Available online at www.sciencedirect.com
ScienceDirect
Industrial Crops and Products 26 (2007) 142–150
INDUSTRIAL CROPS AND PRODUCTS
AN INTERNATIONAL JOURNAL
www.elsevier.com/locate/indcrop

Variations in fiber length and some pulp chemical properties of *Leucaena* varieties

M.J. Díaz[a,*], M.M. García[a], M.E. Eugenio[a], R. Tapias[b], M. Fernández[b], F. López[a]

[a] *Chemical Engineering Department, Facultad de Ciencias Experimentales, Campus El Carmen, Universidad de Huelva, 21071 Huelva, Spain*

[b] *Agroforestry Science Department, Escuela Politécnica Superior, Universidad de Huelva, La Rábida, Palos de la Frontera (Huelva), Spain*

Received 14 April 2006; accepted 7 February 2007

Abstract

To identify non-wood fast-growing species utilizable for pulp and paper production six *Leucaena* varieties were tested. Concurrently, these species were also tested for suitability as pulp materials on a laboratory scale. Biomass productivity of three *Leucaena* varieties (*Leucaena diversifolia*, *Leucaena collinsii and Leucaena leucocephala*) studied ranges from 67.14 to 9.44 t ha^{-1} (o.d.b.) under Mediterranean conditions for the year first sprouts. The main physico-chemical properties of the pulp produced from these varieties were also evaluated as functions of the following parameters: NaOH solubles, alcohol-benzene extractives, hot water extractives, lignin, α-cellulose and holocellulose.

The study confirms the feasibility of the MD-organocell pulping process for *Leucaena* varieties. MD-organocell pulping provides an efficient delignification. In this process, the operation temperature, among studied, has a positive effect pulp measured properties. Large amounts of lignin from 83.24 to 95.05% of the initial content are removed during the pulping process, depending on the *Leucaena* variety.

Keywords: Pulping; *Leucaena*; Alternative pulp raw materials

1. Introduction

Soil degradation has been described as an important problem in Europe: 12% of total European land area has been affected by water erosion and a 4% by wind erosion (Van den Born et al., 2000). Among the main effects of soil degradation are reduced vegetative cover, decrease in water quality, lower efficiency of water resources management and increased risk from pests and diseases due to limited biological control (ICRAF, 2002). Despite proposals for a number of solutions and the investment of time and resources, soil erosion continues being a substantial problem (Zalidis et al., 2000). The possible solutions involve a sustainable agricultural management that uses natural resources to enhance soil productivity without jeopardizing land's future potential. There are many studies concerning bioremediation for highly contaminated areas (Pascucci and Kowalak, 1999; Naidja et al., 2000; Leung et al., 2000; Lombardi and Ramalho, 2003). Under this perspective, the use of *Leucaena* in soil restoration has been studied in several countries

* Corresponding author. Tel.: +34 959 21 99 90; fax: +34 959 21 99 83.
E-mail address: dblanco@uhu.es (M.J. Díaz).

0926-6690/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.indcrop.2007.02.003

(Vanlauwe et al., 1998; Sharma et al., 1998). *Leucaena*, a fast-growing leguminous shrub from Central America that is frequently used in agroforestry systems, producing protein-rich foliage for livestock and pods bearing edible seeds. *Leucaena* has been reported growing poor soils (Rout et al., 1999; Ma et al., 2003) where it has been found to provide an effective cover to prevent leaching of heavy metals from the mine tailings to the neighboring environments.

On the other hand, the use of non-wood fast-growing species for papermaking could have a great advantage as they provide remediation for the environmental problems associated with the industrial use of that vegetable species. Moreover, the use of fast-growing species for pulp production may offer some advantages in terms of the shorter time required to activate production in comparison with woody plants (Oggiano et al., 1997). In this way, short rotation coppice is based on the harvest of fast-growing species every few years and their resprouting from stump after harvest (Kauter et al., 2003). This fact provides trimming residues (branches of 0.5–5 cm thickness). These wastes could be used as papermaking raw material. There are not previous references to the use of *Leucaena* varieties wood for pulp and papermaking.

