USE OF NONWOOD PLANT FIBERS FOR PULP AND PAPER INDUSTRY IN ASIA: POTENTIAL IN CHINA

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(ABSTRACT)

The pulp and paper industry around the world has been growing rapidly. As a result there has been a huge demand for pulp and paper making raw material. Recent years have seen a spurt in use of nonwood fibers being used as a raw material for this purpose.

Although some of the nonwood fibers used for papermaking are used because of their fine paper making qualities, majority of nonwood fibers is used to overcome the shortage of wood fibers. As a result their use is more widespread in countries with shortage of wood.

The use of nonwood fibers in pulp and paper industry is fraught with problems. Right from supply of raw material to the properties of finished paper, majority of nonwood raw material has proven to be economically inferior to wood. But over the last few years, technological breakthrough in almost all the fields of papermaking have made nonwood more competitive with wood as a raw material for papermaking.

Although till recently, use of nonwood fibers for pulp and paper making was concentrated in countries with limited wood supply, it is now showing an increasing trend even in countries with adequate wood supply due to environmental considerations. With time this trend can be expected to grow further and it can be safely said that the future of nonwood plant fibers as pulping and papermaking raw material looks bright.

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INTRODUCTION

1.1 Problem Statement and Justification

Worldwide, the forest products industry is a dynamic, vital and growing enterprise. Demand for paper has been forecast to grow by nearly 50% by 2010. This represents a growth rate of 2.8% per year. Demand growth for mechanical wood products (i.e. for structural purposes) is also expected to advance at a rate of 1-2% per year (McNutt and Rennel, 1997).

Growth in pulp and paper production entails massive felling of trees, which in turn leads to deforestation. Increasing competition for wood supplies coupled with gradually rising costs of wood have generated renewed interest in the use of nonwood plant fibers for papermaking in the highly industrialized countries (Sabharwal and Young, 1996). The use of agricultural-residues in pulping and papermaking might be desirable because it averts the need for disposal, which currently increases farming costs and causes environmental deterioration through pollution, fires, and pests.

During the last twenty-five years, there has been a great increase in global nonwood pulping capacities. In 1970, nonwood pulp production was only 6.7% of the worldwide pulp production. By 1993, it had risen to 10.5% and is expected to rise to 11.3% by the end of 1998 (Table 1, Atchison, 1996). Because of this increased use and opportunities for further substitution for wood based fibers, it is important to examine the potential benefits and problems associated with the use of nonwood plant fibers in pulp and paper industry.

The demand for nonwood plant fibers for papermaking is expected to increase in the highly industrialized nations of Europe and North America due to the above environmental concerns like depleting forest resources and disposal of agricultural residues. Europe has an additional problem with the shortage of short fibered hardwood pulp, which can be replaced by some nonwood fibers. This will require knowledge of the processes and developments already in place in the countries already using these raw materials in the paper industry. Already, a number of nonwood fibers are commonly used in many countries for papermaking. Straws are by far the largest source of nonwood fibers followed by bagasse and bamboo (Table 2, FAO, 1996)

Most of the increased use of nonwood plant fibers has been attributed to the tremendous demand in paper and increase in nonwood pulping capacities in China (PRC). At present China produces more than two thirds of the nonwood pulp produced worldwide followed by India, a distant second. Table 3 gives a list of the top 25 countries utilizing nonwood fibers. These countries account for 99% of the total nonwood fiber used in papermaking. A look at the Chinese nonwood paper industry would therefore provide us with a good view of the problems and opportunities faced by the use of nonwood plant fiber in pulp and paper industry. From this case study we can also suggest applications appropriate in other countries.

1.2 Objectives

The objectives of this project are threefold; 1) to study the forces responsible for development and use of nonwood plant fibers in pulping and papermaking; 2) to identify technological and economic problems associated with use of nonwood plant fibers in pulp and papermaking, and solutions available; and 3) to review the use of nonwood fibers in Chinese paper industry and identify opportunities available in other countries.

CHAPTER 2

BACKGROUND

2.1 Literature Review

China's paper and board production increased from 4.93 million metric tons in 1979 to 21.61 million tons in 1995, the third largest in the world. During this period China has experienced increases in pulp and papermaking capacity at an average annual rate of 6% and at times has been as high as 10%. More than 80% of this has been for pulping nonwood fibers (Xing, 1995; Atchison, 1996).

It is expected that by the end of the century, total paper and paperboard consumption in China will reach 34 million metric tons (Cao, 1996). On the other hand, estimated pulp production in China will be 21 million metric tons and paper production not much higher at 25 million metric tons (FAO, 1996). This leaves a shortfall of 9 million metric tons. To make up this shortfall, many new projects and expansions are being started in all regions of China (Table 4). This growth in capacity will spur a further demand for raw materials, which cannot be met, by the forest plantations. Therefore, nonwood plant fibers will be a major source of pulp in china for some time to come.

Apart from China, many other countries are looking to nonwood plant fibers for papermaking. Usually, this is due to a shortage of wood residues in these countries, and readily available nonwood fiber resources. In many countries, pulp production is based entirely on nonwood plant fibers and another 21 countries - led by China and India - depend on nonwood plant fibers for more than 50% of pulp production (Atchison, 1992 b). The economic advantage in many developing countries is the presence of nonwood resources, a growing domestic market for paper, reasonable labor costs, and absence of wood raw materials (MacLeod, 1988).

Advantages of nonwood mills include:

- There is little strain on ecological balance as they are based on annually renewable raw materials often abundant in supply and with disposal problems;
- No outflow of foreign exchange is required to import raw materials;

- Abundant availability of agricultural-residues;
- Sale of agricultural-residue provides additional revenue to farmers who have little other opportunities for outside income;
- Employment is provided to rural labor; and
- Locating mills across the entire country satisfies regional requirements and there is a reduced need for a complex transportation system. (Judt, 1991 a)

Around the world, wood fiber supply is expected to tighten (McNutt, 1996, McNutt and Rennel 1997). Even in the US. The wood fiber supply is expected to tighten in the not so distant future (Atchison, 1992 a; Rosenberg, 1996). In India there already is a shortage of wood fibers (Wayman, 1995 b). Even the European Union suffers from shortages of wood fibers and search is on for alternative fibers (Chaudhuri, 1995; Paavilianen and Torgilson, 1995; Alcaide et al, 1991, 1993). Japan is also investigating the use nonwood plant fibers for pulp and paper manufacture (Sameshima, 1994).

Over the last several years, a number of plants have been tested for their papermaking qualities (Alcaide et al, 1991, 1993; Yilmaz, 1995 a, b, c; Eroglu et al, 1994). A number of centers and organizations like Paper Industrial Research Institute of China (PIRIC), United Nations Industrial Development Organization (UNIDO), Central Pulp and Paper Research Institute (CPPRI) in India, and International Agro-Fiber Research center in Wisconsin Madison have been involved in this research (Sabharwal and Young, 1996; Judt, 1991 c; Judt, 1993; Assumpcao, 1992). These efforts have provided information and a number of nonwood fibers have been identified as potential raw material for the paper industry.

Of the many nonwood plant fibers, bagasse is considered the most promising, and it has been the focus of significant amounts of research. From storage, handling, and depithing (Atchison, 1988; Rangan, 1995; Michelsen, 1994) to pulping and bleaching (Prasad et al, 1996; Yu et al, 1994; Rangamannar, 1988) research has shown bagasse to be a viable paper fiber source. Special consideration has been given for its use for newsprint (Atchison, 1993, 1993; Rangan and Rangamannar, 1995). As a result, a number of mills in the world are currently using bagasse as their primary raw material (Potter, 1996; Pappens, 1991; Rangan, 1996). In fact, it comprises more than 10% of all nonwood fiber used in papermaking (FAO, 1996).

Straw is another major source of nonwood fibers. Significant work has been done to investigate its use, and investigate the special problems associated with straw. One main problem has been the presence of silica (Yilmaz, 1995; Judt, 1991; Brink, 1988). This causes problems in washing of pulp and also in the recovery of spent liquor. Pulping (Yilmaz, 1995; Brink, 1988), bleaching (Pekarovicova et al, 1994; Brink et al, 1988) and handling (Jeyasingam, 1994) of straw have also been a major focus of research.

One very promising raw material, on which significant research has been done in the US, is kenaf (Tao et al, 1995; Mayers and Bagby, 1995; Kaldor, 1992; Kokta et al, 1993; Pande, 1996; Mittal and Maheshwari, 1995b). This is due to its inherently low lignin content and therefore higher cellulose content. Other raw materials being investigated are hemp (Judt, 1994; Zomers et al, 1994; Jeyasingam, 1994; Wong and Chiu, 1995), Jute (Akhtaruzzaman and Shafi, 1995; Sabharwal et al, 1995; Sarkanen and Resalati, 1988), abaca (Peralta, 1996), reed (Chen et al, 1994; Paavilianen and Torgilson, 1995) and bamboo (Bajpai and Bajpai, 1996; Knight, 1994). This is by no means a comprehensive list of the fibers used in the paper industry.

A number of economic studies have focused on the feasibility of nonwood mills (Kauppi, 1989; Saha et al, 1990; Perham, 1990; Hurter, 1990; Ray et al, 1992). Not all of the studies have been encouraging to those interested in nonwood pulp mills. However, there have been a number of mills that have continued to use nonwood plant fibers as their main raw material. Some examples of these are:

- Tamil Nadu Newsprint and Paper Limited (TNPL) in India produces 50,000 metric tons of newsprint and 40,000 metric tones of uncoated printing and writing paper annually (Prasad, 1996);
- The Taiwan Sugar Corporation’s bleached bagasse pulp mill was producing more than 300 tons per day of pulp in 1988 (MacLeod, 1988);
- There is a bleached kenaf market pulp mill, the Phoenix Paper Mill in Thailand (MacLeod, 1988);
- Stanger, in South Africa, makes 60,000 tons/yr. of 35 different grades of paper from bagasse and is a leader in woodfree paper production in South Africa (Pappens, 1991);

- Tribeni Tissues Limited, in India, is the only mill to use raw jute for pulp manufacture. It is blended with other pulps to produce specialty paper (Sabharwal, 1995);
- Century pulp and paper mill, in India, will start a 220 tpd bagasse based unit (Potter, 1996); and
- Saica, in Spain, is the world's largest straw pulp and paper maker, with a capacity of 400 tons/day (Marcus, 1994).

In Sweden it has been determined that the optimum size nonwood fiber mill tends to be around 100,000 ton/yr (Chaudhuri, 1995). However a number of nonwood mills are smaller and cannot afford to install expensive pollution control methods. Pressure to comply with pollution control requirements is main concern of nonwood papermills. Continued work in this field has yielded promising results (Gupta, 1994; Huaiyu et al, 1995; Sadawarte, 1995; Wong et al, 1990)

2.2 History

Wood, as a papermaking fiber is a relative newcomer. For 90% of its existence of almost 2000 years, paper has been made exclusively from nonwood plant fibers.

The first true paper, credited to Ts'ai Lun in 105 AD in China, was apparently made form true hemp (*Cannabis Sativa*). First among the papermaking fibers were hemp and China grass (*Ramie, Boehmeria nivea*). As demand for paper grew, so did the search for other suitable raw materials. The first suitable raw fiber that Chinese found (i.e. straight from the plant) apparently was the inner bark of Mulberry (*Broussonetia papyrifera*). Another raw material used was Bamboo (Atchison and McGovern, 1989).

During the next several centuries, the art of papermaking grew far and wide from Japan in the east, to Siam (now Thailand) in the south, to Chinese Turkestan in the west. In Turkestan, in 751 AD, papermaking was learned by the Arabs who brought it westward over their trade routes. Papermaking reached Samarkand, Baghdad (793 AD), Damascus, Cairo (900 AD), and Fez (1100 AD). From there it spread to Spain in 1151 AD then to France in 1348 AD and later on to Germany in 1390 AD. In the region where paper mulberry, bamboo and China grass were not available, replacement raw materials such as linen and cotton rags were used (Atchison and McGovern, 1989).

In 1450, the invention of printing using movable type in Germany resulted in a great reduction in the cost of book publishing. This created a demand for printing surfaces which parchment could not meet. During the next 150 years, mills for making paper by hand were built in nearly every country in Europe (Atchison and McGovern, 1989).

As printing costs declined, the literacy rates increased and many schools and universities were founded. This increase in literacy led to increase in publishing and in particular, the first newspapers around the year 1600 AD.

The resulting increase in demand could not be met only from rags and old ropes. Therefore, the search for alternative raw materials was intensified. Laboratory experiments were conducted on hundreds of vegetables, leaves, barks, weeds and wood. Trial copies of books were actually printed on paper made from asbestos (in 1727), lime tree bark (in 1786), marshmallow, swamp moss (in 1799) and straw (in 1800) (Atchison and McGovern, 1989).

With the advent of Fourdrinier continuous web paper machine in 1805 followed by the cylinder machine in 1809, increased the speed of paper production thus resulting in an increased production at lower cost. This further improved the demand for raw materials (Atchison and McGovern, 1989).

In 1827, straw was brought into successful commercial use. However, straw by itself, could not satisfy demand for all grades and experiments on other raw material continued.

