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Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production

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Abstract

Fiber dimensions and lignin and cellulose content of various highly productive, non-wood plants and agricultural residues were examined to assess their suitability for paper production. Plants like kenaf (*Hibiscus cannabinus* L.) and giant reed (*Arundo donax* L.) internodes gave very good derived values, especially slenderness ratio, which is directly comparable to some softwood and most hardwood species. Cotton (*Gossypium hirsutum* L.) stalks, miscanthus (*Miscanthus × giganteus*) and switchgrass (*Panicum virgatum* L.) have shorter fibers resulting to poorer flexibility and Runkel ratios, but still satisfactory slenderness ratios. Finally, fibers from olive tree (*Olea europea* L.) and almond tree (*Prunus dulcis* L.) prunings presented relatively short and thick fibers producing the poorest derived values among all the species examined. Fiber dimensions did not differ significantly within each species, when samples from different stalks/branches or different positions (base, middle top) were examined. The only exception were cotton stalks, where those differences did not have any significant effect on fiber derived values.

Chemical analysis of the raw plant materials revealed satisfactory levels of α-cellulose content (close to 40%) and Klason lignin content (<30%) compared to those of hardwoods and softwoods. Relatively increased (>25%) lignin content in miscanthus, switchgrass and almond prunings may require additional pulping time and chemical charge compared to those of other non-wood raw materials. Analysis of samples at various heights/lengths of the plant materials showed that lignin and cellulose content depends on tissue maturity, but does not change significantly within each species.

Keywords: Fiber dimensions; Lignin and cellulose content; Non-wood plants; Agricultural residues; Mechanical strength

1. Introduction

World paper consumption was about 300 million tons in 1996/1997 and is expected to rise above 400 million tons by the year 2010 (Hurter and Riccio, 1998). In view of the shortage of conventional raw materials for pulping and the increasing demand for paper products worldwide, non-wood plants and agricultural residues attracted renewed interest, especially in Mediterranean countries like Spain, Italy and Greece with insufficient forest resources. Non-wood plants offer several advantages including short growth cycles, moderate irrigation and fertilization requirements and low lignin content resulting to reduced energy

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and chemicals use during pulping (Hurter and Riccio, 1998).

In 1998, Greece imported about 400,000 t of newsprint and other paper products at a cost of about €300 million (Greek National Statistical Service, Division of Industry and Commerce, 1999). It is, therefore, evident that new, domestic sources of pulp and paper raw materials would not only reduce imports, but they would also provide an economic incentive to the agricultural and industrial sectors of Greece.

The importance of plant materials fiber dimensions and their derived values (slenderness ratio, flexibility coefficient and Runkel ratio) on pulp and paper mechanical strength is well documented. Seth and Page (1988) have shown that, under certain conditions, tearing resistance depends strongly on fiber length, whereas Horn (1978) reports that increase in raw material fiber length enhances the tearing strength of hardwood pulps. Using multiple regression analysis, Horn and Setterholm (1990) also found that the majority of variation in burst and tensile strength in hardwood pulpsheets could be accounted for by fiber length and cell wall thickness. Kellogg and Thykeson (1975) and Matolcsy (1975) have also pointed out the significance of fiber dimensions in predicting wood pulp mechanical properties. In an extensive review of the literature, Dinwoodie (1965) stressed the importance of the three derived values on pulp strength, whereas researchers like Saikia et al. (1997) and Ogbonnaya et al. (1997) have successfully used those derived values to assess the suitability of various non-wood fiber raw materials for pulp and paper manufacture.

Paper strength also depends on the lignin and cellulose content of raw plant materials; pulp mechanical strength and especially tensile strength is directly proportional to cellulose content (Madakadze et al., 1999), whereas lignin is an undesirable polymer and its removal during pulping requires high amounts of energy and chemicals.

The objectives of the present study were to (a) examine the fiber dimensions and lignin and cellulose content of several non-wood plants and agricultural residues, (b) estimate their suitability for paper production using various indices and (c) assess their potential as raw materials for paper production by comparing their examined properties with those of softwoods and hardwoods, which are taken as reference materials traditionally used for paper production.