The objectives of this study were to quantify the variations of six *Leucaena* varieties: (a) on the yield obtained (total biomass and trimming residues wood) throughout 2 years, (b) on the chemical composition changes of the raw material during that period, (c) on the chemical characteristics of the pulp obtained, and (d) the fiber length of the prunings.

2. Experimental

2.1. Experimental design for field experiments

Field experiments were carried out in two plots with a complete randomized block design with four replicates per varieties/provenance. In each replication, 16 plants were planted in 18 m^2 (9500 plants ha^{-1}). No fertilization was added to plots. Many nitrogen fixing species can convert substantial quantities of atmospheric nitrogen into a combined form. *Leucaena* has been reported to fix 100–500 kg of N ha^{-1} yr^{-1} (Kumar et al., 1998; Parrotta and John, 1992). Therefore, it is not necessary to supply N to *Leucaena* crops, although it would be advisable to apply N during the plantation stage. However, high soil N levels, particularly as nitrates, are known to inhibit nodulation and the nitrogen-fixing process (Duhoux and Dommergues, 1985). Nevertheless, K and P considerably affect growth of *Leucaena*, although their impact depends on field conditions (Burleigh and Yamoah, 1997).

Leucaena leucocephala from Honduras (H), *L. leucocephala* from India (I) *L. leucocephala* var. K360 (K360), *Leucaena collinsii*, *Leucaena diversifolia* and *Leucaena salvadorensis* were the varieties used in this experiment. The soil at the experimental site was sandy loamy with a pH of 6–8 and having moderate to substantial depth.

Representative foliage and branch wood samples were collected (varieties-wise, quadruplicate) for moisture estimation and chemical analyses, in a random fashion. For yield estimation, four randomly selected plants per plot were cut at the base of the crown. The samples were immediately transferred to the laboratory in double-sealed polythene bags. After recording the fresh weights, they were dried to constant weights at 70 °C, and ground to pass through a 2 mm sieve. Estimates of dry weight biomass were obtained from the fresh weights of various plants types and their corresponding moisture contents. Dry/wet ratios were used to correct the field weight determinations and obtain biomass on a per plant basis. The average biomass of component parts per plant was multiplied by the number of plants per plot and extrapolated to a hectare.

2.2. Characterization of the raw material and pulp

Four samples, representing five *Leucaena* varieties aged from 1 to 2 years, and the sprouts again of the plant after the first year cut, were collected. Total and wood dry weights were measured. The harvesting started in January 2004 according to harvest schedule in Table 1. The first (year 1) and second (year 2) harvests from original stands, planted in February 2003, gave us the information on effect of harvesting age. The 12 months cycle, the new sprouts after the first year cut (year 1 sprouts) was harvested in February 2005.

Leucaena wood trimmings samples were milled to pass a 8-mm sieve, since no diffusional limitations were observed for this particle size in preliminary studies. Samples were air-dried, homogenized in a single lot to avoid differences in composition among aliquots, and stored.

Aliquots from the homogenized wood lot were subjected to moisture determination (drying at 105 °C to constant weight) and to quantitative acid hydrolysis with 72% sulfuric acid following standard methods (Browning, 1967). The solid residue after hydrolysis was recovered by filtration and considered as Klason lignin. The moisture of wood was considered as water in the material balances.

Table 1
Biomass yielded from *Leucaena* varieties during 2 years

Varieties	Year 1		Year 2		Year 1 sprouts	
	WD[a]	TD[b]	WD	TD	WD	TD
Leucaena diversifolia	4.83 (0.17) AB[c]	7.45 (0.96) AB	28.25 (2.19) B	43.58 (3.31) B	28.32 (0.41) B	43.69 (6.41) B
Leucaena collinsii	3.02 (0.15) A	3.09 (0.21) A	11.10 (1.32) A	11.35 (1.27) A	9.22 (1.09) A	9.44 (2.99) A
Leucaena leucocephala (H)	9.35 (0.11) B	12.76 (0.74) C	17.14 (1.27) AB	23.39 (1.65) AB	28.40 (1.47) B	38.75 (6.43) B
L. leucocephala (I)	9.07 (0.39) B	13.51 (1.09) C	20.79 (2.02) AB	30.94 (2.25) AB	45.12 (2.86) B	67.14 (8.37) B
L. leucocephala (K360)	7.78 (0.02) B	12.34 (0.08) BC	16.09 (0.98) AB	25.58 (2.09) AB	31.50 (2.64) B	49.95 (4.22) B
Leucaena salvadorensis	–	–	–	–	–	–