Between 1840-1885, experiments on wood yielded four commercially successful pulping processes. Pulps from these processes proceeded to displace straw from a number of paper grades. But straw held its own as a major raw material for corrugated board for sometime and reached its peak in 1940 with a production of 2/3 million tons. Since then, due to the economics of supply and high labor cost of collection, nonwood plant fibers have been almost entirely replaced by wood as papermaking raw material in most developed countries (Atchison and McGovern, 1989).

Today, the highest ratio of nonwood to total papermaking pulp capacities are in the developing market economies of Asia, Africa and Latin America, as well as the centrally planned economies of Asia. Some of these regions have more nonwood plant pulping capacities than wood pulping capacities. Indeed, China has more than twice as much.

Further, total nonwood plant pulping capacity worldwide is increasing faster than the wood pulping capacity. Their respective annual rates of increase were 6% annually for nonwood as compared to 2% annually for wood pulp during the period from 1988-1993. It is expected to be 2.5% annually for nonwood and 1% for wood during the period from 1993-1998. As a result, nonwood plant pulping capacity (as a percentage of total papermaking pulp capacity) has increased from 6.7% in 1970 to 10.6% in 1993. It currently stands at 10.4% and is expected to reach 11.2% by 1998.

Of the total 20,887,000 metric tons of nonwood plant fiber pulp produced in 1995, 15,957,000 metric tons were produced in China. This accounts for over 76 percent total world nonwood plant fiber pulp production and over 83% of total Chinese pulp production. At the same time, the level of pollution from these mills is very high. In 1996, Nan Ping city, a mid-size city in Fujian Province, had 86 small papermills. These paper mills discharged 19 million gal/year of wastewater and 26,000 tons/year of COD* (51% of the total COD discharge for the city). Some of these mills were closed in 1996 (Xing, 1996).

Due to the expected shortage and rising prices of wood for papermaking in the US, nonwood fibers are expected to be a source of papermaking fibers in the US in the near future (Atchison, 1992 a). At the same time, Europe has a shortage of short fibered hardwood pulp and is thus an importer of this kind of pulp. Some of the nonwood fibers have the properties to replace these fibers. The use of nonwood fibers for papermaking is thus also expected to grow in Europe.

The development of these industries will need to borrow from the experiences of the nonwood mills already in existence around the world. Since most are in China, a look at that country's nonwood fiber paper industry would therefore be of some help.

* Chemical Oxygen Demand

CHAPTER 3

WHY USE NONWOOD PLANT FIBERS IN PAPER PRODUCTION?

3.1 Shortage of wood fibers

Trees needed to meet virgin wood fiber demand of the forest products industry are already growing except for the new fast growing plantations. Therefore, in global terms, there will not be a long-term fiber shortage. However, fiber supplies within and across particular regions will tighten. These regional imbalances are already significant and will continue to grow. As can be seen from Figure 2, Asia is presently the largest fiber deficit region, followed by Western Europe. At the same time, Asia is the focus of fiber demand growth for pulp and paper, housing and wood for fuel. If this assessment is accurate, pulp and paper industry's dependence on virgin fibers must be reduced by expansion in the use of recovered paper and growth in the use of nonwood plant fibers in Asia (McNutt and Rennel, 1997).

In India, forest based resources are being rapidly depleted while the demand for paper is increasing (6-7% per anum). In order to resolve this situation, the government of India has extended concessions and relief to stimulate use of agriculture-based cellulose raw materials. As a result, use of forest based raw materials has decreased from 84% in 1970 to 43% in 1994 and use of agriculture-residues has increased from 9% to 32% the rest being made up of recovered fibers. Ninety mills are agriculture residue based with installed capacities of 974,000 metric tons (Gupta, 1994).

Use of nonwood plant fibers for pulp production in China is not a matter of choice but a matter of necessity. China is not rich in wood resources. Its forests are limited in size and area available for future plantation. Its total forest area is approximately 119 million hectares, which covers only 12% of the total land area and represents 0.12 hectares per capita compared to the world average of 1.1 hectares per capita. Planted forests account for about one quarter of all forested area and contribute to the raw material supply. This area under plantation is further expected to increase as the demand for wood grows. Even with expansion of the national forest, nonwood plant fibers will constitute a major source of fiber for pulp (Al-Simaani et al, 1992). Currently, quality trees, such as spruce, for papermaking are difficult to find. Only 7-8% of total harvested wood, approximately 7-8 million m^3 per year, is going to the paper industry, whereas the amount being burned for fuel is 50-60 million m^3 per year. Adding to the problem is the decades old dispute over what should be the primary raw material for the Chinese paper industry, straw or wood (Xing, 1995).

3.2 Surplus of nonwood plant fibers

The abundance of nonwood fibers in some countries is also responsible for its use in papermaking. Sometimes, the use in papermaking is considered the best way to dispose of nonwood fibers.

Jute has a long historical role in socio economic development in Bangladesh. In recent years, jute has faced stiff competition from synthetics. As a result, demand for jute in local and overseas markets has shrunk. The situation is further aggravated by a comparatively high growth of low quality jute, from 46-54%, from 1977 to 1986. About 200,000 metric tons of jute, with an additional 45,000 metric tons of jute cuttings, remain as surplus in Bangladesh (Akhtaruzzaman and Shafi, 1995). The Bangladesh government is therefore exploring other possible uses of jute. Use in papermaking is one option being considered.

In Vietnam, surplus of bamboo led to the establishment of a pulp and paper mill. But, the supply of bamboo over the years has diminished as the percentage of land under forestation went down from 50% to 30%. As a result, the mill had to use eucalyptus as additional raw material (Hamilton, 1989).

In Europe and Americas, the use of agricultural residues in pulping has a further advantage because it averts the need for disposal, which currently increases farming costs and environmental deterioration through pollution, fires, and pests (Alcaide et al, 1991).

3.3 Special papermaking properties of selected nonwood plant fibers

Apart from the above reasons, some nonwood plant fibers are in demand for papermaking due to the special properties that make them better than wood fibers for specialty papers. Abaca is an excellent raw material for manufacture of specialty paper. Its long fiber length and high strength make it a superior material for the production of thin lightweight papers of high porosity and excellent tear burst and tensile strengths (Peralta, 1996). It has special properties for making strong products like tea bags, large sausage casings, currency paper, cigarette and filter paper, and specialty products that require high wet strength combined with high porosity.

Kenaf possesses several natural advantages over wood pulp. This 14-foot high plant's rapid growth permits two harvests per year in some areas. Comparatively soft and fibrous, kenaf requires less energy to pulp than wood. Owing to the absence of lignin, kenaf is naturally bright. It requires neither chemical delignification nor peroxide bleaching, and kenaf newsprint does not yellow with age and exposure to light as with that made from wood (Rosenberg, 1996).

Sisal can be made into strong products. Cotton linters are used for premium quality letterhead paper, currency paper, dissolving pulp and other specialty products. Bagasse and straw are best at contributing excellent formation to papers and can replace hardwood chemical pulps for printing and writing paper.

CHAPTER 4

NONWOOD FIBER AS RAW MATERIAL FOR THE PULP AND PAPER INDUSTRY

Many plant fibers have been proposed for papermaking, and under test conditions many of them have produced products with desirable properties. But these desirable properties are not sufficient for their use in the paper industry. Necessary characteristics are, ample supply of raw material, availability at the pulp mill throughout the year, ability to store without deterioration, geographically concentrated, moderate collection and storage costs, high yield of good quality fibers, low cost conversion to pulp, and sufficient demand for the product at a price that will ensure profitable operation (Maddern and French, 1989). Estimated annual collectible yields of some nonwood plant fibrous raw materials are given in Table 5. A comparison of the fiber dimensions of some nonwood and wood fibers is given in Table 6 and their chemical properties are shown in Table 7.

The minimum fiber length necessary to produce acceptable paper strength properties is dependent on many factors, and fiber lengths are not unequivocally related to paper strength properties (Young, 1997). Different fiber lengths are desirable for different properties in paper. For example, longer fiber length is desirable for strength properties in paper, but they tend to bunch together and as a result do not provide good formation. Shorter fibers on the other hand provide excellent formation.

In 1994, the raw material for the Chinese paper industry comprised 12.3% wood pulp, 29.1% recovered fiber, 45.4% straw pulp, 4.9% reed pulp, 2.1% cotton pulp, 1.6% bagasse pulp, 0.9% bamboo pulp and 3.7% other pulps (Orgill 1997). Expected fiber consumption in China in the year 2000 is given in Table-8.

Nonwood plant fibers that are currently used in the paper industry can be broadly divided into three groups based on their availability. These are agricultural residues, natural growing plants and nonwood crops grown primarily for their fibers.

4.1 Agriculture residues

4.1.1 Sugarcane bagasse (*Saccharum officinarum*)

Among the many agricultural fibers used for pulp manufacture, sugarcane bagasse is the one with most promise. Bagasse is easily accessible and readily available in many countries. It is especially abundant in some of the wood poor countries. Bagasse is the residue from the production of cane sugar crushed stalk after the sugar-laden juice has been extracted. The major obstacle in pulping bagasse is the high pith content of stalks, which represents about 30% by weight of the stalk. The pulp is generally comparable to hardwood pulps (Casey, 1980).

Sugarcane is grown in most tropical and sub-tropical countries for its high sucrose content. Following the processing of cane through a series of presses or diffusers to remove sugar juice, the fibrous bagasse residue is usually burnt in sugar mill boilers. However, in many areas, bagasse has greater economic value if it is pulped. In fact, it satisfies requirements for a successful papermaking fiber better than any other crop fiber. Bagasse has been commonly used in South China as a raw material for paper making (Yu et al, 1994).

Average fiber length of sugar cane is 1.7 mm (0.8-2.8 mm), and average fiber width is 0.02 mm (0.01-0.034 mm). Fibers are thick walled, of varying length and have mostly blunt ends (Ilvessalo-Pfaffli, 1995). In blends of various proportions, it is used to make printing & writing paper, bristol board, tissue paper, glassine and greaseproof paper, duplex and triplex paper. Corrugating medium, linerboard, wrapping and bag papers, multiwall sack and newsprint substitute.

4.1.2 Corn stalks (*Zea mays*)

Corn is a major crop in a number of countries, and as a consequence, the stalks are considered a good fiber source for low grades of paper. The idea of corn stalk usage in papermaking has been considered, reconsidered, and abandoned a number of times due to changes in availability of fibers as raw materials.

Corn stalks are similar to sugarcane in structural features with an average fiber length of 1.5 mm (0.5-2.9 mm) and average fiber width of 0.018 mm (0.014-0.024 mm).

Typical fibers are fairly narrow, thick walled and have blunt or pointed ends (Ilvessalo-Pfaffli, 1995).

4.1.3 Cotton stalks (*Goossypium*)

After cotton fibers have been removed from the plant, the whole stalk may also be used for pulping and papermaking. A number of studies have also been conducted on cotton as a possible source of raw material for papermaking (Alcaide et al, 1991, 1993). These studies have yielded good results as to the possibility of using cotton stalk pulp in blend with other pulps to produce good quality paper. Cotton stalk fibers have an average fiber length of 0.6-0.8 mm and an average fiber diameter of 0.02-0.03 mm (Ilvessalo-Pfaffli, 1995).

4.1.4 Rice straw (*Oryza sativa*)

Rice straw is used for papermaking in the countries of southern and eastern Asia (i.e. China, India, and Sri Lanka) and in Egypt. However rice straw is costly to collect and store, and it has high silica content. Despite these drawbacks, it is a favored fiber source in the wood short countries, due to its ready availability. Average fiber length of the rice straw fiber is 1.4 mm and average fiber width is 0.009 mm (Ilvessalo-Pfaffli, 1995). In blends of various proportions, it is used to make printing and writing paper, glassine and greaseproof paper, duplex and triplex paper, corrugating medium, strawboard and “B” grade wrapping paper.

4.1.5 Wheat straw (*Triticum aestivum*)

Straw was a major source of fibers for the paper industry in Europe and North America until the wood pulp industry was fully established. At present, straw is used in areas where wood is scarce (i.e. in Europe, Asia, Africa and Central and South America).

Wheat straw fibers 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). Typically fibers are fairly narrow, thick-walled, and have a blunt or pointed ends (Ilvessalo-Pfaffli, 1995). In blends of various proportions, it is used to make printing and writing paper, glassine and greaseproof paper, duplex and triplex paper, corrugating medium, strawboard and “B” grade wrapping paper.

4.1.6 Cereal straw

Several types of cereal straw are used including those from rye (*Secale cereale*), oat (*Avena sativa*), and barley (*Hordeum vulgare*). Of these rye is the most suitable for pulp production due to its availability, and the greater yield and strength properties of its pulp.

4.2 Natural growing plants

4.2.1 Bamboo (*Dendrocalamus strictus*)

Bamboo generally grows in warm tropical climates. Bamboos have uneven geographical distribution and appear prominently in the natural vegetation of many parts of the world. Bamboo grows from sea level to the snow line.

Bamboo grows in two distinctly different forms, i.e., single stemmed or densely clumped. They are the fastest 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. The diameter of the stem is usually 5-15 cm. Maturity is not reached until the culm is 3 to 4 years old (Ilvessalo-Pfaffli, 1995). Fiber length of bamboo varies from species to species. In some species it also varies from bottom to top and, in some cases, it varies with internodal length.