2. Materials and methods

2.1. Raw materials

Four species of non-wood plants were selected for the study: kenaf (*Hibiscus cannabinus* Everglades 71 variety), giant reed (*Arundo donax*), switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus* × *giganteus*). The above species have experimentally been cultivated as energy production crops in Greece at the Center of Renewable Energy Sources (CRES) at Pikermi, Attica. All species have shown good adaptability to the Greek pedoclimatic conditions with satisfactory biomass production, ranging from 8 to 35 t/ha, whereas irrigation and fertilization requirements range from 300 to 700 mm and 40–120 kg N/ha, respectively (Mardikis and Namatov, 1999).

In addition to the above four plants, three types of agricultural residues were also examined: cotton (*Gossypium hirsutum*) stalks, olive tree (*Olea europea*) and almond tree (*Prunus dulcis*) prunings. Cotton stalks usually remain in the field after cotton collection at an annual amount of about 475,000 t (available dry weight), whereas olive and almond tree prunings (amounting to 980,000 and 43,000 t, respectively) are either burned in situ or used as a fuel in fireplaces or wood stoves (Panoutsou et al., 1999).

2.2. Fiber dimensions and derived values (indices)

2.2.1. Fiber dimensions

Five stalks were obtained from each non-wood plant species and cotton, whereas five branches (prunings) were collected from olive and almond trees respectively. In order to get more representative results, three samples from each stalk/branch were taken at 10% (base), 50% (middle) and 90% (top) of its height/length respectively, an approach similar to that followed by Paraskevopoulou (1987, p. 64). For fiber length determination, small slivers were obtained and macerated with 10 ml of 67% HNO_3 and boiled in a water bath (100° ± 2° C) for 10 min (Ogbonnaya et al., 1997). The slivers were then washed, placed in small flasks with 50 ml distilled water and the fiber bundles were separated into individual fibers using a small mixer with a plastic end to avoid fiber breaking. The macerated fiber suspension was finally placed on a slide (standard, 7.5 cm × 2.5 cm) by means of a medicine dropper (Han et al., 1999). For fiber diameter, lumen diameter and cell wall thickness determination, cross-sections were obtained from the same height/length as above and were stained with 1:1 aniline sulfate–glycerine mixture to enhance cell wall visibility (cell walls retain a characteristic yellowish color). All fiber samples were viewed under a calibrated microscope; a total of 25 randomly chosen fibers were measured from each sample for a total of 75 fiber measurements from each stalk/branch and 375 measurements for each of the four fiber dimensions of each species. For kenaf, measurements were made for bark/core fibers and for reed for nodes and internodes fibers.

2.2.2. Derived values

Three derived values were also calculated using fiber dimensions: slenderness ratio as fiber length/fiber diameter, flexibility coefficient as (fiber lumen diameter/fiber diameter) × 100 and Runkel ratio as (2 × fiber cell wall thickness)/lumen diameter (Saikia et al., 1997; Ogbonnaya et al., 1997). The values were then compared to those of softwoods and hardwoods to assess the suitability of the plant raw materials for paper production.

2.3. Lignin and cellulose content of plant raw materials

The raw plant materials were analyzed for α-cellulose and acid insoluble (Klason) lignin; α-cellulose was determined using a colorimetric method with the anthrone reagent. 0.3 g (dry weight) ground (0.5 mm) samples were treated and boiled (at 100 °C) with a mixture of nitric/acetic acid (1:8, v/v) for 1 h to remove lignin, hemicelluloses and xylosans after successive centrifugations, and diluted with 67% H_2SO_4 (v/v). Cellulose was then determined at 620 nm using cold anthrone reagent (Updegraff, 1969). The method is suitable for analyzing a large number of samples and has been used to determine cellulose in other plant materials (Aguiar, 2001). For each species, three samples (small cylindrical pieces), one from the base (B), one from the middle (M) and one from the top (T), were analyzed for each stalk/branch for a total of 15 samples per species. Due to differences in chemical composition between nodes and internodes in reed (Neto et al., 1997), six stalks were analyzed (18 samples, 9 for nodes and 9 for internodes). Klason lignin was determined using the APPITA P11s-78 method (APPITA, 1978); TAPPI method 211-om 93 was employed for correction of ash content at 525 °C (TAPPI, 1996). The same number of samples as in cellulose determination was used, except for switchgrass (total of five samples), whose thin stalks were less than 3 g (dry weight) required to analyze for lignin.

2.4. Statistical analysis

Data collected was subjected to analysis of variance (ANOVA, $P < 0.05$) for each species separately using appropriate statistical software. Sources of variation were stalk sampling height and branch length as well as individual stalks and branches. Error bars in all graphs refer to 95% Just Significant Confidence Intervals. This approach provides a more accurate picture of standard error and allows a direct visual comparison of means for analyses within each species (e.g. reed chemical composition).