L. leucocephala from Honduras (H), *L. leucocephala* from India (I) *L. leucocephala* var. K360 (K360). The values in parenthesis are standard deviation.
[a] WD: wood dry basis biomass (t ha^{-1}).
[b] TD: total dry basis biomass (t ha^{-1}).
[c] Values followed by the same letter in the same column do not differ significantly ($p < 0.05$).

Characterization experiments involved the following parameters: hot water solubles (Tappi 257), 1% NaOH solubles (Tappi 212), ethanol-benzene extractives (Tappi 204), Klason lignin (Tappi 212), α-cellulose (Tappi 203-OS-61), holocellulose (Wise et al., 1946).

Leucaena wood trimmings were used including the bark, which was very thin and difficult to strip off and accounted for only 1–2% of the overall mass.

For the measurements of fiber length *Leucaena*s were macerated in a solution containing 1:1 HNO_3 and $KClO_3$. For maceration of sample, five fronds were chosen. A drop of macerated sample was taken on a slide and fiber length was measured under a microscope. For measuring fiber length, 200 fibers were measured from 10 slides and average reading was taken. The arithmetic mean fiber length $\bar{L}_i$ is

$$\bar{L}_i = \frac{\sum(n_i L_i)}{\sum(n_i)} \quad (1)$$

where $L(i)$ and $n(i)$ are the length (mm) and the number of fibers, respectively.

2.3. Pulping procedure

The method called the MD-organocell process has been used by adding ethanol and anthraquinone to the alkaline liquor. Under this process pulps with high yield, low residual lignin content, high brightness and good strength properties can be produced (Shatalov and Pereira, 2004).

Cellulose pulps were obtained using a 4-L batch cylindrical reactor that was heated by means of electrical resistances and linked to a control unit, including the required instruments for measurement and control of the pressure and temperature. The control unit included temperature and pressure gauges, as well as appropriate safety devices. The cooking liquor was recirculated by means an air motor. Finally, to open the reactor, the liquor was quickly refrigerated by a heat exchange to obtain low-pressure levels. The initial liquor to solid ratio was 8:1 (dry wt. basis), the aqueous soda concentration in the cooking liquor was 21% by weight, the ethanol concentration was 30% by volume and the anthraquinone concentration was 0.05% by weight. The temperature was set to 185 °C during 60 min and a preheating of 30 min to reach the mentioned temperature. Following cooking, the pulp was separated from the liquor and disintegrated, without disturbing the fibers, during 3 min, washed on a sieve of 0.16 mm mesh, defibered and passed through a Strainer filter (0.4 mm mesh) in order to isolate the uncooked material.

2.4. Statistical analysis

All treatments in this study were in a completely randomized design with four replications. Statistical analyses were performed using ANOVA and the differences among varieties were compared using Tukey's test. The means were separated based on least significant difference at 0.05 probability level.

3. Results and discussion

3.1. Biomass production

All the *Leucaena* varieties showed a good soil and climatic adaptation to the zone (La Rábida, Huelva, southwestern Spain) with except for *L. salvadorensis* that suffered a great mortality. It could be due to the low temperatures and frosts that the plant could not surpass (Felker et al., 1999).