Average fiber length of bamboo is 2.7-4.0 mm and its average fiber diameter is 0.015 mm (Ilvessalo-Pfaffli, 1995). In blends of various proportions, it is used to make printing and writing paper, bristol board, duplex and triplex paper, linerboard, wrapping and bag paper, multiwall sack and newsprint substitute.

4.2.2 Esparto (*Stipa tenacissima*)

Esparto grass grows wild in North Africa and in the Mediterranean steppe areas of southern Spain. The grass generally grayish green in color, occurs as long rolled up leaves that may reach lengths of 1 m. It is coarse and strong and grows in bunches or clumps about 3 m in diameter. Where growth is prolific, the clumps tend to merge into one great mass to cover many square miles. About 12-15 years is required to establish esparto from seed to a form suitable for harvesting (McDonald, 1969).

Commencing in the middle of the last century, esparto grass grown in Algeria and parts of southern Spain became an important source of raw material for fine papers. The fiber comes from the leaf of the plant. Leaves roll into tubes in hot weather as they ripen, giving a superficially solid appearance. They are pulled out in clumps and compressed into bales for shipping. Unlike the stems, the leaves are free of nodes and are relatively easy to pulp, which is usually accomplished with the soda process (McDonald, 1969).

Fibers of esparto are thin and round, about 0.01 mm in diameter and a little over one mm long. They have very tiny canal or lumen and are therefore very springy. Being fine and short they produce a bulky, smooth, well formed paper that is unexcelled as the main ingredient for fine printing and lithographic paper (Clark, 1985).

4.2.3 Reeds (*Phragmites communis* Trinius)

The most commonly used reed (*Phragmites communis*) is a tall perennial grass, which grows generally in marshes. Reeds grow abundantly in swamplands, river bottoms lands and delta areas of Russia, Romania, Egypt, northern China, North Korea and Spain. Depending on conditions, such as soil characteristics, hydrologic condition, amount of nutrients, and pH, the diameter will vary from 9 to 22 mm and the height from 2.5 to 5 meters (Wiedermann 1989).

The plant is mature by the end of September the beginning of October, but it is necessary to allow an additional 4-6 weeks to complete the food accumulation in the root stock, which will ensure the following year’s reproduction. In April, the young stalks contain as much as 80% moisture. By July, this moisture content is down to 60-65% and as low as 26-27% in December. The decrease in moisture content helps control the degradation of reed in storage and reduces the cost of transport (Wiedermann, 1989).

The leaf sheath is deficient in cellulose and may contain up to 10% silica, and are consequently discarded at harvest. Fiber length of the stalk ranges from about 0.35 to 3.35 mm with an average of 1.8 mm and the fiber width varies from 0.006-0.022 mm with a average of 0.014 mm (Wiedermann, 1989). In blends of various proportions, it is used to make printing and writing paper, duplex and triplex paper, corrugating medium, linerboard and “b” grade wrapping paper.

4.2.4 Sabai grass (*Eulaliopsis binata*)

Sabai grass grows wild in the lower Himalayas, central India and southern China. It is a tufted grass having stems 60-90 cm in height and long leaves which are present mostly at the base. Sabai grass has been a significant source of fiber for papermaking in India, and has also been used in Pakistan and Nepal. The species was a staple fibrous raw material before 1925 and is characterized by its durability, strength, and hardness (McGovern et al, 1989). Quality of the pulp is similar to that of esparto and is therefore used for high-class book and printing paper. Until 1952, sabai grass represented about 22% of the total fibrous material pulped in India. Use in recent years has however declined due to difficulties in procurement, although some plantations have been established to produce the grass on a limited scale (McGovern, et al., 1989).

Average fiber length is about 4.1 mm, with a range of 0.5 mm to 4.9 mm. Widths are about 0.01-0.016 mm. Fibers are relatively thick walled with narrow lumen, and the ends are pointed and never forked (Ilvessalo-Pfaffli, 1995).

4.2.5 Papyrus (*Cyperus papyrus*)

The papyrus plant is a perennial, nonwoody sedge growing in great profusion in the Upper Nile River and elsewhere in Africa, the Middle East, and southern Europe. The triangular, smooth-sided (no nodes), leafless stem is 3-5 cm in diameter at its base and reaches a height of 2-5 m. The stem itself is composed of a cortex or rind surrounding a pith section. The pith section itself is structured from fiber bundles embedded in thin walled cells (parenchyma). Vessels, sclerenchyma, and epidermal cells are also present. The cortex comprises a dense section of fiber bundles. Papyrus plants have been indicated as having an annual growth rate of 45 ton/ha., dry weight (McGovern et al, 1989).

The pith section occupies 80-90% of papyrus stems volumetrically and 30-80% by dry weight. Inflorescence accounts for about 20% of the total plant, less roots. Fibers in the pith section amount to 10% of the total fiber weight. Thus, the proportion of fibers in the stem may vary from about 20-75%. Fibers themselves show a great range in length and diameter depending on species, origin and location in stem. Papyrus plants have an average fiber length of 1.8 mm and an average fiber width of 0.012 mm (McGovern et al 1989).

4.3 Nonwood crops grown primarily for their fiber content

4.3.1 Bast Fibers

Fibers from the bast, or bark of some nonwood plants are used for papermaking. What follows is a review of several of these species and their potential for paper making.

4.3.1.1 Jute (*Corchorus capsularis*)

Jute is characterized by high cellulose content and its fibers are quite long. Chemical and morphological properties, therefore, favor its use in making pulp (Akhtaruzzaman and Shafi, 1995). Jute is primarily grown in Bangladesh, India, China and Thailand and the plant grows to a height of 2.5-3.5 meters. The outer bark comprises about 40% of the stem by weight and is mainly used for low value added products such as rope, cordage and gunnysacks. The inner wood core accounts for the remaining 60% of the stem (Sabharwal, 1995). Commercial jute consists of fiber bundles of 1.8 to 3 meters in length. Individual fibers are 2-5 mm in length and assembled in a parallel manner with ends overlapping to produce continuous filaments containing 10-30 fibers per cross-section. As in woody tissues, individual fibers are held together by lignin containing middle lamellae (Sarkanen and Resalati, 1988).

Average fiber length of jute fibers is 2.5 mm and average fiber diameter is 0.02 mm (Ilvessalo-Pfaffli, 1995). In blends of various proportions, it is used to make printing and writing paper, and tag, wrapping and bag paper.

4.3.1.2 Ramie (*Boehmeria nivea*)

Ramie, also known as China grass, is indigenous to China and adjacent countries. It is a perennial plant growing to a height of 1.5-2.5 m. It is commercially grown in a temperate climate in many countries including China, Japan, Russia, Egypt, Libya, and North and South America. Ramie fibers consist of pure cellulose, and are remarkable for their length and width. They are the strongest and most durable of the vegetable fibers.

Waste and short fibers are used for the manufacture of paper, and average fiber length is 120 mm and the average fiber width is 0.05 mm (Ilvessalo-Pfaffli, 1995).

4.3.1.3 Sunn Hemp (*Crotalaria juncea*)

Sunn hemp is an annual plant grown mainly in India and Pakistan, and grows to a height of 2-3 m. Fibers are separated from the inner bark by retting, and are stronger when wet. Due to this property, the fibers are especially desirable for making fishing nets and ropes, and this is where most of the fiber supply goes. Old fishing nets are therefore one of the largest source of crotalaria fibers for papermaking (Ilvessalo-Pfaffli, 1995).

The average fiber length of sunn hemp is 8 mm and its average fiber width is 0.03 mm.

4.3.1.4 Hemp (*Cannabis sativa*)

Fiber hemp is an annual plant reaching a height of 4-5 m and yielding 12-14 tons of dry matter/yr. ha. About 10-12 tons dry matter/yr ha can be harvested as fiber mass, 35% of which are long bast fibers and 65% are short core fibers (Zomers et al, 1994). Cellulose content of hemp fiber increases as the plant matures. In most countries, hemp harvesting is done by hand (Jeyasingam, 1994 b).

The diameter varies from 5-20 mm depending on the location, growth per hectare, and how seeds are sown. The female hemp plant produces seeds. In any field the proportion of male to female plants are generally in the ratio 50 to 50. It is generally believed that the male plant is superior in respect of fiber compared to the female plant. The reason for this being the lignification in male plants does not take place as quickly as in female plants.

It takes about 80-150 days for plants to be mature for fiber harvesting. It is critical to harvest hemp at the proper time to maximize fiber quality. Early harvesting results in poor yield and weak fibers, whereas delayed harvesting can produce stems that are difficult to separate during the process of retting. Late harvested plants produce fiber much more coarse and harsh.

Hemp fiber for papermaking can have a fiber length from 15-55 mm and an average length of 20 mm. The diameter can vary between 0.016 and 0.22 mm, and the fiber is distinguished by having forked ends (Jeyasingam, 1994 b). In blends of various proportions, it is used to make specialty papers like cigarette paper, lightweight printing and writing paper, condesor paper, and security and currency paper.

4.3.1.5 Kenaf (*Hibiscus cannabinus*)

The kenaf plant is a tropical crop native to Africa. It is an annual plant with a single, straight, unbranched stem consisting of an outer fibrous bark and an inner woody core. Kenaf stalks grow to 5-6 m in length and 25-30 mm in diameter over a period of 5-6 months, at which time it is harvested.

Raw kenaf fiber obtained from the outer bark is actually a bundle of fibers. The outer bark, or bast, is about 40% of the stem by weight and the inner woody core is about 60%. Kenaf has been used on a limited scale as a substitute for wood in the production of pulp and paper in Thailand and China. It contains approximately 65.7% cellulose, 21.6% lignin and pectins (Tao et al, 1995; Mayers and Bagby, 1995). Kenaf pulped with kraft, soda, or neutral sulfite is superior to commercial hardwood pulps and except for tear, is comparable to softwood kraft pulps and superior to softwood sulfite pulps (Mayers and Bagby, 1995).

Fibers from the bast are 3-4 mm long while those from the core are 0.6 mm long (Sabharwal et al, 1994; Kokta et al, 1993), their average diameters are 0.02 mm and 0.03 mm respectively. In blends of various proportions, it is used to make printing and writing paper, newsprint, multi-sack, linerboard, tissue paper, bleached paperboard, cigarette paper and other lightweight specialty papers.

4.3.1.6 Flax tow (*Linum usitatissimum*)

Flax is an annual plant that is cultivated in temperate climate for both its fibers and linseed oil. When planted densely for fiber production, the plant grows to a height of about 1 m. Bast fibers, known as linen, are separated from the inner bark by retting. Flax has an average fiber length of 30 mm and an average fiber diameter of 0.02 mm (McGovern et al, 1989). Raw material for flax pulp is obtained from three sources:

- Textile wastes (old rags and new cuttings). This is the purest form of raw material.

- Fiber waste remaining when bast fibers are removed from textile flax. Relatively clean raw material, known as “textile flax tow”.
- The entire plant after the removal of the seeds from seed flax. This raw material is of low quality, and is known as “seed flax tow”.

In blends of various proportions, it is used to make specialty papers like book paper, lightweight printing and writing paper, condensor paper, currency and security paper, and cigarette paper.

4.3.1.7 Old ropes or rags made from these fibers

Several bast fibers are used to make other products like rope, nets and textiles. When these get old and cannot be used for their original purpose, they serve as a source of nonwood raw material for the paper industry.

4.3.2 Leaf Fibers

Several plants have leaves containing fibers that are suitable for papermaking. In fact, some of these are excellent papermaking fibers. Two of the more commonly used plants are described in this section.

4.3.2.1 Abaca (Manila hemp) (*Musa textilis*)

Abaca fiber, also known as Manila hemp, is obtained from the leaf sheath of a banana like plant grown mainly in the Philippines. The abaca plant propagates itself through suckering, or growing of shoots from roots. When all the leaves have been formed from the stem, flower buds develop, at which time the plant is mature and is ready for harvest. Under normal conditions, the first harvest is completed from 18-24 months after planting. Subsequent harvests are completed at 3-4 month intervals.

The harvesting process consists of two stages, namely topping, where the leaves are cut with the knife, and tumbling, where topped stalks are tumbled down with a cutting knife. The next step is tuxying, where the tuxy is extracted from the leaf sheath by hand or mechanical spindle stripping. The stripped fibers are then dried before grading(Peralta, 1996).

Quality of abaca pulp is affected by the type of cleaning which determines the grade of fibers. Excellent fiber grades are made into pulp for very porous and high strength specialty tissues, such as tea bag papers and meat casings. Fair to residual grades are made into pulp for specialty papers with high tear and tensile strengths such as vacuum bags and wrapping papers (Peralta, 1996).

Abaca plant has an average fiber length of 6.0 mm and it has an average fiber diameter of 0.024 mm. In blends of various proportions, it is used to make specialty papers like superfine, lightweight, bond, ledger, currency and security paper, tea bags, filters, linerboards, wrapping and bag paper.