3. Results and discussion

3.1. Fiber dimensions and derived values (indices)

The fiber dimensions and their derived indices are shown in Tables 1 and 2. As a dicot, kenaf has two distinct kinds of fibers—long bark fibers, which account for 35% of its fibrous part, and short core fibers, which account for the rest (Manzanares et al., 1997). Bark fibers have very good derived values (especially slenderness ratio) compared to those of some softwoods and certainly to most hardwoods. Therefore, papers made from kenaf bark fibers are expected to have increased mechanical strength and thus be suitable for writing, printing, wrapping and packaging purposes (Saikia et al., 1997; Neto et al., 1996). Core fibers, on the other hand, are shorter and thicker producing a poor slenderness ratio, which in turn reduces tearing resistance dramatically. This is partly because short and thick fibers do not produce good surface contact and fiber-to-fiber bonding (Ogbonnaya et al., 1997). However, as shown in Table 3, core fibers are still highly flexible with a good Runkel ratio and low felting power and can thus complement the higher mechanical strength of the bark fibers (Khristova et al., 1998). So, the whole stem could produce a pulp of

Table 1
Fiber dimensions of plant materials

Plant material	Length (mm)	Diameter (μm)	Lumen diameter (μm)	Cell wall thickness (μm)
Non-wood fibers				
Kenaf (bark)	2.32 ± 0.21	21.9 ± 4.6	11.9 ± 3.4	4.2 ± 0.8
Kenaf (core)	0.74 ± 0.08	22.2 ± 4.5	13.2 ± 3.6	4.3 ± 0.7
Kenaf (whole)[a]	1.29	22.1	12.7	4.3
Reed (internodes)	1.22 ± 0.07	17.3 ± 2.4	8.5 ± 2.4	4.4 ± 0.8
Reed (nodes)	1.18 ± 0.06	18.8 ± 2.7	8.6 ± 2.3	5.6 ± 0.7
Miscanthus	0.97 ± 0.08	14.2 ± 2.5	5.9 ± 2.2	4.1 ± 0.8
Switchgrass	1.15 ± 0.10	13.1 ± 2.8	5.8 ± 3.9	4.6 ± 0.9
Cotton[b]	0.83 ± 0.08	19.6 ± 3.2	12.8 ± 2.9	3.4 ± 0.7
Wood fibers				
Olive tree[c]	0.85 ± 0.07	15.1 ± 2.0	6.2 ± 1.9	4.5 ± 0.8
Almond tree[c]	0.77 ± 0.06	13.1 ± 1.8	4.3 ± 1.3	4.4 ± 0.8

'±' refers to standard deviation.

[a] Based on 65% core–35% bark fiber content.

[b] Stalks.

[c] Prunings.

good quality and strength. Using the whole stem is a more attractive method as it bears significant practical and economic advantages: it is a simple process and free of the additional separation costs. Kugler (1988) reported that newsprint paper of excellent quality can be made from whole kenaf stalks and that kenaf pulp can be mixed with conventional softwood pulps to produce a wide range of paper grades.

Table 2
Derived values (indices) for plant materials

Plant material	Derived values		
	Slenderness ratio	Flexibility coefficient	Runkel ratio
Kenaf (bark)	105.9	54.3	0.7
Kenaf (core)	33.3	59.5	0.5
Kenaf (whole)[a]	58.3	57.5	0.67
Reed (internodes)	70.5	49.2	1.0
Reed (Nodes)	60.0	46.0	1.3
Miscanthus	68.3	41.5	1.3
Switchgrass	87.7	44.2	1.5
Cotton[b]	42.3	65.3	0.5
Olive tree[c]	56.2	41.0	1.4
Almond tree[c]	58.7	32.8	2.0
Softwoods[d]	95–120	75	0.35
Hardwoods[d]	55–75	55–70	0.4–0.7

[a] Based on 65% core–35% bark fiber content.

[b] Stalks.

[c] Prunings.

[d] From Smook (1997).

