the technical issues are related to the economic, environmental and ethical contexts. Morphological is based on the cell wall characteristic from which the fibre is derived. Anatomically, plant fibres are composed of narrow, elongated sclerenchyma cells in which most of the matured fibres have well developed usually lignified walls responsible for support of the plant [23]. The length and width of the fibre are important morphological characteristics, which can be used in estimating the pulp quality of fibres. Fibres suitable for pulp and paper production possess an estimated fibre length to width of about 100:1. This is different in other fibre such as the textile fibre with a fibre length to width ratio of about 1000–1 ratio. This ratio in coniferous trees (softwood) is 60–100:1 and in deciduous trees (hardwood) it is 2–60:1 [24, 36]. The average fibre length ranges from 1 to 30 mm being shortest in grasses and longest in cotton [23]. The average ratios of fibre length to diameter range from 50:1 to 1500:1 in non-wood species. In general, stalk fibres are short, having fibre lengths and length to diameter ratios of the same order as hardwoods. They also tend to be more heterogeneous and exhibit a wider distribution of lengths and length ratio to diameter ratio of hardwoods [24]. Mostly all non-woods are composed of a lower lignin content with a higher hemicellulose content. The varying chemical composition in these non-wood plants depends on the type of soil and the growing conditions, which could involve the climatic conditions [42]. Non-wood fibres have higher silicate, nutrient and hemicellulose contents than that present in wood [43]. **Table 1** contains summarised information on essential morphological properties of various non-wood fibres for pulping.

As reported by Rousu and Rousu [41], low bulk density, short fibre length and high content of fines are most important features of non-wood raw materials. The low bulk density affects the logistic of non-wood raw materials thereby restricting the size of the mills to be considerably smaller than that of the woody materials. It was emphasised that presence of large number of fines and short length of fibres affect especially the drainage properties of the pulp and dewatering process of the paper machine. Plants like miscanthus, switchgrass and cotton stalks show shorter fibres compared to the length of fibres from kenaf and reed. Pulped fibres of miscanthus and switchgrass results in satisfactory pulp tear indices and bursting strengths for producing papers with good printing and writing purposes [40]. These properties are also applicable to kenaf bark fibres. **Table 2** shows additional common properties of non-wood plant fibres while **Table 3** depicts properties of papers produced from some non-wood plant.

The most important physical properties of non-wood fibres are the presence of short fibres ($\leq$ 2 mm) and low bulk density with a high content of fines. These properties are responsible for the drainage properties of the pulp and also dewatering in the paper machine [8]. The strength and rigidity of papers produced are affected by the lumen size and cell wall thickness of the fibres. **Table 4** shows the mechanical properties of some selected non-wood plants such as the bast fibres and seed fibres.

	Pulping Process	Pulp yield (%)	Uses	Morphological properties			Chemical properties					
				Kappa number	Length (mm)	Fibre diameter (μm)	Lignin (%)	Ash (%)	Silica (%)	Alpha cellulose (%)	Pentosans (%)	Cross & Bevan cellulose (%)
Stalk fibres												
Cereals												
Rice[a]	Soda[d]	40–43 39[d]	Paper		1.48	13	12–16				23–26	43–49
Rice[b]		38.8		13.6	1.48	13						
Wheat	Soda[d]	39–62 67[d*]			1.48	13	16–21	4–9	3–7	29–35	26–32	49–54
Wheat[b]	Soda[d]	46.7 50[d]		16	1.4[b]	13						
Rye					1.48	13	16–19	2–5	0.5–4	33–35	27–30	50–54
Oats					1.48	13	16–19	6–8	4–7	31–37	27–38	44–53
Barley					1.48	13	14–15	5–7	3–6	31–34	24–29	47–48
Mixed cereal straw	Lime Lime Soda or Kraft Soda or Kraft	55–65 70–82 44–46 65–68	Coarse paper Strawboard Paper corrugation			12.9[d]						
Corn[b]		50.5		23.4		18						
Cotton[b]		44.5		33		20-30						
Grain sorghum												
Hesperaloe												
Grasses												

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				Morphological properties			Chemical properties					
	Pulping Process	**Pulp yield (%)**	**Uses**	**Kappa number**	**Length (mm)**	**Fibre diameter (µm)**	**Lignin (%)**	**Ash (%)**	**Silica (%)**	**Alpha cellulose (%)**	**Pentosans (%)**	**Cross & Bevan cellulose (%)**
Esparto	Soda Soda[d]	45–50 52[d]	Paper		1.10		17–19	6–8	2–3	33–38	27–32	50–54
Sabai	Soda	45–50	Paper		2.08		17–22				18–24	54–57
Lemon												
Switchgrass					1.37 0.76[c]		34–36	1.5–2		43	22–24	
Miscanthus												
Reeds												
Papyrus	Soda	38–35			1.50							
Phragmites	NSSC	50–53	Paper				22				20	57
Communis reeds	Soda or Kraft	46–51 53[d***] 62[d]	Paper		1.50		22	3	2	45		
Arundo donax					1.18		21	4–6	1.1–1.3	29–33	28–32	
Elephant grass[c]					0.75[c]							
Canes												
Sugar cane (bagasse)	Soda or Kraft	60 70 63 50–52	Industrial paper Corrugating Linerboard Bleached paper		1.51[c]-1.7	20	19–24				27–32	49–62

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				Morphological properties			Chemical properties					
	Pulping Process	Pulp yield (%)	Uses	Kappa number	Length (mm)	Fibre diameter (μm)	Lignin (%)	Ash (%)	Silica (%)	Alpha cellulose (%)	Pentosans (%)	Cross & Bevan cellulose (%)
Bagasse[b]		50.5		13.3	1.7	20[d]		1.5–5	0.7–3	32–44		
Bamboo	Soda	44–45	Paper		1.36–4.03	8–30	21–31	1.7–5	1.5–3	26–43	15–26	57–66
	Kraft	46–47 45[d]	Paper									
Bamboo[b]		45.9		24.6	2.7	14.4[d]						
Bast fibres												
Textile flax tow	Soda	60–67	Paper		28	21	10–15	2–5	<1	50–68	6–17	76–79
Seed flax tow	Soda	42–45	Cigarette paper		27	22	23	2–5		34	25	47
Kenaf	Soda or Kraft	46–51	Paper		2.74	20	15–18	2–5	<1	31–39		
Jute 1	Lime	62	Industrial paper		1.06	26	21–26	0.5–1		39–42	18–21	57–58
	soda	55	paper									
Jute 2					2	20						
Whole jute[b] plant		55.6		30.3		20						
Common hemp			Cigarette paper, Strength additives to waste paper, Light weight papers		20	22						
Leaf fibres												
Abaca	Monosulphite	60–63	Thin paper			20	9	1	<1	61	17	78
	Soda or Kraft	45–54	paper									