4.3.2.2 Sisal (*Agave sisalana*)

Sisal is a nonwood leaf plant native to Mexico. It has successfully thrived in semi-arid regions of Brazil, Tanzania and Kenya. Sisal leaves have a width of about 10 cm., a length of about 1-1.5 m and a weight of 500-700 g. Sisal grows all the year round, and the first harvest can be made 2-2.5 years after planting. Sisal produces 180-240 leaves throughout its productive period of 4-6 years.

Sisal leaves are harvested manually and are transversely cut to 50 mm length and hammermilled. Juice and pitch are removed through vertical screens, and chaffed sisal fibers are transported by conveyers to the drying process. Sisal fiber chaff, after having been dried, is pressed into bales for pulping (Kilpinen, 1994).

Sisal leaves have an average fiber length of 3.0 mm and average fiber width of 0.02 mm. In blends of various proportions, it is used to make superfine, lightweight, bond and ledger paper, currency and security paper, tea bags, filters, publication paper, linerboard, wrapping and bag paper.

4.3.3 Seed Hair Fibers

Some plants have seeds covered with fibers. These fibers are also suitable for papermaking. What follows is a discussion of four types of fibers used for papermaking.

4.3.3.1 Cotton fibers

Cotton fibers come from the seedpod of cotton plants. Regular cotton fibers are too long and too expensive for conventional papermaking. They are therefore only used in specialty papers. Most of the cotton fibers produced go to the textile industry. The average fiber length of cotton fibers is 25 mm and the average fiber diameter is 0.02 mm (Kilpinen, 1994). In blends of various proportions, it is used to make high grade bond ledger book and writing paper.

4.3.3.2 Cotton linters

Cotton linters are those fibers that remain on the pod after the long fibers of cotton have been removed for textile use. Cotton seeds are purchased by cottonseed oil mills. These mills need to remove the cotton linters from the seeds. This is accomplished by cutting them from the seeds with circular saws protruding through a grid. The linters can be removed with one or more passes through the saws by controlling the depth the saw protrudes the grid and the dwell time within the cutting chamber. If they are removed in one operation, they produce a grade called mill run, which is a mixture of long and short fibers. If more than one pass is used, then the longer fibers are removed in the first pass and are known as first cuts. The second cut removes the shorter fibers known as the second cuts. These are used by the paper industry both for conversion to cellulose derivatives and for rag content fine paper (Kilpinen, 1994).

The fiber length of mill runs is approximately 3-7 mm; first cuts are 5-7 mm and second cuts are 3-5 mm. The average fiber diameter is 0.03 mm. In blends of various proportions, it is used to make high grade bond ledger book and writing paper.

4.3.3.3 Cotton rags

Cotton rags are among the best fibers available for papermaking. These are the old cotton textiles that are not suitable for their intended use. Due to the mechanical action that these fibers undergo while in use as a cloth, they do not require a lot of refining prior to papermaking. The fiber lengths of the fiber are similar to that of the cotton fibers.

4.3.4 Textile wastes of various types

Textile wastes other than cotton rags are also an important source of papermaking fibers. Textiles like linen are especially important in papermaking. As with cotton rags, these fibers have also undergone mechanical treatment and are thus ready for papermaking.

CHAPTER 5

PROBLEMS WITH UTILIZING NONWOOD PLANT FIBERS

Utilization of nonwood plant fibers, although very popular, has certain inherent drawbacks. Majority of these problems are technological, and require research in this area to be more competitive with wood fibers. The following section discusses some of the problems faced by mills using nonwood plants as their raw material and some of the solutions that have been offered to make nonwoods more attractive as papermaking raw material.

5.1 Technological

5.1.1 Availability

Agricultural-residues are bulky and thus are not easy to handle. There is a need to develop efficient bailers to densify the material for efficient handling transport and storage.

Bamboo has an unusual habit of flowering only once in its life. Flowering occurs in irregular cycles of 30-60 years. Nearly all the clums of one species start to flower at the same time, irrespective of their age, and the flowering spreads, covering large areas. After the flowering the plant dies, and there will be an interruption of supplies of 8-10 years (Ilvessalo-Pfaffli, 1995). The phenomenon of flowering is not understood and more study needs to be done.

Yield of most of these raw materials per hectare is low, about 1 ton/ha. in some of the cases. As a result, they need to be collected over a large area to meet the needs of a paper mill. Table 9 shows the comparison of some of these raw materials according to their yields and potential yields.

5.1.2 Storage and handling

Since most nonwood plants are annual, they have seasonal availability and a relatively short harvesting period. Mills need to procure material during harvest and store it for the rest of the operating year. During storage, these raw materials tend to deteriorate thus providing lower yields. Table 10 shows a comparison between deterioration suffered during storage of wood and some nonwoods. From the data, it is evident that efficient storage methods need to be developed to prevent or reduce this deterioration.

Due to its peculiar problems, much research has been done on the storage and handling of bagasse. Most of this research, though, can be applied to other raw materials as well.

Bagasse deteriorates during storage due to actions of undesirable microorganisms (Al-Simaani et al, 1992). Considerable amounts of bagasse are rendered unsuitable for pulping due to biodegradation. Residual sugar, heterogeneity of tissues, and environmental conditions facilitate the growth of microorganisms in bagasse piles. The type of damage done to bagasse can be classified into two categories: chemical degradation and discoloration. Chemical degradation is the consequence of biochemical reactions. This process affects yield and properties of pulp (Rangan, 1995).

Wet bulk storage of bagasse, originally developed by E. A. Ritter and his collaborators in South Africa, has been a fundamental advance. It has proven to be a superior method for storing bagasse (Atchison, 1989). Product quality improves, the preservation of the bagasse is excellent, and less chemicals are required in pulping and bleaching operations (MacLeod, 1988; Hamilton, 1989).

Development of efficient depithing has been a major boost to the bagasse pulping industry. Moist depithing at the sugar mill, taking out as much pith as possible, reduces any fuel value loss. A secondary wet depithing stage, just prior to charging to the digester, removes additional pith and any dust or dirt. Two stage depithing of bagasse has been the pattern for quite some years now (MacLeod, 1988; Hamilton, 1989).

Two stage depithing , the process of separating the undesirable pith content from the useful bagasse fiber, has also been successfully adopted for straw. In this case dry dusting is followed be wet cleaning. RAKTA a rice straw mill in Egypt was the first to install this process (MacLeod, 1988).

Studies in storage of straw have indicated that straw moisture content should be kept between 10-12%. At higher moisture content straw is subject to microbiological degradation and decay. Another problem is the danger of slow combustion developing in the stack creating a potential fire hazard (Jeyasingam, 1988).

5.1.3 Pulping

In general, pulping of nonwoods is easier compared to wood. Nonwoods have a low lignin content and therefore require less chemicals during cooking, where the raw material is chemically treated under high temperature and pressure to separate the lignin form the fibers. Although kraft or sulfate is the preferred pulping procedure for wood, nonwoods are generally cooked by soda and sulfite as well as sulfate processes. In China sulfite is the preferred mode of pulping.

One of the biggest developments in the pulping of bagasse and straw was the rapid-cooking horizontal-tube continuous digester invented in the mid-fifties. Until this invention rotating and tumbling digesters were running at 4-6 hour cycles. These were batch digesters that could cook a certain amount at a time. The continuous digester was able to cook bagasse and straw in less than 10 minutes. Table 11 shows a comparison for cooking times for different raw materials. In this kind of digester, raw material was added at the top and cooking liquor was introduced at the bottom continuously. Cooked pulp was obtained at the bottom while spent liquor came out at the top. The first commercial rapid-cooking, horizontal-tube, continuous digester was installed in Cuba in 1959. Since then there has been a shift away from batch digesters in bagasse pulping. This shift greatly accelerated the growth of bagasse pulping (MacLeod, 1988).

High energy costs and inferior pulp quality, in general, renders the mechanical pulping of jute less attractive in spite of the obvious advantages of higher yields and less pollution. A study on boimechanical pulping of jute demonstrates the advantages of biological pretreatment before refining (Sabharwal, 1995).

Because of the coarseness and stiffness of the fiber bundles, processing of kenaf remains a problem (Tao et al, 1995). Similarly, nodes of bamboo are harder to cook since they are highly lignified. Significant research with these fiber sources is required before they will be used efficiently.

Most nonwood plants are high in silica content. This high content of silica causes many problems. Washing is difficult because of poor drainage of pulp and high viscosity of black liquor. Washers twice the normal size are required for washing of these pulps. One development in this regard has been the lime-alkali-oxygen pulping process. In the alkali-oxygen process used for straw, adding lime solves the silica problems. When lime is added to the cooking liquor, silica reacts to form calcium silicate, which is insoluble in water. The silica thus remains in the pulp, which is an advantage during the peroxide bleaching stage (Yilmaz, 1995 a, b).

Another problem suffered by nonwood plant pulping has been low yield. Studies on anthraquinone pulping have been quite promising in this regard. Anthraquinon pulping improves yield by up to 5% and kappa number by up to 5 (Hart et al, 1994).

5.1.4 Bleaching

Bleaching of bagasse and other nonwood fibrous raw materials has not been easy. Due to the rapid discoloration during storage most of them have a low initial brightness. This results in mechanical pulp with low initial brightness. Studies conducted on this front have shown that enzymatic pretreatment can improve brightness by 2% ISO (Prasad et al, 1996).

5.1.5 Papermaking

Nonwood fibers are slow to drain, and therefore, cause problems in the paper machine. Because of this, the paper machine cannot be run at high speeds, thus lowering the production. Table 12 illustrates this difference in the maximum speeds for different raw material.

Short fibers of most nonwood plants provide excellent formation and acceptable strength properties. However, these fibers also have low wet strength, and are therefore not easy to pick up at the couch. They therefore require a certain amount of wood pulp in the furnish to improve the runnability.

Technically, to obtain the necessary quality profile and runnability 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-fiber machines. Typically, a paper machine using large percentage of bagasse in the furnish might run at 680-720 m/min., compared to 1,000-1,300 m/min. for a wide modern newsprint paper machine using wood pulp.

5.1.6 Chemical Recovery

As evident in Table 13, most nonwood paper mills are small in scale as compared to wood based paper mills. These mills almost never have a chemical recovery system. Most of these mills operate at profit margin of 6-10% and thus the question of installing recovery systems does no arise. They are therefore among the worst polluters. But these mills are now under pressure to clean up or close down.

A study of five such mills in India has shown that pollution from these mills can be greatly reduced by following at source control measures instead of end of pipe control measures (Gupta, 1994). Table 14 shows the reduction in pollution load after these measures were undertaken. This shows that with a little careful control of the waste generated in these paper mills, the overall pollution load can be greatly reduced.

The main problems existing in Na-based sulfite pulping of bagasse are the technique and economy of pulping spent liquor treatment and chemical recovery. Spent liquor of ammonium sulfite pulping can be used as fertilizer material directly. The same advantage is offered by K-based sulfite pulping spent liquor. For small or medium scale pulp mills, whole K-based sulfite pulping liquor (with neutralization if required) may be used for agricultural purpose directly (Huaiyu et al, 1995). The benefits of using of ammonium based liquor, as evident from Table 15, are that the waste liquor instead of being a pollutant can be used as a fertilizer and has been shown to positively effect the crop yields..

Large mills, where chemical recovery is practiced, have their own problems. Black liquors from nonwood fiber pulping typically have viscosities ten times higher than kraft liquor from pine, for example, so they are hard to handle at high solid contents. There is also a high silica content, 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.

Desilication of black liquor has been worked on, and three companies - Lurgi, Dorr-Oliver, and Kraftanlagen - have developed processes. The first two use boiler flue gas to precipitate the silica, and both processes have been piloted at the RAKTA rice straw mill in Egypt. The Dorr-Oliver method uses lime to accomplish this task (MacLeod, 1988). Work funded by United Nation's Industrial Development Organization (UNIDO) and Swedish Industrial Development Authority (SIDA) also resulted in the successful commissioning of a desilication pilot plant (Judt, 1991 b).

5.2 Economic

5.2.1 Supply

Agricultural-residues are locally available either for free or at a very low cost. The main cost in such cases is incurred on collecting and transporting these raw materials. Table 16 shows a comparison between the cost of kenaf and southern pine in the US. At locations where labor costs are high and the raw material scattered, the collection costs can be prohibitive and make these raw materials undesirable for pulp and paper production. Due to the bulk of these raw materials, transportation can also be a major cost factor in processing. Most of these raw materials are collected manually and as such the labor costs constitute a big percentage of the total raw material costs. Therefore, in countries with extremely low labor rates, pulp production with these raw materials can be highly favorable relative to wood pulping (MacLeod, 1988).

Most sugar mills use bagasse as fuel. So, when considering bagasse, an important factor is the cost of replacement fossil fuel for the sugar mills (Atchison, 1992 b). If fuel replacement costs are high it can generate competition for use of bagasse for papermaking. In some countries where replacement fuel costs for bagasse are very inexpensive, production costs for nonwood based paper are lower than in wood based mills (MacLeod, 1988). There have been studies on setting up joint sugar and paper mill complexes. This would not only cut the transport costs of bagasse but also favorably effect the power requirements of the paper mills (See Table 17 based on Rangan, 1995)

Plants like abaca, sisal hemp esparto and others require manual harvesting and other processes. These labor-intensive processes result in expensive raw material. Most of these materials are used in only high value specialty paper.