Reed (*A. donax*) internode fibers were shorter and thinner than those of kenaf bark, still with a good slenderness ratio (close to that of some hardwoods) and an acceptable Runkel ratio. Their low flexibility is expected to have an inevitably negative effect on tensile and bursting strengths as well as on folding endurance (Ogbonnaya et al., 1997). Node fibers have somewhat poorer characteristics as they are shorter and thicker than internode fibers thus producing less advantageous indices (Table 3). Comparing reed pulp with pulps from hardwoods and especially from eucalyptus (*Eukalyptus globulus*) Shatalov and Pereira (2002) found that, in general, the reed pulps have lower mechanical strength, but still higher tearing resistance probably due to reed's relatively high slenderness ratio. Nevertheless, pulps from the internode parts of *A. donax* are expected to give paper suitable mainly for newsprint or they can replace conventional pulps (in relatively low proportions) to produce quality writing and printing papers especially after beating (Shatalov and Pereira, 2002; Scott et al., 1995, pp. 74, 77). It is worth noting, however, that reed stalks and especially nodes consist of over 55% parenchyma cells which have a significantly negative effect on pulp mechanical strength (Horn and Setterholm, 1990; Shatalov and Pereira, 2002). This negative impact is enhanced by the shorter and thicker node fibers which gave poorer indices (especially Runkel ratio). However, this effect can be minimized by using suitable

Table 3
Fiber dimensions along the stalk/branch of the plant raw materials

Fiber dimension	Stalk height/ branch length (%)	Non-wood fibers					Wood fibers	
		Kenaf[a]	Reed[b]	Miscanthus	Switchgrass	Cotton[c]	Olive tree[d]	Almond tree[d]
Length (mm)	10	2.30 a	1.20	0.94	1.12	0.81	0.90 a	0.80 a
	50	2.33	1.22	0.97	1.14	0.83	0.87	0.78
	90	2.37 b	1.25	0.99	1.17	0.84	0.82 b	0.74 b
Diameter (μm)	10	22.09	17.47	14.18	13.29	20.28 a	15.21	13.22
	50	21.65	17.14	14.16	13.21	19.96	15.15	13.04
	90	21.52	17.03	14.01	12.91	18.07 b	14.96	12.90
Lumen diameter (μm)	10	11.03	8.51	6.11	5.87	12.86 a	6.23	4.40
	50	10.69	8.29	5.91	5.93	13.35 b	6.29	4.30
	90	10.90	8.35	5.97	5.60	12.32 c	6.09	4.28
Cell wall thickness (μm)	10	4.53	4.48	4.04	4.71	3.71 a	4.49	4.41
	50	4.37	4.42	4.13	4.63	3.31 b	4.44	4.37
	90	4.32	4.34	4.02	4.56	3.18	4.43	4.30

Differences in values followed by a different letter for each species and dimension are statistically significant at $P < 0.05$ (Tukey grouping).

[a] Bark.

[b] Internodes.

[c] Stalks.

[d] Branches.

screening techniques before pulping along with a rise in costs.

Miscanthus, switchgrass and cotton stalks presented shorter fibers than kenaf and reed, with switchgrass having the longer fibers among the three. Miscanthus and switchgrass have very good (>60) slenderness ratios, basically due to their thin fibers. This results in satisfactory pulp tear indices and bursting strengths for printing and writing purposes (Cappelletto et al., 2000; Law et al., 2001). Despite the fact that these two species presented relatively poor flexibility and Runkel ratios, Madakadze et al. (1999) and Cappelletto et al. (2000) have also reported pulp tensile and bursting strengths, which allow for newsprint paper production. Alternatively, pulp produced from miscanthus and switchgrass, can be mixed with softwood, hardwood or recycled paper pulps to increase either printability (Madakadze et al., 1999) or mechanical strength (Cappelletto et al., 2000). As in the case of reed (*A. donax*), a large proportion (>30%) of miscanthus and switchgrass stems consist of short parenchyma cells and vessel elements, which should be removed before pulping (Law et al., 2001). On the other hand, cotton stalks have low slenderness ratio, but still very good flexibility and Runkel ratios, which can yield pulps with acceptable breaking length, tear and burst indices suitable for newsprint paper production (Jimenez et al., 1993; Scott et al., 1995, pp. 74, 77 and 79).

Finally, olive tree prunings (branches) have short fibers with thick cell walls, which account for the relatively poor values in all the derived indices. In fact, Jimenez et al. (1993), have produced pulpsheets from olive tree fellings with very low mechanical strength, whereas Lopez et al. (2000) produced beaten kraft pulpsheets with higher breaking lengths and burst indices, but still with a very low tear index. Based upon the fiber derived values we have observed, almond prunings are expected to produce pulps with similar mechanical strength to those of olive tree fellings. Pulps from these two species could be used as blends to partially replace hardwood pulps in various paper grades, but still in relatively low ratios.