Table 2
Physico-chemical characterization of the first year *Leucaena* varieties and sprouts, after prunings, with 1 year

	Fiber length (mm)	Hot water solubles (%)[a]	1% NaOH solubles (%)	Ethanol-benzene extractives (%)
L. diversifolia	0.806 (0.09) A	3.24 (0.06) A	17.38 (0.79) A	4.44 (0.27) A
L. collinsii	0.692 (0.05) B	4.30 (0.05) B	20.02 (0.82) B	4.64 (0.08) A
L. leucocephala (H)	0.844 (0.23) A	5.01 (0.05) C	20.26 (1.08) B	6.05 (0.16) B
L. leucocephala (I)	0.893 (0.08) A	3.98 (0.04) AB	18.44 (1.22) A	4.64 (0.12) A
L. leucocephala (K360)	0.769 (0.10) A	6.81 (0.06) D	23.41 (0.99) C	8.19 (1.01) C

The values in parentheses are standard deviation. Values followed by the same letter in the same columns do not differ significantly ($p < 0.05$).
[a] Percentages with respect to initial raw material (100 kg o.d.b.).

Biomass accumulation for the *Leucaena* varieties studied shows wide variations (Table 1).

Above-ground biomass yield per hectare basis was significantly higher for *L. leucocephala* varieties. Among the three *L. leucocephala* was *L. leucocephala* (I) the highest total dry biomass yielded (13.51 t ha^{-1}), nevertheless, *L. leucocephala* (H) showed the highest wood dry basis biomass (9.35 t ha^{-1}). *L. diversifolia* registered the four highest biomass yield (7.45 t ha^{-1}) and *L. collinsii*, the lowest. During the second year, contrary to expectations, *L. diversfolia* recorded the highest total and wood biomass yield but not significantly with respect to *Leucaena* varieties. As a result, *L. diversifolia* growth was delayed. Significant differences in yield obtained were observed within the different varieties and cuttings in the first and second growing season. Thus, the year 1 sprouts cutting gave a significant higher total biomass yield than the first year or second year cuttings. The prunings of *Leucaena* varieties stimulate the growth in height and the production of biomass by 72–97%. The plants of 2 years of *L. diversifolia* have a similar total and wood dry basis weight than that the sprouts obtain after the first harvest. However, in *L. leucocephala* (I) great differences in the plants weight have been found (30.94 t ha^{-1} for 2 years plants and 67.14 t ha^{-1} for sprouts obtain after the first harvest). *L. collinsii* showed, again, the lowest biomass production (9.44 t ha^{-1}).

3.2. Chemical characteristics of raw materials

The chemical characterization for *Leucaena* varieties for first year and year 1 sprouts (Table 2) and second year (Table 3) are shown.

In Table 2 higher fiber length values for *L. leucocephala* with respect to other *Leucaena*s is observed. However, no statistically significant differences in fiber lengths has been found among the others *Leucaena* varieties with the exception of the lower values found for *L. collinsii*.

Hot water solubles, 1% NaOH and ethanol-benzene extractives shows lower values for *L. leucocephala* (I) and *L. diversifolia*. Pulp yield is negatively correlated with the extractives content (ethanol-benzene, 1% NaOH and water solubles), therefore a greater pulping yield could be supposed for these varieties.

Table 4 shows the chemical characterization of the others bibliographic raw materials (hardwoods, softwoods and alternative raw materials). The quantity of hot water and 1% NaOH solubles and ethanol-benzene extractives shows similar values when compared with wood materials (Table 4) and their values are relatively lower when they were compared with non-wood and some other annual plants.

The holocellulose content of the *Leucaena* varieties under investigation was higher than 68%, with respect to o.d. material, meaning a cellulose/hemicellulose ratio

Table 3
Physico-chemical characterization of the second year *Leucaena* varieties

	Fiber length (mm)	Hot water solubles (%)[a]	1% NaOH solubles (%)	Ethanol-benzene extractives (%)
L. diversifolia	0.822 (0.42) A	2.66 (0.14) A	15.92 (1.07) A	3.75 (0.44) A
L. collinsii	0.680 (0.14) B	3.18 (0.19) B	21.89 (1.26) C	5.79 (0.61) B
L. leucocephala (H)	0.861 (0.16) A	2.59 (0.04) A	18.73 (0.98) B	6.41 (0.11) B
L. leucocephala (I)	0.920 (0.10) A	2.50 (0.23) A	17.88 (1.78) B	5.84 (0.53) B
L. leucocephala (K360)	0.778 (0.12) AB	4.30 (0.65) C	17.65 (1.19) B	3.81 (0.46) A

The values in parentheses are standard deviation. Values followed by the same letter in the same columns do not differ significantly ($p < 0.05$).
[a] Percentages with respect to initial raw material (100 kg o.d.b.).