In 1996, farmers in the US sold straw, from wheat and other cereal crops, at $10 per ton for animal bedding. In contrast, wood chips are priced at $100/ton. If straw is bought at $40/ton and, consideration is given to the low yield of straw, the two pulps would cost $58/ton and $106/ton for straw and wood respectively (Rosenberg, 1996). So it is cheaper to use straw and it would expected that its use would be more widespread. However, due to supply problems, this is not the case.

Kenaf’s low density (0.25 times the density of typical wood chips) raises transport, handling and storage costs. In addition, specially designed harvesting and handling equipment and large storage areas are needed for the kenaf harvested. Each mill must carry approximately eight months supply of kenaf in order to function efficiently.

5.2.2 Storage and handling

Since most of these raw materials result from annual crops, they need to be acquired over a short period of time and stored for use for the rest of the year. Therefore, expense is incurred in protecting this raw material from deterioration during storage. Most of the raw material is bulky and thus requires large storage spaces. A number of measures such as covered storage and chemical treatment of raw material before and during storage are also required to ensure that the raw material does not deteriorate. This can be expensive.

At the same time, a large inventory of raw material has to be kept, putting an economic burden on the mill. Because of this, mills have been known to close or switch to other raw materials.

5.2.3 Pulping

In general pulping of nonwood plants is cheaper than wood. They are low in lignin and, thus, do not require as much chemical. However, the cost advantage achieved in pulping and bleaching is offset in washing, papermaking and chemical recovery.

In washing, since black liquor is highly viscous, larger washing equipment is required for nonwood fiber. Moreover, due to its high viscosity, to achieve a fair amount of washing, a lot of water is required, thus, reducing the solid content of the black liquor and increasing the load on the evaporators.

5.2.4 Bleaching

During storage, most of the nonwoods tend to deteriorate and get colored. The resultant pulp therefore is not high in brightness. To make this pulp desirable, it has to be subjected to enzymatic pretreatment or a more severe bleaching action. In either of the case the resultant pulp has higher chemical/enzyme requirement and is thus a little costlier (Bajpai and Bajpai, 1996).

5.2.5 Papermaking

Since the nonwood pulps are slow to drain, the paper machine section must have a reduced speed. As can be seen in Table 12, machines running wood fibers are some times as much as three times as fast as the machines running nonwood fibers like straw. Because of this slow production time, the overhead cost for paper made from nonwood fibers is higher.

5.2.6 Chemical Recovery

Chemical recovery is the biggest economic hurdle to the functioning of the nonwood paper mills. Most of the nonwood paper mills are small scale and do not have enough capital to install a recovery system. So they discharge the effluents directly into the environment. Governments all over the world are now in the process of closing such mills. Even the mills that are big enough to afford a recovery systems have problems peculiar to nonwoods.

The biggest problem is the presence of silica. Silica present in the raw material dissolves in the cooking liquor resulting in highly viscous black liquor. To be able to handle the black liquor, it is kept at a low solid content leaving the washing section. As a result, the load on the evaporators increases reducing their efficiency and increasing the recovery costs (McLeod, 1988).

During evaporation, the silica starts to precipitate and deposits on the evaporator walls. This greatly reduces the heat transfer through the evaporator walls. Due to this, the evaporators do not function at their full capacity. Silica that stays with the cooking chemicals forms calcium silicate and then slows the settling rate of lime sludge. Also the lime sludge contaminated with calcium silicate is not fit for reburning, and chemicals are therefore not fully recovered. This puts a further burden on the cost of cooking chemicals for the mill.

5.3 Pulping Economics in China

Having taken a look at the various stages where nonwood pulping can be expensive compared to wood as a papermaking raw material, let us take a look at the actual pulping costs for various raw materials in China. Table 18 gives us pulping costs for four different nonwood fibers, straw, cotton, wheat straw and rice straw, as compared to wood. All the mills have pulping capacities of under 50 tons per day and thus fall under the category of small sized mills (Xufang and Jin Tao, 1997).

The average costs of production for straw is the highest at about 3888 yuan/ton followed by cotton at 3706 yuan/ton, wood (bleached) at 3143 yuan/ton, wood (unbleached) at 2122 yuan/ton, wheat straw at 2009 yuan/ton and rice straw at 1988 yuan/ton. Except for straw, the rest of the figures seem to be in order. Cotton being the specialty fiber is the costliest, followed by wood and rice and wheat straw almost equal as the cheapest.

A break up of the production costs indicates that difference in cost of production of pulp follows the same pattern as the cost of raw material. Cotton is the costliest fiber at an average price of 2318 yuan per ton of pulp produced. The raw material costs of the two mills using cotton are vastly different at 2 yuan/kg and 0.58 yuan/kg. But looking at the amount of raw material being used, it can be inferred that the cheaper raw material is high in impurities. Wheat and rice straw are by far the cheapest raw materials costing less than a quarter of the price of cotton per ton of pulp produced (See Table 18).

The production cost of bleached pulp from these raw materials is not much different. They range from 2087 yuan per ton for straw, 1768 yuan per ton for wood to 1388 yuan per ton for cotton. Cotton, by virtue of having no lignin content, requires less effort in pulping and thus its raw material cost makes up for the major portion of production costs. Wheat and rice straw are also easier to pulp. But, compared to almost 50% yield of wood, their yield is in the range of 25-30%. This increases the processing cost of the pulp, which is nearly 75% of the total production cost.

These figures indicate that economically wheat and rice straw are cheaper substitutes for wood as paper making raw material. Because of this, they are the leading papermaking raw material in China (See Table 8).

CHAPTER 6

AVAILABILITY OF NONWOOD FIBERS

There is an abundance of nonwood fibers potentially available for the paper industry. Table 16 shows estimates from 1982, which have only increased as time has passed. Unfortunately, due to various technical and economic reasons, only around 3% of these fibers are used for papermaking.

In 1995 around 545 million tons/annum could be produced in the world. Nonwood fibers have been used in many countries like China, India, Spain, Italy, Turkey, Denmark and Romania (Yilmaz, 1995). Nearly 2.2 million tons of jute bast alone (excluding core) is reported to be potentially available world wide. The 14.5 thousand tons of bast material used in India constituted just 1% of the total jute bast material available in India in 1990-91 (Sabharwal et al, 1995).

The Philippines produces around 61,500 tons/yr. of abaca, which accounts for 85% of the total world demand. The remainder comes from Ecuador, which produces around 11,500 tons per year (Judt, 1993). In Thailand it is possible to contract with farmers to grow eucalypti, bagasse, bamboo or straw on land unsuited for rice production -- or instead of food crops (Meadows, 1995 b). At the Phoenix paper mill in northern Thailand, design of the first production line was completed with the intention of processing kenaf. But the farmers received better prices for sugarcane and thus the supply dwindled. The mill therefore concentrated on bamboo which turned out to be a good cash crop for farmers since bamboo shoots are a much sought after Thai food delicacy. When planning a second production line with 400,000 tpy of bamboo and 30,000 tpy of kenaf, to ensure a steady supply, the mill took the following steps: 1. Technical assistance was made available to farmers free of cost; 2. Bamboo planting was promoted by providing seedlings, fertilizers and insecticides at cost; 3. Minimum prices for the raw material delivered to the mill were guaranteed; and 4. Interest free financial assistance was provided (Guest, 1996 a). Similarly at Panjapol, also in Thailand, the mill pays cash to farmers for bamboo and eucalyptus (Guest, 1996 b).

In China, bamboo grows in the southern and western provinces of Hunan, Sichuan, Fujian, and Jiangsu among others (see Figure 1). Bamboo forest covers an area of approximately 3.3 million hectares (Al-Simaani et al, 1992). Unlike other nonwood plants that are cultivated or limited to a certain area, reeds grow widely and abundantly in the marshes throughout China (Chen et al, 1994). Reeds are a major source of nonwood fibers for papermaking in China (See Table 8).

CHAPTER 7

SUPPLY AND DEMAND IN CHINA

(MILL PROBLEMS, PROCUREMENT OF RAW MATERIAL)

7.1 Small mills versus large mills

Pulp mills in China are classified into three categories according to production capacities as follows :

- Small size mills with capacities less than 10,000 tons/yr.
- Medium size mills with capacities of 10,000-30,000 tons/yr.
- Large Size mills with capacities of above 30,000 tons/yr.

Approximately 200 pulp mills are of medium or large size and account for 42% of the total pulp production in China. The remaining 58% is produced in a staggering number of small mills. According to Xing, the 1993 edition of The Almanac of China's Paper Industry listed 5,603 paper mills, and it is assumed that thousands of small paper mills go unlisted. Although these small mills suffer from drawbacks of low operating efficiency and environmental pollution due to lack of chemical recovery, they remain the major contributors to the Chinese pulp and paper industry. The main reasons for the great number of small mills include:

- Nonwood raw materials are bulky and scattered in small and remote areas. Hence proximity to raw material resources will reduce cost of handling and transportation;
- Normally small mills serve local markets' needs within a province, thereby reducing the cost of final product distribution;
- Limited capital available for investment by provincial and municipal authorities or bank loans from within the country or abroad and;
- Low cost labor (Al-Simaani et al, 1992).

The overall distribution of sizes of nonwood pulp mills in several Asian countries is shown in Table 13. The supply situation is confounded by competition between small scale paper mills and the large papermakers. Political considerations tend to tip the scales in favor of the small mills, so shortages for large mills are especially acute (Cao, 1996).

7.2 Raw material required for large mills

Since most nonwood raw materials are annual crops, mills have to procure it over a short period of time. Also, the raw material needs to be in sufficient quantity to satisfy the raw material need for the rest of the year. Since most of these materials have low per hectare yield, they have to be collected from a large area. This causes the cost of raw material to increase. This raw material is also bulky and therefore, the transportation costs are further increased.

Once procured, this raw material needs to be stored. As already stated, it is very bulky and needs a large area for storage and special precautions since it can be highly combustible. The raw material also deteriorates over time and results in a lower yield. This means that the mill has to procure more raw material than would be theoretically required for an year's operation. Unlike the small mills, that sometimes use different raw materials depending on their availability, the large mills have to stick to one raw material as they cannot change the cooking process as easily. One of the reasons for this is the fact that larger mills have a recovery system and any change in the cooking process or raw material will entail a change in the recovery process too.

Large mills are often required to have a large inventory of raw material to ensure their smooth operation. This ties up financial, land and other resources causing the mills to opt for other raw materials.

CHAPTER 8

USE OF NONWOOD PLANT FIBERS IN SPECIFIC PAPER AND PAPERBOARD GRADES

Any grade of paper can be produced from several nonwood plant fibers and in blends with wood fibers. Some grades of paper have been made from 100% nonwood fibers. Table 17 of this report provides a comprehensive look at the grades of paper made from various nonwood plant fibers.

Abaca or manila hemp is the best papermaking fiber available. It has excellent properties for making strong products like tea bags, large sausage casings, currency paper, cigarette and filter paper, which require high wet strength, often combined with high porosity (MacLeod, 1988). Tea bags are the largest market for abaca specialty paper, accounting for 16,000 tons/yr. In addition abaca is preferred in stencil paper, electrolytic paper, cigarette plug wraps, vacuum-cleaner bags, medical tissue and other nonwoven disposable products.

Bagasse pulps are now used in practically all grades of paper including bag, wrapping, printing, writing, toilet tissue, toweling, glassine, corrugating medium, liner board, bleached boards and coating basestocks (Atchison, 1993). Newsprint has been successfully produced on a commercial scale using a kenaf peroxide chemithermomechanical pulp (CTMP). Pulp blends with 25% kenaf CTMP can be used as reinforcing pulp in recycled newsprint (Mayers and Bagby, 1995). 30-50% kenaf CTMP can be blended with a loblolly pine kraft pulp and made into linerboard with acceptable strength properties (Mayers and Bagby, 1995).

Flax and true hemp are used to make cigarette paper around the world (Macleod, 1988). Sisal can be made into very strong products such as liner board, wrapping and bag paper. Cotton linters are used for premium quality letterhead paper, currency paper, dissolving pulp and other specialty products (Macleod, 1988). Bagasse and straw are best at contributing excellent formation to papers and can replace hardwood chemical pulps pound for pound for printing and writing paper (Macleod, 1988).

Pulps made from nonwoody annual plants (e.g., rice and wheat straw, bagasse, flax, or kenaf) are suitable as reinforcing fibers in pulps made from wastepaper. Wheat straw has been shown to be suitable furnish for writing and printing paper (Pekarovikova et al, 1994).

Traditionally hemp bast fibers have been used as raw material for specialty papers like bible, cigarette, currency, insulating and condenser tissue paper (Zomers et al, 1995). Esparto, with a little addition of softwood pulp for strength, makes good writing, postage-stamp, and check papers. It is specially preferred for those application that need a clear watermark with an accurate register (Clark, 1985). In China, sabai grass is used for carbon body paper (Ilvessalo-Pfaffli, 1995).

CHAPTER 9

CONCLUSIONS

With the cost of imported pulps and waste soaring, and the wood resources being limited for the developing countries, the technology of nonwood pulping will continue to develop at a rapid rate. This, along with the rapid rise in demand for paper products, represents a major potential market for suppliers to pulp and paper industry. It is expected that the current surge in new mills will continue for several decades.