3.2. Fiber dimensions along the stems/branches of plant raw materials

Table 3 presents the change in fiber dimensions from the bottom to the top of the stem/branches of the materials under investigation. Fiber length increases from base to the top for all the non-wood plants; in a detailed study on kenaf, Han et al. (1999) observed a similar pattern of fiber length change, although they found the shorter fibers in the middle and the longer at the top of the stem. However, a viable comparison with the above work cannot be made since the authors have used different sampling, maceration and measurement techniques and did not provide any statistical analysis of their results. Olive tree and almond tree branches exhibited a different trend with the longer fibers at the base and the shorter at the top. Using the same techniques with those for kenaf, Han et al. (1999) reported similar patterns of fiber growth in Red Pine (*Pinus resinosa*) and Aspen (*Populus tremuloides*) trunks, but more detailed analyses are needed before a valid comparison between wood and non-wood fiber growth can be made. Generally speaking, fiber diameter decreased from bottom to the top, probably due to a similar decrease in cell wall thickness; this can be explained by the fact that cell wall growth is dependent on the accumulation of metabolism products (cellulose, hemicellulose, lignin, waxes, etc.), which increases with maturity (Fahn, 1990, p. 29; Vallet et al., 1996). However, in most cases, differences in fiber dimensions along the stalks/branches for each of the plant materials were not statistically significant (ANOVA, $P < 0.05$) (Table 3). Cotton stalks were a striking exception, but even in their case, the difference in the derived values is relatively small and therefore rather unlikely to have any significant impact on pulp mechanical properties (Table 4).

Although pulp mechanical strength also depends on other processing variables (pulping conditions, bleaching, beating, etc.), the use of certain indices associated with fiber dimensions is still a useful tool in predicting the suitability of various raw plant materials for papermaking.

Table 4
Changes in derived values along cotton stalks

Derived values	Height of stalk (%)		
	10	50	90
Slenderness ratio	39.9	41.7	44.6
Flexibility coefficient	63.5	67.3	65.7
Runkel ratio	0.57	0.50	0.52

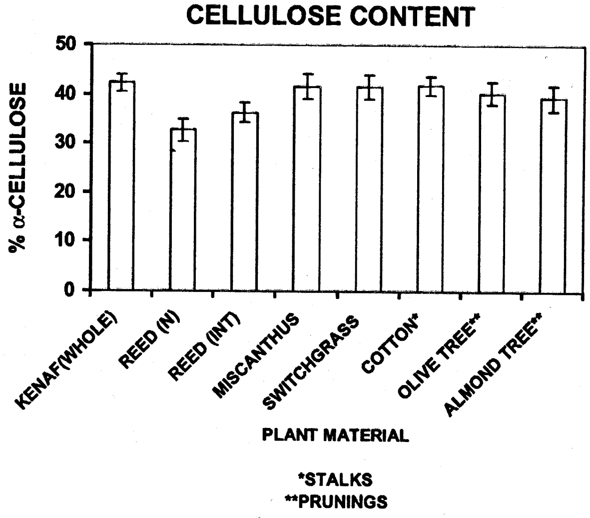

Fig. 1. Cellulose content of the raw plant materials (error bars refer to 95% JSCI).

3.3. Lignin and cellulose content of plant raw materials

The contents of the basic three chemical substances (α-cellulose, Klason lignin and ash) of the plant raw materials are presented in Figs. 1–3. α-cellulose content was satisfactory (close or above 40%) for all species, even though a slight overestimation might have occurred due to possible interferences of the colorimetric method. According to the rating

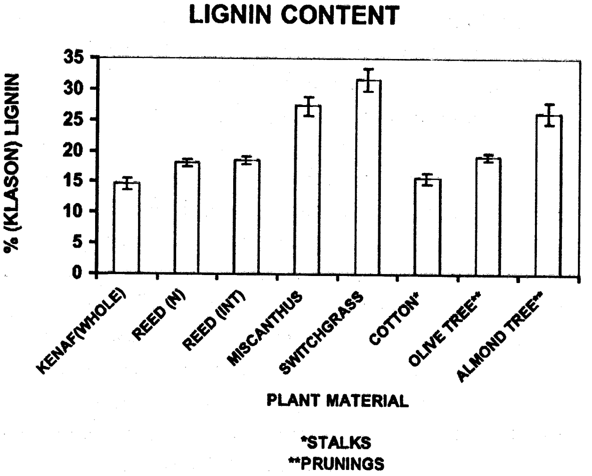

Fig. 2. Lignin content of the raw plant materials (error bars refer to 95% JSCI).