	Pulping Process	Pulp yield (%)	Uses	Kappa number	Length (mm)	Fibre diameter (µm)	Lignin (%)	Ash (%)	Silica (%)	Alpha cellulose (%)	Pentosans (%)	Cross & Bevan cellulose (%)
				Morphological properties			**Chemical properties**					
Sisal	Soda	69	Paper			17	8–9	0.6–1	<1	43–56	21–24	55–73
Seed hull fibres												
Cotton staple	Soda or Kraft		Paper			20						
Cotton linters	Soda or Kraft		Paper Dissolving pulp			21						
Cotton rags	Lime soda Soda		Paper paper									
Golpata fronds[b]		37.2		27.2	1.73	10						
Kash[b]		57.9		20	1.52	16						
Dhanicha[b]		43.3		29								
Banana stem[c]					1.55[c]							
Date palm rachis[c]					0.89[c]							
Core fibres												
Kenaf					0.6	30	17.5				19.3	
Woods												
Coniferous					3.0	30	26–34	1	<1	40–45	7–14	53–62
Deciduous					1.25	25	23–30	1	<1	38–49	19–26	54–61

[a][36], [b][2], [c][7], [d][8, 25, 29]. *uncleaned fibre, ***clean reeds, [10, 24, 44].

Table 1. Morphological properties and chemical properties of non-wood fibres [36].

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Non-wood plants	Cold water solubility	Hot water solubility	1%NaOH	Lumen Diameter	Cell wall thickness	Alcohol/benzene extractives %	Bulk density (kg/m³)
Prosopis alba		4.7	20.8				
Chamaecytisus		3	16.1				
Phragmites		5.4	34.7				
Retama monosperma		3.8	16.9				
Arundo donax		6.7					
Banana pseudo-stems		5.4					
Paulownia fortuna		9.6	31.5				
Wheat straw	5.8–11	14	41–42.8			0.5	
Rice dishes	10.6	13	49.1				
Barley fodder	16	16	47				
Rye straw	8.4	9.4	37.4				
Oat straw	13.2	15	41.8				
Sorghum stalks		21.7	41.6				
Amaranth	23.5	28	46.8				
Orache	4.6	6.5	27.5				
Jerusalem artichoke	26.6	31	48.5				
Cynara cardunculus L.		10					
Miscanthus sinensis		9.1		3.7–8.9	3.3–4.9		
Kenaf							1220–1400
Kenaf core				9.6–16.8	3.6–5.0		
Kenaf (whole)				12.7	4.3		
Date palm rachis	5.0	8.1	20.8				
Posidonia oceanica	7.3	12.2	16.5				
date palm leaves		10.8	29.9				
Switch grass				1.9–9.7	5–6	1.1	
Cotton				9.9–15.7	2.7–4.4		1550
Reed (nodes)				6.3–10.9	2.7–4.1	1.1	
Bagasse							550–1250
Hemp							1400–1500

Source: [40, 45–47].

Table 2. Additional common fibre properties of some non-wood plants.

	Density (kg/m³)	Brightness	Tensile (kNm/kg)	Burst (Kpa)	Tear index (Nm²/kg)	Folding endurance
Poplar	669–683.4	77.1–77.9	47.9–52.1	189–211.4	5.5–6.1	25.4–30.6
Willow	698–709.4	74.8–76.2	58–61.8	248–264.8	4.2–5	50.1–63.9
Switchgrass	824–854.8	78.1–79.1	86.4–96.4	389–415.6	5–5.6	1093–1169
Alfalfa	719.9–742.2	79.2–79.8	97.2–106.8	510–548.6	5.6–6.6	491.2–544.8

Source: [48, 49].

Table 3. Paper properties of some bleached non-wood plants.

Properties	Tensile strength (Mpa)	Specific tensile strength (Mpa)	Young's modulus (Gpa)	Specific Young's modulus (Gpa)	Failure strain (%)
Abaca	12		41		3.4
Banana	529–914	392–677	27–32	20–24	1–3
Pineapple	413–1627	287–1130	60–82	42–57	0–1.6
Sisal	80–840	55–580	9–22	6–15	2–14
Bamboo	575	383	27	18	
Flax	500–900	345–620	50–70	34–48	1.3–3.3
Hemp	310–750	210–510	30–60	20–41	2–4
Jute	200–450	140–320	20–55	14–39	2–3
Kenaf	295–1191		22–60		
Ramie	915	590	23	15	3.7
Coir	106–175	92–152	6	5.2	15–40
Cotton	300–700	194–452	6–10	4–6.5	6–8
Kapok	93.3	300	4	12.9	1.2

Source: [48].

Table 4. Mechanical properties of some non-wood fibres.

Fibres with large lumen and thin walls tend to flatten to ribbons during pulping and papermaking, thereby causing a good contact between the fibres and consequently having good strength characteristics [50]. The low bulk density of the non-wood raw materials makes it easy to access the amount of cellulose contained compared to wood raw materials. The chemical composition of the non-wood fibrous raw materials also varies over a broader range than wood (**Table 1**) [24]. Analysis obtained in the past has not produced a consistent data about the actual chemical composition of these non-wood plant materials. According to Hurter [24], plant stalks like cereals, grasses, reeds and bamboos have high pentosan contents higher than the pentosan content of hardwoods. The lignin content in some cases could be the same or lower than the content present in wood materials. In corn stalk fibres, it is reasonable to

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assume that lignin is the principal binding material. Delignification of this fibre result to an increment in the fineness and a corresponding decrease in the strength of the fibres. The complete removal of lignin results in the single cells that are too small to be suitable for high-quality fibrous applications [51]. Ash and silica content is high, and this is exceptionally feasible in rice straw. The high amount of hemicellulose content contributes to little stiffness and strength of fibres during paper production [52].