Added to this is the rapid increase in population in most of these countries. This puts additional pressure on the available land resources that inhibit the growth of forest plantations. As a result alternative raw materials are playing an important role in the paper industries in the developing countries.

Around the world, there is a case for use of nonwood fibers for papermaking. There is a shortage of short fibers in the European Union due to lack of hardwood trees. They are at present discovering the advantages of using nonwood fibers to fill this need. In the US, pressure from environmental groups and rising cost of wood, may force the use of nonwood plants for papermaking.

Pulping of agricultural residues is of increasing interest due to economic and environmental factors. Some of these factors are:

- For fine papermakers, short fibered pulp gives better formation and opacity. These can be provided by nonwood fibers, especially straw pulp, which consumes less refining energy than wood fiber.
- Governments of the USA and the EC countries are trying to curtail surplus grain production by encouraging the farmers to grow non-food crops on agricultural land.
- Environmental regulations prohibit burning of stubble in the fields, and this has increased the availability of straw for nonagricultural use in North America and western Europe.
- Environmental pressure groups are trying to limit clear felling of old growth forests to protect animal life, and to protect sensitive forests and favor bio-diversity in plantations. (Chauduri, 1993)

- Current drive towards increased implementation of sustainable forest management is also driving paper industry to look for alternative fiber sources.

Over the years, research in the field of nonwood pulping has yielded many results. Consequently, use of nonwood fibers in papermaking has not been as troublesome as in the past. But, a number of problems still continue to plague the nonwood paper industry.
On the supply side, new harvesters and balers are being developed. The harvesters will allow better harvesting of straw and other agricultural residues making harvesting more economical while the new balers will provide more compact bales thus reducing the transport costs. Development is also being made in design specialized harvesting equipment for other raw material as well.

New and improved chemical treatment methods are being applied to prevent nonwood fibers from deteriorating over their long storage periods while at the same time reducing their pulping costs. Individual raw materials have also seen large scale research in various pulping and papermaking fields to improve their economic viability as raw material.

Significant progress has been made to develop bagasse pulping, which has turned out to be the most promising nonwood raw materials for papermaking. Developments in depithing, storage, pulping and bleaching of bagasse have resulted in lower production costs. These developments have also found implementation in the use of other nonwood plants. Bagasse fibers also have good papermaking properties. Use of bagasse has a further advantage of having lower collection costs since it is obtained from sugar mills, which take care of collection. Therefore, in countries where the replacement fuel cost for bagasse in sugar mills is low, use of bagasse as papermaking raw material is an attractive prospect. There have also been studies on establishing joint sugar-paper mill complexes, further lowering the production costs.

Bamboo is also an important raw material in several countries besides China. Over time, most of the technological problems associated with its use have been overcome. Since it grows, and can be harvested all year round, mills do not need to carry a large inventory. This makes it a one of the better raw materials among nonwoods. Its fiber properties are also excellent for papermaking.

Another major nonwood raw material has been straw. Although, use of straw as a papermaking raw material had some problems, research has provided answers to most of them. Bailing and storage are a couple of areas that have seen new developments. The major development has been the development of efficient desilication equipment (Judt, 1991 b). Since straw has inherently high silica content, especially rice straw, this has further reduced the problems associated with pulping of straw. Added to that, the universal availability of straw should make it an attractive papermaking raw material in countries with low collection costs.

Another promising raw material that has been a center of attraction, especially in the US, has been kenaf. Research has indicated it to be a potentially important raw material. Studies on some other raw materials have also yielded encouraging results.

One of the major problems associated with nonwood fiber pulping, pollution, has also been addressed. Most nonwood fiber pulp mills are small and not operate at large profit margins. Therefore, they do not find it economical to install a chemical recovery systems. As a result they are among the major polluters. Studies have identified ‘at source’ pollution control and the use of ammonium sulfite cooking liquor as two potential solutions.

In China, use of nonwood plant fibers in papermaking continues to grow. Although in recent times, the emphasis has been on the growth of wood pulp based paper mills, the growth of nonwood paper mills has not slowed. In fact, it is expected to grow faster than wood based paper mills for some time to come. The government in China has taken steps to close polluting paper mills. This has resulted in further developments in the pollution control methods. Significant government sponsored research is also going on in the field of nonwood papermaking (Judt, 1994)

With countries where currently nonwood fibers are not a big source of fibrous raw material increasing the amount of nonwood fibers used in papermaking raw material, the experiences in China will be very important reference. China is by far the largest producer of nonwood pulp paper. Therefore these experiences with practical aspects of nonwood papermaking will be helpful since they will provide us with the data required to set up profitable nonwood fiber based paper mills.

Since China is conducting a major expansion in its papermaking capacities (See table 4), there is a potential for investment in the Chinese paper industry. Although, the Chinese government does not allow foreign ownership in the paper industry, there is a big, and growing, market for the equipment suppliers.

At present most paper mills in China have old equipment. This results in costly paper with paper quality being poor (Cao, 1996). They will therefore be needing newer and more efficient machinery for papermaking. With increasing global business presence, China will have to adhere to more strict environmental standards. This will result in a need for pollution control technology and equipment. These are just two of the potential markets for equipment suppliers.

Fueled by various environmental and other factors, the use of nonwood plant fibers for pulping and papermaking is also expected to grow in the countries where till now it has been largely ignored. Reduction in burning of straw requires that straw be put up for alternate use and paper production is one use where enough research has already been done around the world. Also, curtailing grain production to maintain grain prices will require the farmers to grow alternate crops and here also papermaking raw material is a real alternative.

With these considerations it can be safely said that use of nonwood plant fibers for pulp and paper industry will continue to grow at a fast rate and also grow as a percentage of total papermaking raw material for some time to come.

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TABLES

Table 1 - World papermaking capacities

	Total papermaking pulp capacity, (million metric tons)					Average annual increase, (%)			
	1970	**1985**	**1988**	**1993**	**1998 est.**	**70-85**	**85-88**	**88-93**	**93-98**
Total papermaking grades - all fibrous raw material	113.5	164.4	175.7	197.1	208.6	2.9	2.2	2.5	1.1
Total papermaking grades of wood pulp	105.9	151.0	160.1	176.4	185.1	2.8	2.0	2.0	1.0
Total nonwood plant fibers papermaking pulp	7.6	13.4	15.6	20.7	23.5	5.1	5.0	6.0	2.5
Percentage of nonwood plant fibers pulp to total papermaking pulp	6.7	8.1	8.8	10.5	11.3	N.A.	N.A.	N.A.N.A.	

(Source: Atchison, 1996)
Note: 1998 Figures are estimated

Table 2 - Worldwide nonwood papermaking pulping capacities

Raw material	Total papermaking pulp capacities, million metric tons			
	1993	1995	1998	2000
1. Straw	9.566	9.829	10.892	10.892
2. Sugarcane bagasse	2.984	2.668	3.254	3.277
3. Bamboo	1.316	1.323	1.508	1.508
4. Miscellaneous raw materials	6.870	7.067	7.710	7.720

(Source: FAO, 1996)

Table 3 - Leading countries in nonwood papermaking pulp capacities

Country	1995: Nonwood pulping capacity (000 metric tons)	1995: Total pulping capacity (% from nonwood)	2000: Nonwood pulping capacity (000 metric tons)	2000: Total pulping capacity (% from nonwood)
1. China	15,954	85.8	17,672	84.2
2. India	1,523	58.0	2,001	61.3
3. Pakistan	415	100.0	491	100.0
4. Venezuela	264	70.4	260	65.0
5. Mexico	230	24.1	230	24.1
6. Columbia	215	48.3	252	46.8
7. Turkey	191	27.4	191	27.4
8. Thailand	171	51.7	221	34.2
9. Greece	150	85.7	160	84.2
10. Italy	145	23.6	145	23.6
11. Argentina	140	12.8	140	12.8
12. Brazil	140	2.1	182	8.0
13. Spain	140	7.5	141	7.2
14. Egypt	127	100.0	127	100.0
15. Cuba	108	100.0	108	100.0
16. Iraq	101	100.0	101	100.0
17. South Africa	99	6.4	113	7.0
18. Vietnam	95	54.9	100	40.0
19. Iran	90	25.0	90	25.0
20. Indonesia	86	3.1	86	1.4
21. Bangladesh	75	34.3	75	34.3
22. Ecuador	74	100.0	77	100.0
23. DPR Korea	50	47.2	50	47.2
24. Peru	50	100.0	50	100.0
25. Romania	44	8.8	74	9.3
Subtotal 25 countries	20,677	N/A	23,137	N/A
Total all Countries	20,887	10.45	23,397	10.7

(Source: FAO, 1996)

Table 4 - Major green field and expansion projects in China

Mill (City/Province)	Capacity (tpy)	Fiber Species	End Product
Beihai (Beihai/Guangxi)	70,000	Masson Pine	Viscous pulp
Guangning (Guangning/Guangdong)	44,000	Bamboo; Masson pine	Market pulp; Printing and Writing
Guangzhou* (Guangzhou/Guangdong)	30,000	Secondary fiber	Deinked pulp
Ditto*	50,000	Masson pine	CTMP
Ditto*	170,000	Masson pine	Newsprint
Hayang* (Hanyang/Hubei)	35,000	Eucalyptus	CTMP
Hexian (Hexian/Guangxi)	50,000	Masson pine	Market pulp; Printing and Writing
Huaqiao (Foshan/Guangdong)	70,000	Market pulp; Secondary fiber	Coated white board
Huanghai (Yellow sea) (Rizuo/Shandong)	170,000	Imported chips	Market pulp
Jilin* (Jilin/Jilin)	150,000	Poplar; Larch	Newsprint
Jiangmen* (Jiangmen/Guangdong)	50,000	Market pulp	Coated art
Leshan* (Leshan/Sichuan)	80,000	Masson pine	Market pulp; Printing and Writing
Leizhou (Leizhou/Guangdong)	50,000	Eucalyptus	Market Pulp; Printing
Liwen (Dongguan/Guangdong)	20,000	Market pulp	Coated art
Liujiang* (Liujiang/Guangxi)	24,000	Reed	
Mudanjiang* (Mudanjiang/Reilongjiang)	170,000	Pine; Larch; Poplar	CTMP & KP
Ningbo* (Ningbo/Zhejiang)	350,000	Secondary fiber; Market pulp	Coated white board
Puxi (Puxi/Hubei)	50,000	Bamboo	Market pulp; Offset printing
Qihe (Qihe/Shandong)	34,000	Secondary fiber	Kraftliner

Table 4 (Continued)

Mill (City/Province)	Capacity (tpy)	Fiber Species	End Product
Quingzhou* (Quingzhou/Fujian)	170,000	Masson pine	Market pulp (Unbleached)
Ditto*	170,000 (Bleaching plant)	Masson pine	Market pulp (Bleached)
Shanghai Corp. (Shanghai)	70,000	Secondary fiber	Deinked pulp
Shaowu (Shaowu/Fujian)	50,000	Bamboo	Market pulp; Offset printing
Shanwei (Shanwei/Guangdong)	150,000	Southern pine	Market pulp
Simao (Simao/Yunnan)	51,000	Yunnan pine	Market pulp; Printing
Tianjin No. 4* (Tianjin)	40,000	Market pulp	Coated art
Tianjin No. 5* (Tiankjin)	30,000	Market pulp; Cotton linter	Bond; Writing
Wuhan (Hankuo/Hubei)	34,000	Secondary fiber	Board
Xinhuo (Shanghai)	120,000	Secondary fiber; Market pulp	Coated white board
Xuecheng (Xuecheng/Shandong)	20,000	Secondary fiber; Market pulp	Coated white board
Ya’an (Ya’an/Sichuan)	35,000	Bamboo	Market pulp; Printing
Yalujiang* (Dandong/Liaoning)	100,000	Birch; Larch	CTMP
Yangzhou* (Yangzhou/Jiangsu)	42,000	Market pulp	Coated art
Yibin* (Yibin/Sichuan)	20,000	Masson pine	Newsprint
Yichun (Yichun/Jiangxi)	34,000	Bamboo	Offset printing
Yintai (Yintai/Shandong)	100,000	Market pulp	Coated art
Ditto	120,000	Secondary fiber; Market pulp	Coated board
Yuanjing* (Yuanjing/Hunan)	17,000	Kenaf	Newsprint
Yueyang* (Yueyang/Hunan)	26,000	Masson pine	CTMP

Table 4 (Continued)

Mill (City/Province)	Capacity (tpy)	Fiber Species	End Product
Zhenjiang* (Zhenjiang/Jiangsu)	24,000	Reed	Coated art
Zixing (Suzhou/Jiangsu)	100,000	Market pulp	

* Expansion projects and added capacities

(Source: Xing, 1995)

Table 5 - Estimated annual collectable yields of various nonwood plant fibrous raw materials