Table 4
Chemical characterization of some raw material (bibliographic references)

Raw material	Holocellulose (%)	Lignin (%)	α-Cellulose (%)	Hot water solubles (%)	Ethanol-benzene extractables (%)	1% NaOH solubles (%)	References
Wood materials							
Eucalyptus globulus	80.5	19.96	52.8	2.84	1.15	12.42	Alonso (1976)
E. globulus	79.5	21.24		2.91	1.40	12.84	Gilarranz et al. (1999)
Pinus pinaster	60.5	30.20	42.9				Parajó et al. (1993)
Pinus pinea	69.6	26.22	55.9	1.99	2.57	7.98	Alonso (1976)
Non-wood materials							
Cannabis sativa L. (hemp)		21.80	37.3				Antunes et al. (2000)
Cynara cardunculus L.	63.4	19.6	38.0	13.00	5.01		Antunes et al. (2000)
Gossypium hirsutum L. (cotton)	72.9	21.45	42.3	3.33	1.42	20.34	Jiménez et al. (1993)
Hibiscus cannabinus L. (kenaf)				6.70	2.00	26.10	Khristova et al. (2002)
Panicum virgatum L. (switchgrass)	78.5	18.14		15.12	3.71	45.44	Law et al. (2001)
P. virgatum L. (switchgrass)	81.0	19.54		12.44	1.69	27.92	Law et al. (2001)
Triticum sp. (wheat straw)	70.7	21.67	41.3		2.45		Sun and Tomkinson (2004)
Olea europaea (olive)	69.1	17.60	41.0	17.30	12.20	30.0	Díaz et al. (2005)

higher than 1.2. This ratio is very important due to the capital role that hemicelluloses play in papermaking (Cordeiro et al., 2004). High values in holocellulose content were found for *L. collinsii*, *L. diversifolia* and *L. leucocephala* (I).

Relatively lower lignin content in *Leucaena* varieties has been found with respect to other vegetal species (Table 4 and Ververis et al., 2004). Low values of lignin content have been found in *L. collinsii* and *leucocephala* (K360). These values could suggest that they varieties may require low pulping time and chemical charge compared to those of other non-wood raw materials.The α-cellulose contents found in *Leucaena* varieties are in the range of the normal values expected for other non-wood raw materials and lower than those found for wood-based materials.

In Table 3 in a similar way to that found for Table 2, high fiber lengths has been reported for *L. leucocephala* (I). However, no statistically significant differences have been found among *Leucaena* varieties with except to *L. collinsii.* The lowest fiber length has been shown for this variety.

The hot water solubles, in the second year, continue a similar trend than that followed for the first one values. Then, *L. leucocephala* (K360) is the one where a higher value has been found. For the other measured extractables (1% NaOH solubles and ethanol-benzene extractives) changes on the described trend have been found. The highest value in 1% NaOH solubles, for the second year, among *Leucaena* varieties, has been found for *L. collinsii*. No statistically significant differences have been reported among other *Leucaena* varieties, with except to *L. diversifolia* that is the variety for which the lowest values has been found. The values for ethanol-benzene extractives in *L. collinsii*, *L. leucocephala* (H) and (I) shows no statistically significant differences among them. However, a higher statistically significant difference has been found for *L. diversifolia* and *L. leucocephala* (K360).