The chemical composition of most non-wood raw materials explains the feasibility of these materials in pulp and paper production. The fibres, which are the most valuable constituents in pulp production, are embedded within the cell walls of the plants. The amount of fibres obtained is dependent on the cell walls [44, 53]. Cellulose is the principal component of cell wall and fibre. Other parts include lignin, pectin, hemicellulose, proteins and certain minerals which are contained in the epidermal cells [53, 54]. Variations in cell walls of plant species and plant parts result in differences in pulping properties of the plant materials [33, 44]. Some of the non-wood fibre plants have properties compared to hardwoods as they contain more pentosans (over 20%), holocellulose (over 70%) and less lignin (about 15%) [55] with higher hot water solubility gotten from the easy accessibility of cooking liquors. Grasses and annual non-wood plants have lower lignin content which enables lowers the requirement of chemicals for cooking and bleaching [44, 55].

The chemical composition of some non-woody fibres used for pulp and paper production was examined in other to determine their qualities, and to improve the industrial processes in which these fibres are used as raw materials. The chemical composition of plant materials for pulp and paper production which are most commonly determined includes holocellulose (total cellulose), ethanol-benzene extractives (this contains terpenes, resins, and fatty acids), 1% NaOH extractives (low molecular weight carbohydrates), lignin, and ash content. These compositions are analysed majorly using some conventional methods which have been identified in most literature [11];

- Holocellulose: The holocellulose content of plant fibre is determined using the Norman and Jenkin's standard method. During this analysis, the dry ground raw material of 40–60mesh is prepared and extracted using alcohol-benzene combination. The known weights of the fibrous material are treated with a sequence of the mixture of hypochlorite and sulphite to remove other binding materials. High content of holocellulose contained in a plant fibre results in a high yield of pulp when extracted with suitable pulping technique.
- Ethanol-benzene extractives: The method of determination of these extractives involves the use of Soxhlet extraction of the air-dried plant materials with a combination of ethanol and benzene at 1:2 v/v for about 8 hours. This method is a standard method of analysis known as the standard Tappi method T204 om-88. Plant fibres with a high content of ethanol-benzene extractives tend to leave stains on the paper sheet during papermaking process. The presence of dyes is as a result of precipitation of these extractives upon pulping [46].
- 1%NaOH Extractives: In determining this, the standard method T212 om-88 is used. This is the most common method of analysis which has been employed. It involves the extraction of the air-dried raw materials with 1% of NaOH solution to remove and determine the low

molecular weight carbohydrates. An appropriate mass of the material is then treated with hot NaOH solution (1%) for 1 hour. The extract obtained is then evaporated to dryness, and the residues are determined gravimetrically. Fibres with a higher amount of these extractives tend to produce medium to low pulp yield [46].

- Lignin: This is determined by cold treatment of dry residues from the alcohol-benzene Soxhlet extraction with concentrated sulphuric acid. Lignin is then precipitated by refluxing in diluted acid, and its content is determined gravimetrically. This method of analysis is known as the Norman and Jenkins' method.
- Ash content: This is determined gravimetrically by drying the plant material and combusting it at 525°C in a muffle furnace. This method of analysis is the TAPPI standard method T211 om-93. When the ash content determined in a plant fibre is high, there may be difficulty in refining and recovery of the cooking liquor [46].

The chemical composition varies depending on the non- wood species and the local conditions such as soil and climate, but non-wood materials have higher silicon, nutrient and hemicellulose contents than wood [43]. Owing to these reasons, non -wood materials are pretreated. Part of the leaves and non-fibrous materials may be removed, and this has a positive influence on the ash content and properties of the pulp and paper. Judt [43], explained that the chemical composition of these non-wood materials remains different from that of wood.

The qualities of the pulp to be used in paper production, depends on the morphological characteristics of the fibre obtained from the non-woody plants used as raw materials. These characteristics include the fibre length, width and some other relevant parameters, necessary for estimating pulp properties and qualities. The higher the fibre length, the higher the tearing resistance of paper. Reports made by most researchers show that flax has almost the highest fibre length [10, 24]. The fibre length contributes to the tearing strength of the paper [10]. The strength of paper also depends on the lignin and cellulose content of the raw plant materials. The pulp mechanical and tensile strength is a function of the content of cellulose present in the plant material. The physical characteristics of the fibres are influenced by the functions individual fibres have to perform in the plant itself. These functions include conduction of sap, strengthening of the stalk, and water-proofing the surface of the plants [43]. Presence of a large number of fines and short fibre length affect mostly the drainage properties of the pulp and also the process of dewatering in the paper machine. The primary components of ash content present in most non-wood fibres are the inorganic contents of the plant. This includes different metal salts such as carbonates, silicates, oxalates, silicon, magnesium, calcium, iron, manganese and potassium phosphate. Presence of ash content in vast quantities contributes to the low yield of pulp after the pulping process is carried out [52].

Fines in pulp from bamboo consist of thin-walled cells which collapse easily. The presence of these fines in the pulp tends to strengthen the fibre to fibre bonds in the unbeaten and lightly unbeaten state. These fines in bamboo pulp also give the unbeaten pulp lower freeness value than fines-free pulp. This is a different case in bagasse pulp. Fines in bagasse pulp are mostly pith elements. The wetness and the drainage time of bagasse pulp increase considerably when the number of fines from pith elements is increased. Pulps containing such fines have longer drainage time and this reduces the capacity in the filtering and washing steps of the pulp production and also lowers the paper machine capacity. Fines in pulps of both wood and non-wood fibres may be used to give the final sheet of paper a smooth surface and a high light scattering which are desired properties of paper used for printing. The yield of fibres from leguminous plants is reported [17] too low for being a source of fibre for pulp and paper production.