Fibrous raw material	Collectible as raw material (BD* metric tons per hectare per year)	Equivalent in Bleached pulp (BD* metric tons per hectare per year)
Sugar cane bagasse	5.0-12.4	1.7-4.2
Wheat straw	2.2-3.0	0.7-1.0
Rice straw	1.4-2.0	0.4-0.6
Barley straw	1.4-1.5	0.4-0.5
Oat straw	1.4-1.5	0.4-0.5
Rye straw	2.5-3.5	0.8-1.0
Bamboo, natural growth	1.5-2.0	0.6-0.8
Bamboo, cultivated	2.5-5.0	1.0-2.1
Reeds in the USSR	5.0-9.9	2.0-4.0
Kenaf, total stem	7.4-24.7	3.0-9.9
Kenaf bast fiber	1.5-6.2	0.7-3.2
Crotalaria bast fiber	1.5-5.0	0.7-2.5
Papyrus in Sudan	20.0-24.7	5.9-7.4
Abaca	0.7-1.5	0.4-0.7
Seed flax straw	1.0-1.5	0.18-0.27
Cotton staple fiber	0.3-0.9	0.25-0.86
Second cut cotton linters	0.02-0.07	0.015-0.062
Corn stalks	5.5-7.0	1.55-1.95
Sorghum stalks	5.5-7.0	1.55-1.95
Cotton stalks	1.5-2.0	0.6-0.8

(Source: Atchison, 1989)

* Bone Dry

Table 6 - Fiber dimensions of nonwood plant fiber pulps

Nonwood plant fiber	Average length (mm)	Average diameter (microns)
Abaca	6.0	24
Bagasse	1.0-1.5	20
Bamboo	2.7-4	15
Corn stalks & sorghum	1.0-1.5	20
Cotton fibers	25	20
Cotton stalks	0.6-0.8	20-30
Crotalaria	3.7	25
Esparto	1.5	12
Flax straw	30	20
Hemp	20	22
Jute	2.5	20
Kenaf bast fiber	2.6	20
Kenaf core material	0.6	30
Rags	25	20
Reeds	1.0-1.8	10-20
Rice straw	0.5-1.0	8-10
Sisal	3.0	20
Wheat straw	1.5	15
Wood fibers		
Temperate zone coniferous wood	2.7-4.6	32-43
Temperate zone hardwoods	0.7-1.6	20-40
Mixed tropical hardwoods	0.7-3.0	20-40
Eucalyptus	0.7-1.3	20-30
Gmelina	0.8-1.3	25-35

(Source: Atchison, 1989)

Table 7 - Chemical properties of nonwood plant fibers

Type of fiber	Cross and Bevan Cellulose (%)	Alpha Cellulose (%)	Lignin (%)	Pentosans (%)	Ash (%)	Silica (%)
Stalk fiber						
-rice straw	43-49	28-36	12-16	23-28	15-20	9-14
-wheat straw	49-54	29-35	16-21	26-32	4.5-9	3-7
-barley straw	47-48	31-34	14-15	24-29	5-7	3-6
-oat straw	44-53	31-37	16-19	27-38	6-8	4-6.5
-rye	50-54	33-35	16-19	27-30	2-5	0.5-4
-sugarcane	49-62	32-44	19-24	27-32	1.5-5	0.7-3.5
-bamboos	57-66	26-43	21-31	15-26	1.7-5	0.69
-esparto grass	50-54	33-38	17-19	27-32	6-8	
-sabai grass	54.5		22.0	23.9	6.0	
-phragmite communis reed	57.0	44.75	22.8	20	2.9	2.0
Bast fibers						
-seed flax tow	75.9-79.2	45.1-68.5	10.1-14.5	6.0-17.4	2.3-4.7	
-seed flax	47	34	23	25	5	
-kenaf	47-57	31-39	14.5-18.7	22-22.7	1.7-5.0	
-jute	55-58		21-26	18-21	0.5-1.8	
Leaf fibers						
-abaca (Manila)	78	60.8	8.8	17.3	1.1	
-sisal (Agave)	55-73	43-56	7.6-9.2	21.3-24	0.6-1.1	
Seed hull fibers						
-cotton linters		80-85			0.8-1.8	
Woods						
-coniferous	53-62	40-45	26-34	7-14	<1	
-deciduous	54-61	38-49	23-30	19-26	<1	

(Source: Judt, 1992)

Table 8 - Predicted fiber consumption in China in the year 2000

Fiber Material	Consumption (Million tons)
Reed	3.15
Bagasse	2.3
Bamboo	1.17
Wheat/rice straw	19.35
Waste hemp/flax/cotton	1.5
Wastepaper	11.0
Others	0.65
Total nonwood	39.12
Total wood	15.0

(Source: Yin-ce, 1995)

Table 9 - Stem dry matter yields for nonwood fiber crops

Crop	Annual yield (tons/ha.)		
	Average	Range	Potential
Annuals			
Flax	8	6-9	10
Hemp	10	9-13	15
Kenaf	10	8-20	40
Sorghum	9	8-12	30
Perennials			
Bamboo	7	5-12	20
Reeds	15	10-20	40
Elephant grass	17	17-25	60
Short rotation forestry	9	6-15	40
Agricultural residues			
Straw	2	1-3	4

(Source: Judt, 1994)

Table 10 - Wood and nonwood comparisons

Factor	Hardwood	Fiber Straw	Bagasse	Kenaf
Means of storage	Pile	Stacked bales	Piles or stacked bales	Stacked bales
Losses in fiber prep (%)	5	ca 30	ca 30	ca 30
Power (kwh/ADMT)	480	ca 900	ca 900	ca 900
Steam (MT/ADMT)	4.5	ca 9	ca 10	ca 9

(Source: Perham, 1990)

kwh-Kilowatt hour
MT-Metric ton
ADMT-Air dry metric ton

Table 11 - Cooking Conditions and Results for Short-Period Continuous Pulping of Several Agro-Based Plants

Raw Material	Pulping Process Chemical	Chemical Applied as Na_2O_2 %	Dwell Time min	Steam Pressure psi	Pulp yield %	Perma-nganate Number
Wheat Straw*	Soda	4.6	8	75	67	--
	Soda	10.0	8	80	50	--
Rice Straw*	Soda	9.8	5.5	100	39	4.9
Bagasse**	Kraft	12.0	10	130	52	7.5
Reeds*	Soda	13.8	20	130	48	15.0
Esparto	Soda	12.4	20	120	52	6.0
Bamboo (*Bambusa Arundinacea)*		18.2	30	130	45	10.0
Reeds***	Neutral-sulfite	19.1	25	150	53	12.3
	Neutral-sulfite	10.7	10	150	62	24.4

* Uncleaned raw fiber
** Depithed or Cleaned
*** Cleaned reeds; Chemical applied as Na_2SO_3

Table 12 - Typical Paper Machine Speeds for Straw and Bagasse

Furnish	**Older Machines** (open draw) (meters per minute)	**New Machines** (no draw press section) (meters per minute)
Rice Straw	100-180	200-400
Other Straws	150-250	300-500
Bagasse	200-350	400-650
Wood	250-500	500-800

(Source: Young, 1997)

Table 13 - Size of nonwood pulp mills in leading countries

Tons/day	China	India	Indonesia	Thailand
Less than 50	67%	57%	60%	58%
50-100	21%	09%	00%	14%
Over 100	12%	34%	40%	28%

(Source: Sadawarte, 1995)

Table 14 - Specific pollution load before and after implementation of waste minimization measures

Parameter	Before	After	Reduction
1. Flow m^3/ton	170	120	30%
2. COD kg/ton	990	657	34%
3. BOD kg/ton	202	129	36%
4. TSS kg/ton	336	205	39%
5. TS kg/ton	1210	714	41%

(Source: Gupta, 1994)

COD - Chemical Oxygen Demand
BOD - Biological Oxygen Demand
TSS - Total Suspended Solids
TS - Total Solids

Table 15 - Farmland harvestings with Ammonium Sulfite waste liquor

Plantations	Ammonium sulfite waste liquor applied (Equivalent N_2 in kg/ha)	Croppings (kg/ha)	Increase in croppings compared to no fertilizer added kg/ha	%
Wheat	31.5-72	1580-4000	578	34.2
Rice	58.5-78	4240-4400	635	18.3
Potato	87-109	8080-17000	66190	28.8
Chinese cabbage	63-225	71400-75300	21200	36.0
Lettuce	31.5-63	28100-30200	6470	28.0
Chinese chive	79.5-162	24000-30500	5740	27.0
Spinach	39-242	33500-70000	5910	13.0
Cucumber	28.5	58300	4030	7.4

(Source: Zhong, 1995)

Table 16 - Comparison of kenaf and wood raw materials

	Southern Pine	Kenaf
Growing Cycle (years)	15-20	0.4-0.5
Average yield of dry fibrous material (tons/acre/yr.)	3	6
Bleached yield (percent)	43	46
Delivered cost of fibrous raw material (US $/ton pulp)	120-180	100-120

(Source: Sabharwal, 1994)

Table 17 - Comparison of Steam and Power Requirements (Sugar and Paper Mills)

Sugar mill = 2000 TCD   Paper Mill = 75 TPD

INDIVIDUAL UNITS

	Steam (Tons/hr)	Power Generated (MW)	Power Required (MW)	Power Excess/Shortfall (MW)
Sugar	41.6	3.5	3.5	Nil
Paper	31.2	3.0	6.0	-3.0
Total	72.8	6.5	9.5	-3.0

Purchased power : 3 MW throughout the year

INTEGRATED COMPLEX

	Steam (Tons/hr)	Power Generated (MW)	Power Required (MW)	Power Excess/Shortfall (MW)
Sugar	41.6	6.0	3.0	3.0
Paper	31.2	4.0	6.0	-2.0
Total	72.8	6.5	9.5	1.0 Excess

Purchased power : through sugar season nil
: During off season 2.0 MW

(Source: Rangan, 1995)

Table 18 - Comparison of Pulping Costs for Paper Mills in China

Paper Mill	Annual Production	Production Costs (Yuan/ton)	Of Which Fiber (Yuan/ton)	Fuel (Yuan/ton)	Water (Yuan/ton)	Electricity (Yuan/ton)
Bleached wood pulp						
Hielongjiang Paper	13,138	2,800	N. A.	N. A.	N. A.	N. A.
Kaishantun Chem. Fiber	4,037	3,626	N. A.	N. A.	N. A.	N. A.
Beijing Paper Experimental	1,102	3,200	N. A.	N. A.	N. A.	N. A.
Nanping Paper	3,047	3,021	N. A.	N. A.	N. A.	N. A.
Unbleached wood pulp						
Xingtai Paper	10,110	1,906	4.64 m^3/t at 223 yuan/m^3	767 kg/t at 0.077 yuan/kg	176 t/t at 0.08 yuan/t	250 KWH/t at 0.15 yuan/KWH
Nanping Paper	6,341	2,338	4.3 m^3/t at 399 yuan/m^3	570 kg/t at 0.16 yuan/kg	98 t/t at 0.11 yuan/t	315 KWH/t at 0.12 yuan/KWH
Bleached Straw pulp						
Jiangmen Paper	1,473	3,903	2707 kg/t 0.843 yuan/kg	277 kg/t at 0.326 yuan/kg	391 t/t at 0.08 yuan/t	157 KWH/t at 0.128 yuan/KWH
Hongxing Paper	1,568	3,874	2851 kg/t 0.463 yuan/kg	1137 kg/t at 0.139 yuan/kg	400 t/t at 0.144 yuan/t	812 KWH/t at 0.133 yuan/KWH

Table 18 (Continued)

Paper Mill	Annual Production	Production Costs (Yuan/ton)	Of Which Fiber (Yuan/ton)	Fuel (Yuan/ton)	Water (Yuan/ton)	Electricity (Yuan/ton)
Bleached Cotton pulp						
Wuan Paper	631	4,700				
Shanghai Paper Corp.	5,073	4,033	1560 kg/t 2.033 yuan/kg	417 kg/t at 0.248 yuan/kg	225 t/t at 0.24 yuan/t	N. A.
Taiyuan Paper	1,738	2,386	2543 kg/t 0.58 yuan/kg	745 kg/t at 0.11 yuan/kg	141 t/t at 0.54 yuan/t	1160 KWH/t at 0.15 yuan/KWH
Bleached Wheat Straw pulp						
Xinshuiduanhua	658	2,259	3980 kg/t 0.11 yuan/kg	2175 kg/t at 0.034 yuan/kg	N. A.	662 KWH/t at 0.2 yuan/KWH
Taiyuan Paper	7,595	1,760	2873 kg/t 0.17 yuan/kg	624 kg/t at 0.11 yuan/kg	189 t/t at 0.55 yuan/t	457 KWH/t at 0.15 yuan/KWH
Bleached Rice Straw pulp						
Xingtai Paper	5,092	1,588	N. A.	N. A.	N. A.	N. A.
Jiangmen Paper	2,874	2,500	3356 kg/t 0.169 yuan/kg	1108 kg/t at 0.329 yuan/kg	712 t/t at 0.08 yuan/t	625 KWH/t at 0.218 yuan/KWH
Xinhua Paper	1,495	1,876	3125 kg/t 0.138 yuan/kg	562 kg/t at .032 yuan/kg	N. A.	316 KWH/t at 0.38 yuan/KWH

(Source: Xuifang Sun and Jin Tao, 1997, Personal Communication)
(Figures for the year 1990-91)