The values obtained for the hot water solubles, in the second year, followed a similar trend to that obtained for the first year. *L. leucocephala* (K360) is the one that the highest value has been found. A similar trend, to that described for the first year, had been found for the other measured extractables (1% NaOH solubles and ethanol-benzene extractives) have been found. The highest value, for year 2, in 1% NaOH solubles has been found for the *L. collinsii.*

L. leucocephala (K360) was the variety for which higher values in holocellulose and α-cellulose have been obtained in the second year. Therefore, lower values of lignin have been found for this variety than that obtained

Table 5
Physico-chemical characterization of the first year *Leucaena* varieties* and sprouts, after prunings, with one year, pulp obtained

Pulp	Hot water solubles (%)	1% NaOH solubles (%)	Ethanol-benzene extractives (%)	Holocellulose (%)	Lignin (%)	α-Cellulose (%)
L. diversifolia	0.71 (0.12) B	2.78 (0.40) B	1.90 (0.05) B	94.5 (6.31) A	1.74 (0.41) B	81.39 (2.49) A
L. collinsii	1.23 (0.19) C	3.55 (0.26) C	1.51 (0.07) B	93.4 (8.49) A	1.60 (0.23) B	79.97 (1.99) A
L. leucocephala (H)	0.45 (0.06) A	2.16 (0.91) B	0.55 (0.02) A	96.4 (8.76) A	1.64 (0.18) B	84.03 (3.51) A
L. leucocephala (I)	0.30 (0.09) A	1.93 (0.19) A	1.55 (0.10) B	96.2 (7.78) A	1.06 (0.09) A	84.44 (2.67) A
L. leucocephala (K360)	0.65 (0.15) B	2.56 (0.09) B	0.30 (0.08) A	94.9 (6.17) A	2.68 (0.67) C	82.25 (2.89) A

* The values in parentheses are standard deviation. Values followed by the same letter in the same columns do not differ significantly ($p < 0.05$).

for the rest of *Leucaena* varieties. On the other hand, lower holocellulose and α-cellulose values have been found for *L. collinsii* and *L. leucocephala* (H) with respect to that obtained for the rest of *Leucaena* varieties. High values in lignin content have been found for *L. diversifolia* and *L. leucocephala* (H).

3.3. Chemical characteristics of pulp

In Table 5, the values found for the physico-chemical characterization of the pulps obtained for the different varieties of *Leucaena*, in the first year, are shown.

In the above-mentioned table, low values in hot water solubles for *L. leucocephala* (H) and (I) have been observed. The highest value has been obtained for *L. collinsii*.

In general, for the others extractable parameters measured (1% NaOH and ethanol-benzene), a similar relation than that obtained for hot water solubles has been observed.

No significative statistically significant differences have been found for holocellulose, lignin and α-cellulose contents in pulps, with exception of lignin content found for *L. leucocephala* (I) and (K360).

Table 6 shows the values obtained for the physico-chemical characterization of the pulps obtained for *Leucaena*s in the second year.

The values for hot water solubles in the pulps obtained of *L. leucocephala* (H) and (I) reach higher values with respect to other varieties. The lowest value has been found for *L. leucocephala* (K360). It is possible to emphasize that the *L. leucocephala* (K360) reach the highest value in of hot water solubles (both in first and second year), in fiber length and the lowest value of the same parameters measured in pulp than those obtained for the rest of *Leucaena* varieties. The values observed in 1% NaOH solubles continue a similar trend than that found for hot water solubles. Under that trend, the values found for *L. leucocephala* (K360) reach higher statistically significant differences than that found for the rest of *Leucaena* varieties. No statistically significant differences have been found among other studied varieties, with except to *L. diversifolia.* Also, in that variety, similar to that found in fiber length values, the lowest value in 1% NaOH solubles have been found.

For the second year, similar trends have been observed in hot water and 1% NaOH soluble values for all the studied *Leucaena* varieties. The highest value has been found for *L. leucocephala* (H), no statistically significant differences have been found for the ethanol-benzene extractives values and, however, the highest value has been found for *L. leucocephala* (K360). On the contrary, the lowest value has been found for *L. diversifolia*.

In a similar way to values found for the pulps obtained in the year 1 (Table 6), no statistically significant differences among *Leucaena* varieties have been found for holocellulose, lignin and α-cellulose contents with except to lignin values found for *L. collinsii* that reported higher statistically significant effects.