Report from Marques and Rencoret [10] showed that flax and hemp have extraordinary lengths of fibres as high as 2.8 mm. They have been used traditionally as primary furnish for cigarette paper (burning tube), where strength, opacity and control of air permeability are required. They are used to enhance the strength characteristics of banknote paper. Jute pulp is used for high porosity papers. Its fibre length and diameter make it suitable for finishing paper purposes. Sisal and abaca pulps have an unusually high tearing resistance and high porosity and are well suited for the production of papers with high strength and high porosity. Ibarra and Köpcke [56], reportedly characterised hemicelluloses as undesirable impurities obtained when dissolving pulps and this affects the cellulose processing ability.

4. Sources, handling, forms and preparation of non-wood materials

The handling, storage and preparation of non-wood raw materials for pulping differ in most cases from the well-established systems used for wood pulping processes. In mills using non-wood raw materials, the major drawback is the storage, handling and the process of preparing of these materials. This is because most of these plants (reeds, bamboo, and some grasses) are harvested explicitly for the aim of producing pulp and paper. The non-wood raw material preparation includes chipping (sawmill residue), digesting, washing, screening, cleaning and other processes such as depithing (when bagasse is used as raw material) before processing in the paper machine or pulp drier.

Small bamboos and reeds are handled and stored in bundles while the large bamboos are handled and stored in ranked piles as the woods are stored [24]. The harvested grasses are usually baled for transportation unlike cereals, which are baled before being transported to the mill, and are stored in bale form in large piles. Sugarcane bagasse is obtained from the sugar mills after which sugar cane is being processed, and the residue (bagasse) is collected and baled for storage. Here enlisted various forms of fibres from leaf and bast fibrous raw materials are presented. These include;

- Rags, sacking, ropes, twine and threads made from leaf and bast fibres
- Waste (tow) from the preparation of leaf and bast fibres for textile and rope production
- Waste from the actual manufacture of textiles and ropes
- The retted bast ribbons or stripped leaf fibres that are the raw materials for textile and rope manufacturing
- The whole plant

Cases whereby the whole plant is processed at the pulp mill for the production of bast fibres pulp, there is a high necessity for the removal of the bast fibrous material from the woody stem and also the removal of the leaf fibrous material from the fleshy materials of the leaves. In other cases, the separation or removal has been made, and it would not be necessary. The pulp obtained after the entire stem of kenaf plant is chipped and pulped, is composed of a mixture of both long blast fibres and short fibre pulp from the woody core [24, 25].

Large bamboos are sometimes crushed and chipped, or simply chipped in disk chippers similar to those used for wood or in large drum chippers. In other to attain more excellent results, the chippers for bamboo should be coupled with a force feed. After the chips are obtained, they are then screened stored before pulping in bins. The dust generated during the chipping process is usually collected as used as fuel in the mill boilers [24]. In most cases, reeds and small bamboos are cut in cutters similar to those used for cereal straws, but these cutters are of heavier designs. Air separation stage is required for the removal of leaves from the reeds since there are a lot of leaf materials which are attached to the stalks. This is an important process included in the reed screening system. The chips obtained from bamboo and reeds are usually stored in live bottom bins or bins with travelling screws at the bottom.

Special cutters are employed in the cutting of cereal straws, after which the cut hay is cleaned and screened by pneumatic and mechanical screening systems designed for this purposes [24]. The straws are then hammer milled using hammer mills of special designs which are used to break the bales and cut the straw to the desired length. In most cases, the straw cutting and preparation may be operated only during digester filling. Rice straw contains a lot of impurities such as dirt and leaf materials. For this reason, it is subjected to a wet cleaning stage in addition to the standard dry cleaning process [24]. The difference in the genetics of the biomass can result in variation and the quality of the pulp when the entire plants are used in the pulping process [20].

Before cooking is done in the pulp mill, separation of dust leaves and dirt is done using air fractionation. The bleaching quality of the pulp is improved by the use of mechanical pretreatment in which favours the decrease or removal of the silica and other unwanted particles from the raw material [44]. In Sweden, a dry fractionation system was developed which is composed of a shredding, chopping, milling compartment in a disc mill and also used for the screening of reed canary grass.

Bio-pulping is the treatment of lignocellulosic materials with oxidative lignin-degradation fungal enzymes before the pulping process. This is carried out to increase the strength of the paper and reduce the consumption of energy and also prevent environmental threats. It involves the use of some enzymes such as lignin and manganese peroxidase for oxidative biodegradation processes. Besides the mechanical fractionation fines (small particles other than fibres) are decreased by treating the biomass with white rot fungi (*Phobia radiate* Fr., *P. tremellosa, Pleurotus oestreatus Jacq., Ceriporiopsis subvermispora*) in oxygenated bioreactors before chemical pulping is carried out [57]. This involves the decomposition of lignin and attack of the cellulose contained in the material by fungi by the breakdown of the parenchyma cells thereby decreasing the number of fines [44].

5. Pulping processes

Alila and Besbes [58], reported that non-wood plants generally have lower lignin contents, shorter growing cycles with moderate irrigation requirements, annual renewability and a high annual yield of cellulose compared to wood. Pulping of non-wood plants is of more advantage compared to wood fibre in such that non-wood materials can be pulped with simple chemical systems (caustic soda). The alkali charge required for these materials is normally lower than what is required for wood-based raw material in which the same degree of delignification is achieved thereby reducing the energy required during this process. The pulping strategies which are commonly used for pulp extraction are categorised as mechanical, thermal, semi-chemical or wholly chemical methods. Statistical report has shown that 74.1% of the world pulp was produced using the chemical pulping techniques while 21.4% of pulp is attained by mechanical pulping process and 4.5% of the pulp is produced by using other techniques [59]. Chemical methods are mostly utilised when pulping non-wood fibres and they include Kraft, sulphite, soda, and organosolv pulping processes. The major aim to be achieved when using chemical pulping is the degradation of lignin and hemicelluloses into small water-soluble molecules which can be washed away from the cellulose fibres without depolymerising the cellulose fibres. Specific end-products are produced from a given non-wood fibrous raw material based on the choice of process such as; technique used, size of mill, the chemicals available, and their relative cost [24]. The pulping process applied in pulping of non-wood fibres (**Figure 3**) determines the quality and properties of the total yield of pulp to be obtained. This is a significant factor in considering the type of paper to be produced. Some of these pulping techniques have been in use since the ancient times and are ultimately due for improvement in other to overcome their drawbacks.