Table 19 - Availability of nonwood plant fiber worldwide

Raw material	Potential world wide availability (BD* metric tons)
Sugar cane bagasse	75,000,000
Wheat straw	570,000,000
Rice straw	320,000,000
Oat straw	60,000,000
Barley straw	150,000,000
Rye straw	40,000,000
Seed flax straw	2,000,000
Grass seed straw	3,000,000
Subtotal Straw	1,145,000,000
Bast fibers	
a. Jute - mainly from India and Bangladesh	2,200,000
b. Kenaf and roselle - mainly from India and Thailand	600,000
c. True hemp - mainly from USSR and China	100,000
Subtotal bast fibers	2,900,000
Core material from jute	8,000,000
Leaf fibers	
a. Sisal	400,000
b. Abaca	80,000
c. Hanequen	100,000
Subtotal leaf fibers	580,000
Reeds	30,000,000
Bamboo	30,000,000
Papyrus	5,000,000
Esparto grass	500,000
Sabai grass	200,000
Total cotton staple fiber	15,000,000
Total second cut cotton linters	1,000,000
Corn stalks and sorghum stalks	900,000,000
Cotton stalks	70,000,000
GRAND TOTAL	2,238,080,000

(Source: Atchison, 1989)
* Bone Dry

Table 20 - Use of nonwood plant fibers in pulp and papermaking

Non wood Plant Fiber	Use, by type of paper or paperboard	Furnish: Percent of named fiber	Furnish: Balance
Abaca	Superfine, lightweight, bond, ledger, currency and security, tea bags, filter	10-80	Cotton or wood pulp
	Non-wovens	10-50	Synthetic fibers
	Linerboard, wrapping and bag	10-30	Bagasse or straw pulp
Bagasse	Woodfree printing and writing	20-100	Wood pulp
	Mechanical printing and writing	20-50	20-40% wood pulp, balance groundwood
	Bristol board	50-100	Wood pulp
	Tissue	60-90	Wood pulp
	Glassine and greaseproof	30-90	Sulfite pulp
	Duplex and triplex	20-70	Wood pulp
	Corrugating medium	50-90	Wastepaper
	Linerboard	50-80	Kraft pulp
	Wrapping and bag papers	50-85	Kraft pulp
	Multiwall sack	30-70	Kraft pulp
	Newsprint substitute	80-90 (Chemi-mechanical)	Kraft pulp
	Newsprint substitute	70-80 (Mechanical)	Kraft pulp
Bamboo	Woodfree printing and writing	70-100	Woodpulp and/or straw or bagasse
	Mechanical printing and writing	40-60	Groundwood
	Bristol board	50-100	Woodpulp and/or bagasse pulp
	Duplex and triplex	30-80	Woodpulp and/or straw or bagasse
	Linerboard	60-100	Kraft pulp
	Wrapping and bag	80-100	Kraft pulp
	Multiwall sack	80-100	Kraft pulp
	Newsprint substitute	50-70	Groundwood pulp
Cotton	High grade bond, ledger, book and writing	25-100	Woodpulp
Ekara, Knagra and Nal grass mixed	Woodfree printing and writing	50-70	Woodpulp
	Wrapping	40-60	Kraft pulp

Table 20 (Continued)

Non wood Plant Fiber	Use, by type of paper or paperboard	Furnish: Percent of named fiber	Furnish: Balance
Esparto	Woodfree printing and writing	30-100	Woodpulp
	Lightweight papers	50-70	Woodpulp
Flax	Writing and book	20-60	Woodpulp or cotton pulp
Flax (Contd.)	Lightweight printing and writing	20-80	Woodpulp or cotton pulp
	Condenser	20-60	Woodpulp or cotton pulp
	Currency and security	60-80	Cotton or wood
	Cigarette paper	70-100	Woodpulp
Hemp, true	Cigarette paper	50-100	Woodpulp, bagasse straw or kenaf bast fibers
	Lightweight printing and writing	20-80	Woodpulp, flax, cotton pulp
	Condenser	20-60	Woodpulp, flax, cotton pulp
	Currency and security	60-80	Woodpulp, flax, cotton pulp
Jute	Printing and writing	20-80	Woodpulp
	Tag, wrapping and bag	40-60	Woodpulp or bamboo pulp
Kenaf, bast fiber	Woodfree printing and writing	20-100	Woodpulp, bagasse, straw, reeds or bamboo
	Mechanical printing and writing	20-50	20-40% woodpulp balance mechanical pulp
	Newsprint	20-30	Mechanical pulp from wood, bagasse or kenaf core material
	Multi-sack	50-100	Kraft pulp, bagasse or straw
	Linerboard	50-100	Kraft pulp, bagasse, straw or wastepaper
	Cigarette paper and other lightweight specialty paper	50-100	Woodpulp, flax, hemp or abaca

Table 20 (Continued)

Non wood Plant Fiber	Use, by type of paper or paperboard	Furnish: Percent of named fiber	Balance
	Tissue	60-90	Woodpulp, bagasse or straw
	Bleached paperboard	50-100	Woodpulp, bagasse or straw
Kenaf, whole stalk	Newsprint	80-90 (Chemi-mechanical)	Woodpulp
	Woodfree printing and writing	20-80 (Chemical)	Woodpulp
	Mechanical printing and writing	20-50 (Chemi-mechanical)	Woodpulp
Kenaf, whole stalk (Contd.)	Corrugating medium	50-100	Waste paper
	Linerboard	40-50	Kraft pulp and waste paper
	Multi-wall sack	20-40	Kraft pulp
	Tissue	50-60	Woodpulp
	Bleached paperboard	40-50	Woodpulp
Phragmites communis reed	Woodfree printing and writing	20-100	Woodpulp
	Mechanical printing and writing	20-50	20-40% Woodpulp balance groundwood
	Duplex and triplex	20-70	Woodpulp
	Corrugating medium	50-90	Wastepaper
	Linerboard	50-70	Kraft pulp
	"B" grade wrapping	50-60	Wastepaper and/or Woodpulp
Straw, cereal and rice	Woodfree printing and writing	20-100	Woodpulp
	Mechanical printing and writing	20-50	20-40% Woodpulp balance groundwood
	Glassine and greaseproof	30-90	Sulfite pulp
	Duplex and triplex	20-70	Woodpulp
	Corrugating medium	50-90	Wastepaper
	Strawboard	80-100	Wastepaper
	"B" quality wrapping	50-60	Wastepaper and/or woodpulp

Table 20 (Continued)

Non wood Plant Fiber	Use, by type of paper or paperboard	Furnish: Percent of named fiber	Furnish: Balance
Sisal	Superfine, lightweight, bond and ledger, currency and security, tea bags, filters	10-80	Abaca, cotton or Woodpulp
	Non-wovens	10-50	Synthetic fibers
	Publication paper	10-15	Woodpulp and groundwood
	Linerboard, wrapping and bags	10-30	Bagasse or straw pulp

(Source: Atchison, 1989)

Table 21 - Pollutant loads from paper mills in India (per ton of Paper)

		Agro based without recovery	Wood based with recovery
Volume	m^3	200	130
Total solids	kg	680	195
COD	kg	500	80
BOD	kg	160	20
Organics	kg	350	40
Sodium	kg	90	20

(Source: Sadawarte, 1995)

COD - Chemical Oxygen Demand
BOD - Biological Oxygen Demand

Table 22 - UNIDO s activities in pulp and paper: 1967-1990

Region	**Industrial Operations**	**Other Divisions**	**Total Projects**
Asia and the Pacific	42	14	56
Latin America and the Caribbean	26	5	31
Europe and the Mediterranean	26	2	28
Africa	7	4	11
West Asia Arab States	8	-	8
Arab Region	1	-	1
Global	3	-	3
Interregional	5	11	16
Total	**118**	**36**	**154**

(Source: Judt, 1994)

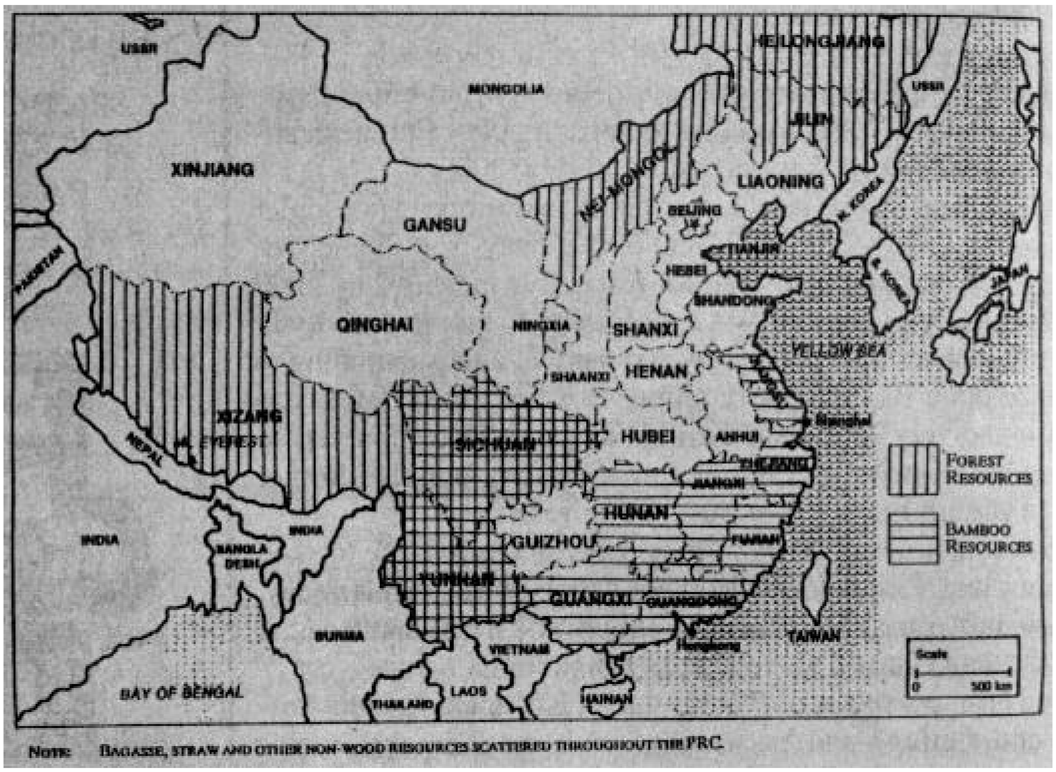

Figure 1 – Raw material locations in People's Republic of China (Source: Al-Simaani et al, 1992)

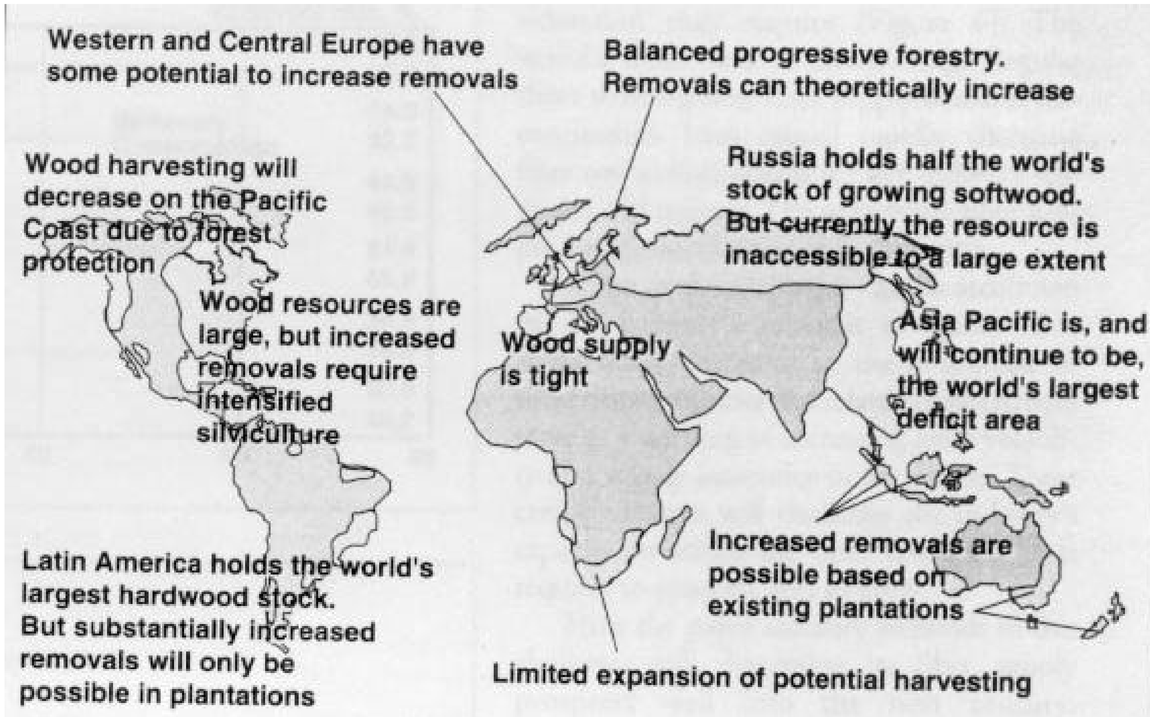

Figure 2 – Main global forest resources and wood deficit areas (Source: McNutt and Rennel, 1997)