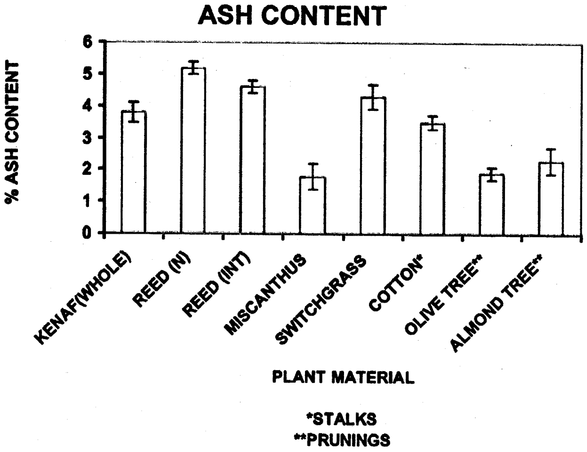

Fig. 3. Ash content of the raw plant materials (error bars refer to 95% JSCI).

system designated by Nieschlag et al. (1960), plant materials with 34% and over α-cellulose content were characterized as promising for pulp and paper manufacture from a chemical composition point of view. Kenaf and switchgrass had the highest cellulose content followed by cotton stalks and miscanthus.

Klason lignin contents were also at satisfactory levels (<30%) for all materials except for switchgrass. Kenaf had the lowest lignin content followed by cotton stalks, reed and olive tree prunings (Fig. 2). This, in practice, means that these materials need, in general, milder pulping conditions (lower temperatures and chemical charges) than those of softwoods and hardwoods in order to reach a satisfactory kappa number. It also indicates the potential of these materials to undergo bleaching more easily and with the utilization of fewer chemicals. Examples of milder pulping conditions leading to satisfactory delignification levels are abundant in the literature. Saikia et al. (1997) report such conditions for kenaf, Wiedermann (1993) for reed, Lopez et al. (2000) for olive tree prunings and Jimenez et al. (1993) for cotton stalks. Swithgrass had the highest lignin content followed by miscanthus and almond prunings. Madakadze et al. (1999); Law et al. (2001) also suggest relatively mild pulping conditions for some switchgrass varieties, which appear to contain less than 25% lignin. In our study, switchgrass contained over 30% lignin, being closer to values reported by Hurter (1997). It is thus evident that switchgrass is expected to need more severe pulping conditions than those of the rest non-wood plants. Cappelletto et al. (2000) also recommend very mild pulping conditions for miscanthus, but this only applies to thermomechanical (TMP) and chemothermomechanical (CTMP) pulping. Kraft pulping certainly needs higher temperatures and chemical charges to ensure satisfactory delignification.

Ash content (carbonates, Ca, K and some trace elements) is higher in switchgrass followed by reed, kenaf and cotton stalks (Fig. 3); although high ash content is undesirable, as it passes in the pulp, ash contents in this study were in the typical range for non-wood plants and are not expected to have any significant effect on pulp mechanical strength properties.

3.4. Lignin and cellulose content of plant raw materials along the stalks/branches

Table 5 presents the change in chemical composition along the stalks/branches of the plant raw materials. There is a general tendency for a decrease in α-cellulose, lignin and ash content as we move from the base of the stalks or branches to the top. This was expected since mature tissues (at the base) accumulate higher amounts of metabolic products than the younger parts at the top. As far as lignin is concerned, results on content changes along the stems reported by Neto et al. (1996) for kenaf and Neto et al. (1997) for reed generally agree with our findings. However, Nishimura et al. (2002) have found higher lignin contents in the middle parts of kenaf stems and the same trend is reported for α-cellulose by Neto et al. (1996) for kenaf, and Neto et al. (1997) for reed. This discrepancy may be attributed either to different methodologies or different plant varieties that we have used in our analyses. In a detailed study of maize (*Zea mays* L.) stalks, Morrison et al. (1998) reported that lignin and cellulose deposition increased with tissue maturation, with maximum rate of lignin deposition following that of cellulose. The statistically significant differences between cellulose and lignin contents especially between the base and top for some species should be taken into account before pulping only if they are associated with specific morphological characteristics such as in the case of reed (Neto et al., 1997; Shatalov and Pereira, 2002).