In addition to pulping techniques, special processes have been developed, and this includes the; pomilio process, the two-stage Cusi process and the NACO and the nitric acid process. In some certain cases, the lime and lime-soda techniques are often required during pulping. They are very old pulping process used in ancient times [24].

The lime or lime-soda pulping methods are usually used for the production of lower grade unbleached pulps. This process is applicable in pulping of rags and jute bast fibre in other to obtain high-grade pulps. Report from Hurter [24] showed that the use of acid sulphite process gave a poor result when used to pulp rags and jute. Most of the pulping techniques are used in pulping non-wood plant stalks and this result in the production of bleachable and high-grade unbleached pulps. The Kraft, soda and the sulphite processes are used majorly in the pulping of leaf and bast fibrous raw materials. Leaf and bast fibres have excellent pulp strength properties which are greater than softwood pulps. Of all the bast fibres, when jute pulped using the soda or Kraft method, the jute fibre strands is reduced to the ultimate fibres, and jute pulps with weaker properties compared to softwood are produced. Jute is an exceptional case of the bast fibres. The use of mild lime or sodium carbonate during pulping process, results in the production of pulp with durable, strong and hard properties. When jute is pulped using this process, long fibres are obtained with increased strength similar or greater than those of softwood pulps.

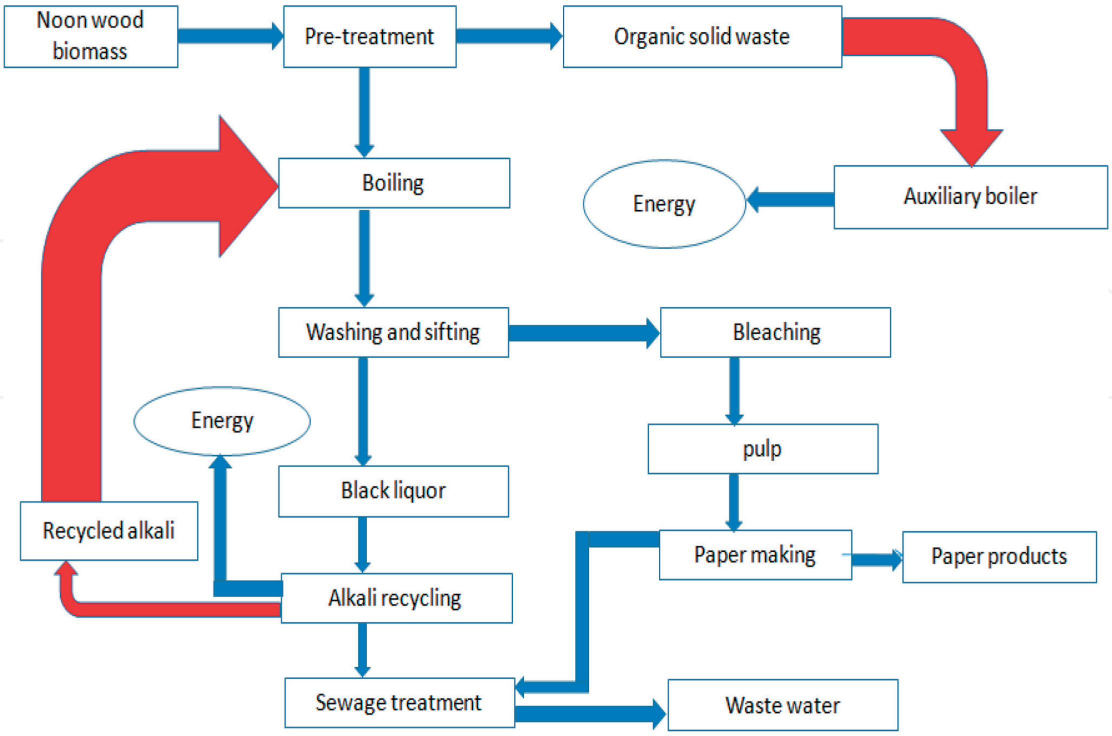

Figure 3. Process flow diagram for pulp and paper production [60].

The favourable method which could be applied in the pulping of bagasse and rice straw is the nitric acid process of pulping. This results in the production of mechanical pulps. The pomilio process has virtually been out of use due to the economic reasons. It consumes a lot of chemicals and has no feasible recovery process for these chemicals. The Kraft pulping technique has a versatile application in dealing with different raw materials coupled with superior pulp quality and more efficient recovery of cooking chemicals. Most of the world's chemical pulp is obtained using this process, and the pulp obtained by the utilisation of this technique is of low and robust brightness properties [11]. This technique is associated with easy recovery and recycling of chemicals, and this has been effective for years with the use of dissolved organics as fuel during this process. Kraft pulping method requires very efficient bleaching sequence to yield the desired level of brightness. This pulping method has been improved by the addition of anthraquinone and extended cooking in other to provide solutions to its shortcomings. Of the numerous advantages associated from the utilisation of this method of pulping, it was reported that release of malodorous and hazardous materials is associated with this pulping technique due to the bleaching process thereby resulting into water pollution [61].

The pulping of cotton is done using the soda pulping technique. Cases where coloured rags are involved, lime-soda may be used. 45–50% yield of chemical pulps was obtained during the pulping of oil palm fronds using soda pulping process [62]. The soda pulping method is also reported to be the most exciting process of pulping empty fruits bunches (EFB) when its efficacy and environmental friendliness is taken into consideration.

Production of bleachable and high-grade unbleachable pulps is highly favoured by the use of conventional Kraft or soda processes. Sulphite or biosulphite pulping process requires stainless steel pulping equipment. The recovery of chemicals using this pulping process is tedious and more complicated. Sulphite pulping is a costly method of pulping. When used in pulping of bast and leaf fibres, pulps obtained are of higher yields and good qualities.