Table 6
Physico-chemical characterization of the second year *Leucaena* varieties* pulp obtained

Pulp	Hot water solubles (%)	1% NaOH solubles (%)	Ethanol-benzene extractives (%)	Holocellulose (%)	Lignin (%)	α-Cellulose (%)
L. diversifolia	1.04 (0.15) B	1.63 (0.11) A	0.65 (0.05) B	94.45 (6.03) A	1.37 (0.12) A	79.89 (4.47) A
L. collinsii	0.93 (0.10) B	2.77 (0.14) B	0.31 (0.11) A	94.63 (5.67) A	3.27 (0.17) B	80.86 (5.76) A
L. leucocephala (H)	1.57 (0.99) C	4.65 (0.19) C	0.39 (0.11) A	94.06 (6.11) A	1.92 (0.12) A	80.56 (5.45) A
L. leucocephala (I)	1.61 (0.12) C	3.15 (0.17) B	0.39 (0.13) A	94.38 (4.41) A	0.90 (0.15) A	82.60 (4.23) A
L. leucocephala (K360)	0.52 (0.07) A	3.29 (0.23) B	0.84 (0.25) C	95.39 (6.33) A	1.43 (0.12) A	82.36 (4.01) A

* The values in parentheses are standard deviation. Values followed by the same letter in the same columns do not differ significantly ($p < 0.05$).

3.4. Raw material and pulp comparison

Comparing Tables 2 and 3, Table 3 shows higher fiber length values for second year *Leucaena* varieties, moreover, statistical significant differences have been found with respect to first year ones. Hot water and 1% NaOH solubles and ethanol-benzene extractives, according to values found for Table 2, shows lower values than that obtained for first year ones. At this point, a similar relation has been found, both for the first year and for the second one, among the contents observed in the different varieties of *Leucaena*. Relatively higher lignin content in *Leucaena* varieties have been found for the second year with respect to the first year ones and similar to that found in other vegetal species (Table 4). The α-cellulose contents found among *Leucaena* varieties, for the second year, reach lower values in *L. collinsii* and *L. leucocephala* (H), similar values for *L. leucocephala* (I) and higher values for *L. diversifolia* and *leucocephala* (K360) than that obtained for the first year ones.

In general, for both years and among the varieties, lower values in solubles and lignin contents and higher values in holocellulose and α-cellulose contents have been found with respect to non-wood materials (Table 4).

Comparing Tables 5 and 6, lower values, in solubles and extractables, for the second year than those found for the first one contents have been observed, with except to *L. leucocephala* (H) and (I). In those varieties, high values have been observed, both in hot water and in 1% NaOH solubles, for the second year with respect to the obtained ones for the first year. To denote that, in the above-mentioned varieties, lower values in solubles and extractables, have been found in the first year obtained pulps, with respect to other studied varieties. In the second year, those varieties, obtain higher values than that obtained for other studied *Leucaena* varieties.

A comparison of the main pulps characteristics obtained for both years in holocellulose, α-cellulose and lignin are shown in Figs. 1–3, respectively.

No statistically significant differences in the holocellulose contents of pulp obtained for *L. diversifolia* and *L. leucocephala* (I) varieties has been show in Fig. 1. Higher values in this parameter have been found for the first year in the varieties *L. collinsii* and *L. leucocephala* (H) than that obtained for the second year ones. Nevertheless, lower values of holocellulose content have been found for the obtained pulps in the first year with respect to the second one in the variety *L. leucocephala* (K360).

Fig. 2 shows a similar evolution to that obtained for Fig. 1. A higher content in α-cellulose for *L. collinsii* for year 1 with respect to found for the year 2 has been found. Also, no statistically significant differences in the α-cellulose contents of pulp obtained for *L. diversifolia*, *L. leucocephala* (H) and *L. leucocephala* (I) has been found. On the contrary to that found for *L. collinsii*, for *L. leucocephala* (K360), lower contents in α-cellulose for year 1 with respect to found for the year 2 have been found.