Table 5
Chemical composition along the stalk/branch of the plant raw materials

Chemical composition	Part of stalk/branch	Kenaf[a]	Reed (internodes)	Reed (nodes)	Miscanthus	Switchgrass	Cotton[b]	Olive tree[c]	Almond tree[c]
α-Cellulose (%)	B	43.8 a	37.7 a	33.9 a	43.7 a	42.6	43.8 a	41.7 a	40.7 a
	M	42.6	36.7	32.6	41.8	41.4	42.2	40.7	39.7
	T	40.2 b	34.4 b	30.8 b	39.1 b	41.0	40.1 b	38.1 b	37.1 b
(Klason) lignin (%)	B	15.5 a	20.5 a	19.7 a	28.5	–	17.6 a	21.5 a	27.3
	M	15.0	18.5 b	18.1	27.7	–	15.4 b	19.4 b	26.5
	T	13.4 b	16.0 c	17.1 b	26.7	–	13.4 c	17.0 c	25.7
Ash (%)	B	4.1 a	4.9 a	5.5	2.1	–	3.5	2.0	2.2
	M	4.0	4.4	5.3	1.9	–	3.7	1.9	2.4
	T	3.6 b	4.3 b	5.2	1.7	–	3.4	1.8	2.3

Differences in values of each chemical component followed by a different letter within each species are statistically significant at. $P < 0.05$ (Tukey grouping).

[a] Whole.

[b] Stalks.

[c] Branches.

3.5. *Cost considerations for paper production from non-wood plants*

Due to their lower lignin content (compared to wood), non-wood plants can be pulped in one-third of the time needed for softwoods and hardwoods. Pulping of non-wood fibers also demands around 30% less chemical charge, and reduced power consumption in pulp refining (Young, 1997, pp. 154, 155). Bleaching of non-wood fibers is also relatively easy. The above information means, in general, a lower cost of production for some grades of paper from non-wood plants. Kaldor (1998) and Paavilainen (1998) have shown the economic feasibility of producing pulp from non-wood fibers in existing wood pulp mills in order to avoid new investments for building non-wood fiber pulp mills with higher operating costs. Pulp mills which would work with the "fee land" system could have high quality kenaf fibers at half price compared to that of Southern pine (*Pinus ellioti* Engelm.) (Kaldor, 1998).

In a production cost study in Northern Greece, Panoutsou et al. (2000) showed that giant reed could be sold at around € 60/t assuming an average biomass yield of 25 t/ha (dry weight) and excluding transportation and chopping costs. Huisman et al. (1997) have also calculated the cost of supply chains of chopped miscanthus at 127 ECU/t in the Netherlands for a biomass yield of 12 t/ha. Assuming an average, annual inflation rate of 2% in the EU, and that 1ECU = € 1 this cost becomes around € 140/t. However, with a reasonable assumption of a 25 t/ha yield for Greece (Mardikis and Namatov, 1999), this price is actually halved. Bearing in mind that hardwood bleached pulp price is around € 400–450/t, there is still a wide margin of about € 300/t to cover pulping, bleaching and equipment costs for paper production from non-wood fibers in Greece.

4. Conclusion

The investigation of fiber dimensions and lignin and cellulose content of various non-wood plants and agricultural residues along with the use of certain indices showed that kenaf is suitable for producing paper of various grades, whereas reed, switchgrass, miscanthus and cotton stalks are suitable for producing mainly writing and printing papers or mixing with conventional wood pulps to produce paper of various uses. Olive tree and almond tree prunings have shorter and thicker fibers producing relatively poor index values. Pulps from these species are expected to be of relatively low mechanical strength suitable only for replacing hardwood pulps in low or moderate proportions to produce newsprint or tissue paper.

The high biomass output of the non-wood plants and the vast amounts of agricultural residues could provide large amounts of non-wood fibers, which could substitute for most of the imported pulp in Greece. Assuming an average of 45–50% screened pulp yield (Young, 1997, pp. 146–147) and the development of local industries, Greece could almost rely on its own raw materials for the production of all newsprint and tissue paper (current imports over 170,000 t) at reasonable costs.

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