Even though the utilisation of non-wood fibres in pulp and paper production has significant benefits, the production of non-wood pulp is problematic. The alkaline process of pulping non-wood materials results in serious environmental problems during the delignification process [41]. More sophisticated versions of the alkaline process have been developed as far as possible in other to provide a solution to the problems of chemical recovery and environmental challenges. In bigger paper mills, the recovery of alkali has not been successful because the dissolution of silicon into cooking liquor has resulted in scaling problems in liquor evaporation. In general, pulps obtained by the alkaline method of extraction are of short fibres.

Organosolv pulping method is one of the most promising alternative methods which is solvent based processed using organic solvents such as acids or alcohols; aqueous ethanol [61] as cooking materials. The major advantage of using organic solvent for lignin removal lies in the fact that such a process offers the possibilities for more efficient utilisation of the lignocellulosic feedstock. The dissolved lignin together with other dissolved components such as extractives can be recovered by simple distilling off the solvent after the digestion process [61]. In some cases, the organic solvents are mixed with alkali; for instance, methanol-NaOH in which involves two stages. The first stage is the dissolution of 20% lignin in a mixture of methanol and water at a temperature of 195°C while the second stage involves the addition of caustic soda to the mixture of methanol and water in other to get rid of the remaining lignin present in the non-wood plant material. This is carried out at a temperature of 170°C. The disadvantage of this method is that it requires additional chemical recovery process for the alkali present. Baptist [11], reported that the properties of pulp obtained by organosolv process are still being investigated and evaluated. The methanol organosolv process has been used in the alkaline sulphite-anthraquinone-methanol process (ASAM) and the soda pulping method with methanol (organocell). The ASAM process is basically alkaline sulphite pulping with the addition of anthraquinone (AQ) and methanol (CH_3OH) to achieve a higher delignification level.

The active cooking chemicals of the ASAM process are sodium hydroxide, sodium carbonate and sodium sulphite. The addition of methanol to the alkaline sulphite cooking liquor considerably improves delignification, and the process produces pulp with better strength properties, higher yields and better bleaching ability compared to the Kraft process. According to literature, four other improved pulping processes have been tested and found most promising. These four methods as reported by Rousu [41] includes; auto catalysed ethanol pulping (ALCELL), acetic pulping combined with minor amounts of formic acid (FORMACELL) [8], peroxyformic acid pulping (MILOX), formic acid pulping (CHEMOLIS). Of all these techniques listed, the Chempolis process is the only one to have survived up to the recent time. Research based on the other techniques has been discontinued. Delignification carried out using the Alcell process is carried out in ethanol-water solution at a high temperature of about 200°C. This process results in the several degraded products which include acetic acid, formic acid and furfural. Acids are applied to act as catalysts during delignification process in this pulping method. Products obtained using this process must be separated from water and ethanol, and this is done by distillation. This separation process is difficult and costly.

Acetic acid serves a dual purpose during delignification. It could serve as a solvent and as a catalyst.

The Formacell process involves the addition of formic acid to the acetic acid delignification process. The addition of these acids lowers the delignification temperature and pressure. The stronger the acids used, the higher the tendency of reducing the delignification temperature and pressure.

The primary objective of Chempolis process is to produce high-grade pulps while operating economically within the size restrictions imposed by the logistic of the raw material acquisition. Rousu [41], gave a vivid report on the improvement made on the attainment of the main goal in which this pulping process was discovered. In other words, to satisfy the process is its main purpose and serve as an alternative method of pulping of non-wood materials with reduced economic and environmental problems as recorded for the previously used pulping techniques, the design of well-defined recovery to recycling cooking chemicals and washing filtrates with no harm from silicon was required. Chlorine and sulphur-free chemicals were prioritised using this process in other to achieve an effluent free mill.

Bio pulping process is another pulping technique which has potential to overcome problems associated with mechanical manufactured pulp and decrease chemical consumption in chemical pulping operations. This technique is environmentally friendly in such that it reduces the use of electrical energy and reduces the amount of chemicals consumed thereby avoiding pollution. It was reported that bio-pulping has an economic and environmental advantage compared to the other methods of pulping. Fungus appears to be the best candidates for bio-pulping process. They are selected for rapid delignification and can demonstrate selective delignification (leaving fibres untouched).

6. Bleaching of pulps

Pulps of non-wood plants with increased content of calcium, potassium, manganese, copper, iron (which makes up the ash content) when bleached without the use of chlorine chemicals, the transition elements form radicals that react unselectively with the pulp resulting to a loss of yield and strength properties. These pulps can be bleached with oxalic acid. Calcium reacts with oxalic acid to form calcium oxalate which deposits easily. This bleaching process impedes the effluent-free operation of the bleaching plant [41]. A solution to the recovery problems encountered during pulping as reported by Rousu [41] is by omitting the recovery of cooking chemicals.

In other to avoid environmental challenges, bleaching should be carried out without the use of chlorine chemicals. This is not feasible in alkaline pulping process due to the presence of inorganic compounds. Rousu [41], suggested a temporary solution to this problem, by the separation of silicon from the liquor.

Presence of lignin and other discolouration in raw pulp makes bleaching or brightening process necessary. Bleaching process through chlorination and oxidation stages further delignify the fibres by solubilising additional lignin from the cellulose. Bleaching agents such as chlorine gas, chlorine dioxide, sodium hypochlorite, hydrogen peroxide and oxygen may be used and applied in a stepwise fashion within the bleaching sequence. Strong alkali (NaOH) is usually added between bleaching sequence to extract the dissolved lignin from the surface of the fibres. The bleaching agents used during bleaching process depends on some factors such as; relative cost of bleaching chemicals, type and condition of the pulp, desired brightness of the paper to be produced, and environmental guidelines and regulations. Chlorine is used as a bleaching agent for pulps obtained from bagasse. Bagasse requires less bleaching chemicals to achieve a bright white sheet paper [63]. In other to reduce the bleaching chemicals and the discharge of harmful chlorinated organic pollutants, oxygen delignification method of non-wood fibres is being adopted. The use of this method results in a decrease in the kappa number after cooking is done at the range of 40–50%.

Some non-wood material and extraction methods used for pulp extraction

i. **Switchgrass:** Different methods have been used for the extraction of pulp from the fibres obtained from the switchgrass. These methods include the combination of soda and sulphite pulping process and also the Kraft process. The fibres after being isolated from the plant are short fibres with low extractives and ash content. It was digested at a temperature of 170°C for 30–45 min with cooking agents in liquor to sold ratio of 6:1 of sodium hydroxide and sodium sulphite [64]. Due to the high crop yield and presence of a high level of high content of cellulose, 49% of the pulp was yielded with a kappa number of 13. Soda pulp of excellent properties was obtained which shows useful application in the production of newsprint.

ii. **Alfalfa stems:** the use of soda and soda anthraquinone (AQ) pulping and also Kraft and Kraft (AQ) methods of extraction at a temperature of 170°C resulted to the production of pulps with economic advantage over traditional pulpwood [49]. The digestion process of alfalfa stems with an average fibre length of 0.78 mm was carried out using 18% alkali level and 25% sulphidity with a biomass ratio of 10:1 for 40 min.

iii. ***Hesperaloe funifera*:** This is composed of a little lignin and large content of α-cellulose. It has fibres with good morphological characteristic. Soda anthraquinone pulping was the major pulping process used to isolate pulp from the fibres. This was performed at a temperature range between 155 and 180°C with the use of soda having concentrations varying between 5 and 15%. The pulp obtained has a vast application, and it is a potential raw material for paper making [65].

iv. **Rice straw:** Rice straw has been pulped using various pulping techniques. Of all these techniques, the highest yield of pulp (42.82 wt%) was obtained with the use of potassium hydroxide. Fibres such as straw are currently not optimal to be used on a 100% basis for papermaking. This is due to the poor drain ability and low tearing strength. Shortcoming from the utilisation of straws includes the high content of silica, low bulk density and the higher water retention capacity of the straws.

v. **Kenaf:** There are two kinds of Kenaf fibres with distinct characteristics. They are the long bark fibres and the short core fibres. Pulp obtained from the kenaf bark fibres are utilised in the production of paper with an increased mechanical strength which is suitable for writing, printing, wrapping and packaging purposes. On the other hand, pulps obtained from the short core fibres are shorter and thicker thereby producing poor slenderness ratio, which induces reduced tearing resistance of paper but having a high tensile and burst strength [59]. This is probably due to the weak surface contact and also a weak fibre to fibre bonding which is a major characteristic of short and thick fibres [40]. The whole stem of kenaf could be isolated to produce pulp of good quality and strength with practical and economic advantages. Pulp obtained from the whole kenaf stalk is mostly efficient in the production of newsprint paper of excellent quality. Utilisation of conventional soda and Kraft pulping of the whole kenaf plant yields pulps with high strength properties. A recent report from Sabharwal, Akhtar [59], demonstrated that blends of 82–95% kenaf chemo-thermomechanical pulp with 5–18% Kraft pulp could produce commercial grade newsprint. Kenaf possesses several advantages over wood pulp. It requires less energy to pulp and produces naturally bright pulp due to the absence of lignin. Newsprint produce from kenaf pulp do not become yellow with age and exposure to light

vi. **Palm fronds:** The utilisation of sulphite pulping in isolation of pulps from oil palm fronds using a high dose of sodium sulphite under slightly alkaline conditions failed to yield pulps with acceptable yield and papermaking properties. According to Wanrosli et al. [62], the reasons for this inefficient sulphite treatment were not clear. It was assumed that the chemical nature of the raw material might have caused liquor impregnation problems. However, pulping of oil palm fronds using soda pulping method resulted in an increase in yield of pulps. The pulp obtained using the soda pulping is of high yield (44%) with excellent strength properties compared to those of hardwoods.

vii. **Bagasse:** the most suitable method of pulping bagasse is the soda pulping technique using sodium hydroxide only. This enables the extraction of sulphur-free pulps. Addition of pulping additives such as anthraquinone in bagasse soda pulping improves pulp yield and delignification rates [66]. In other to avoid wastage of chemicals and minimise ash or silica content in pulps obtained from bagasse, effective depithing is required. Silica can be removed by precipitation from black liquor by partial acidification with carbon dioxide from flue gasses or by addition of calcium oxide.

viii. **Jute:** fibres obtained from the bark of the jute plants produces pulps of good quality with a yield above 60%. It has paper making properties similar to that of softwood materials [2]. Pulp from jute fibres could be used in production of increased quality. The addition of anthraquinone of amine in soda liquor results in the production of excellent quality pulps. Utilisation of the whole jute plant for pulping results in pulp yield of about 45–55% with a good kappa number (gives a measurement for the lignin content relevant for the bleaching ability of pulp) of about 20–35. Jute stick contains high lignin and has short fibre length, hence pulp produced from whole jute plant shows higher tensile but moderate tear strength compared to jute fibre pulp.

ix. **Bagasse:** Pith in pulping of bagasse result in difficulties during pulp washing and clogging of machine. This was reported by Jahan and Gunter [2]. It was emphasised that adequate removal of pith during bagasse pulping result in the production of satisfactory

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pulp, and this also prevents the wastage of chemicals. The removal of pith is possible with either dry or wet bagasse. Bagasse pulps are usually soft and smooth and have been applied in the production of paper grades suitable for writing, printing, tissue grade, corrugating medium and newsprint.

x. **Corn stalks:** Corn stalks have been analysed according to Jahan and Gunter [2], and it has been made feasible that the papermaking properties of pulps obtained from this non-wood plant materials are very useful and efficient with a high water retention ability (due to the high content of fine contained). However, pulp obtained from the corn stalk fibres has lesser tear strength properties. Pulping process of corn stalk fibres produces 50% pulp yield. The application of the alkaline sulphite anthraquinone methanol process improves the bleaching ability of the pulps obtained from the corn stalk. Research on the soda-anthraquinone method of pulping corn stalk has shown higher yield in the pulp yield production and also the kappa number of the pulp [67, 68].

xi. **Kash:** The pulp yield obtained from kash is very high with a low kappa number. Pulp yield from kash is very high and its papermaking properties are comparable to that of tropical hardwood [69]. It has an initial brightness which is suitable for newsprint. The pulp yield obtained is between 56 and 58% [68, 70].

xii. **Dhaincha:** the pulp yield obtained from the fibre of dhaincha is between 42 and 44%. The papermaking properties are prospect of the chemical and morphological properties of this non-wood material. It has a higher slender ratio which facilitates the production of pulp with better tear strength than other similar fibre length material. It has similar papermaking properties to hardwood. The unbleached pulp of dhaincha is highly suitable for packing paper. In other to increase the tear index of the dhaincha pulp, pulp obtained from jute fibre is added [2, 70].

xiii. **Cotton stalks:** anatomically, cotton stalks are similar to hardwood. The pulp yield is about 40–45%, and the kappa number obtained using the soda-anthraquinone process is within the range of 30–35. Pulp from cotton stalk has good papermaking properties with high tensile strength and low tear index [71]. Blended cotton stalk pulps with jute pulp as well as bagasse pulp produce an improved tear index and other properties [2, 72].

xiv. **Golpata fronds:** The chemical and morphological properties of golpata fronds are compared with some non-wood and hardwood raw materials [73]. The anatomical properties showed that the vascular bundles in golpata fronds are very low. Pulp yield from this non-wood material is very low (37%) compared to other non-wood materials such as bamboo, rice straw, whole jute plants.

7. Problems associated with the utilisation of non-wood plant fibres

The use of non-wood biomass is a feasible alternative to wood in pulping regarding environmental conditions, income produced, variety products obtained availability and cost efficiency. This view is although popular but has certain inherent drawbacks [25]. Majority of these problems are technological that require improvement. In some cases, the drawback is as a result of the composition of the non-wood fibres. For instance, plants with higher mineral contents require further processing before pulping can occur. They make pulping process tedious and produce pulp of lesser quality. Few amongst these problems are discussed as follows:

i. **Availability:** Due to the bulkiness of agricultural residue, the handling of these materials is challenging. There is need to develop efficient bailers in other to increase the density of the materials for efficient handling, transport and storage [25]. Aside the bulkiness, there is a low yield of the raw materials per hectare of land and this result in insufficient supplies. The yield of most of these raw materials per hectare is low, and this affects the production. As a result of this, they need to be collected over a large area to meet the needs of paper mill [25].

ii. **Storage and handling:** Most of the non-wood raw materials are annual plants, and they have short harvesting periods. Most of these materials are stored for the rest of the operating year in which it deteriorates, thus limiting the yield required for paper production. As reported by Chandra IV [25], it is evident that efficient storage methods need to be developed to prevent or reduce deterioration of non-wood raw materials. Deterioration of these non-wood raw materials tends to reduce pulp yield and also limit the production of paper. The problem of deterioration is most peculiar with sugar cane bagasse. This occurs as a result of the action of undesirable microorganisms which aid the biodegradation process of bagasse. Presence of residual sugar, heterogeneity of tissues, and environmental conditions facilitate the growth of microorganisms in bagasse piles. The biodegradation process results in the chemical degradation (this is the consequence of biochemical reactions) and discolouration of bagasse thereby reducing pulp yield. The efficient depithing method has been a major boost in bagasse pulping process. Straw is also prone to microbial degradation and decay when stored with high moisture content contained in it.

iii. **Pulping:** Most of the non-wood plants have high silica content, and this has resulted in several problems during washing and yield of pulps. The difficulty in washing is as a result of poor drainage of pulp and high viscosity of black liquor. For this reason, pulps obtained from non-wood materials are washed using washers twice the normal size. The lime-alkali-oxygen pulping process has been developed further to favour the washing process of these pulps. When lime is added to the cooking liquor, silica reacts to form calcium silicate, which is insoluble in water and high content in the black liquor results in various problems in the chemical recovery loop. These problems include; formation of glassy materials, the formation of colloidal gels, hard scales in the evaporator. The anthraquinone pulping method has been developed to improve pulp yield by 5% and kappa number by up to 5 [25]. Due to the low density of crops, in other to favour the pulping of non-wood fibres, they need more pulping liquid and more volumes in process equipment. Pollution from non-wood fibre mills can be up to 20 times that from wood pulp mills.

iv. **Bleaching:** Owing to the rapid discolouration during storage of these materials, most of them have low initial brightness. Bleaching of bagasse and other non-woody fibrous raw materials have proved much difficulty.

v. **Paper production:** paper machines are run at low speeds to prevent the destruction of the machine. This is because most non-wood materials take a long time during drainage. Fibres with low wet strength are not easy to be picked up on the couch during papermaking [25]. Some of these fibres are being blended with some certain amount of wood pulp in the furnish in other to improve the run ability in the paper machines. Technically, in other to obtain the necessary quality profile and run ability of bagasse-based newsprint, 15–20% of chemical pulp must be added to the furnish. Paper machines running on bagasse must also operate at lower speeds than those of wood fibre machines.

vi. **Chemical recovery:** Most of the non-wood paper mills almost never had a chemical recovery system. Large mills, where chemical recovery is practice, have their problems. Black liquors from non-wood fibre pulping typically have viscosities 10 times higher than Kraft liquor from pine, for example, so they are hard to handle at high solid contents. This high solid content, also causing trouble in evaporators, recovery boilers, causticizing equipment, and lime kilns. Scale formation in the evaporator tubes, deposits on the furnace walls of the recovery boilers, slow setting rates of recausticizing white liquor and lime sludge unsuitable for reburning (calcination) are also problems that need to be addressed [25].

8. Conclusion

In order to reduce the effects of environmental hazard, induced by imbalance in the ecosystem due to deforestation, the use of non-wood biomass is an option that can be adopted by paper mills. Non-wood biomasses such as agricultural residues and annual crops have amenable properties appropriate in the production of pulp and papers of high quality. They have similar characteristics to those obtained from paper woods. Non-wood biomasses are readily available and are cost-effective compared to wood materials. Development of efficient pulping and bleaching processes is required for easy production. Majority of the non-wood fibres have almost similar chemical and morphological properties of wood fibres. This makes them efficient and useful in the production of pulp with required qualities and for speciality papers. Fibres with higher lignin content are not readily pulped and therefore produce pulps with low yield.

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