In Fig. 3, higher contents in lignin for the second year in *L. diversifolia* and *L. collinsii*, similar contents in *L. leucocephala* (H) in both years and lower contents in lignin with respect to the values found for the first year in *L. leucocephala* the (I) and (K360) have been found.

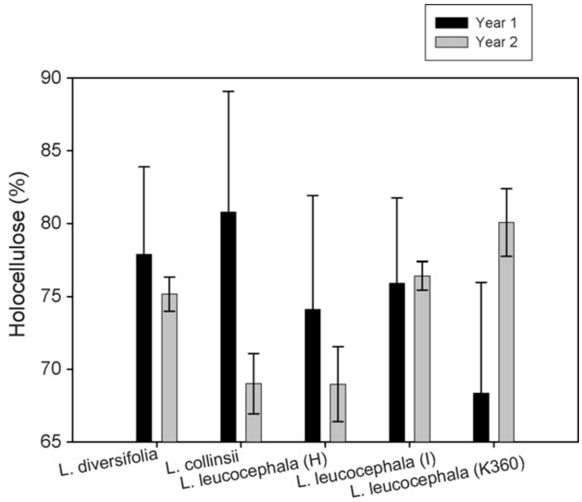

Fig. 1. Holocellulose contents of pulp obtained for *Leucaena* varieties. The single vertical lines are standard deviation.

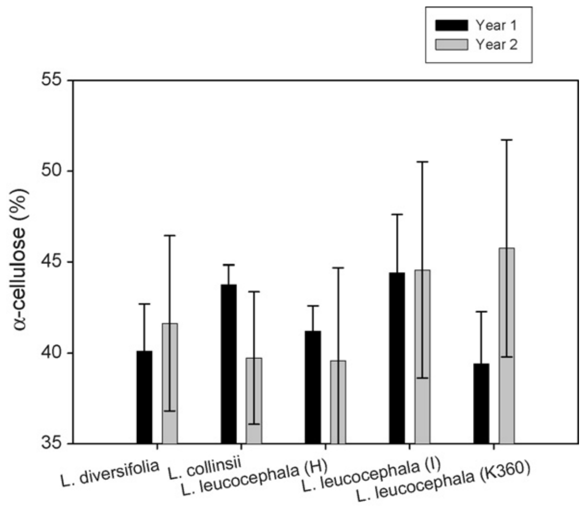

Fig. 2. α-Cellulose contents of pulp obtained for *Leucaena* varieties. The single vertical lines are standard deviation.

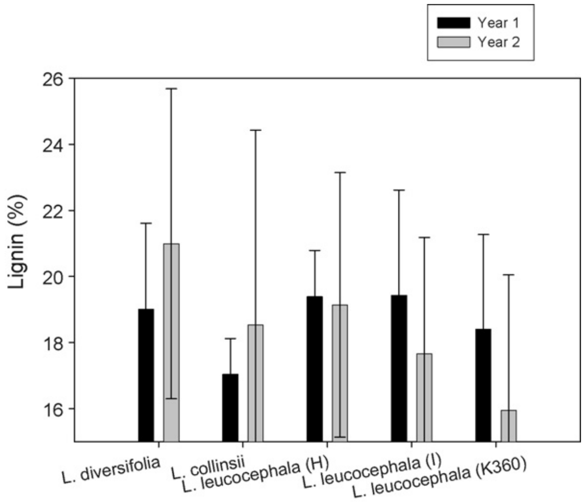

Fig. 3. Lignin contents of pulp obtained for *Leucaena* varieties. The single vertical lines are standard deviation.

4. Conclusions

The chemical characteristics of *Leucaena* varieties, report positively on its possible use as alternative source of cellulose pulp.

Fiber lengths and other raw materials characteristics have been more appropriate for the second year than that for the first one. *L. leucocephala* (I) has obtained the highest value among all the evaluated varieties (0.92 mm). On the contrary, the contents in biomass are higher for the year 1 sprouts than that obtained for the second year. Also in this way, *L. leucoephala* (I) has obtained the wood dry biomass highest value.

The study confirms the feasibility of the MD-organocell pulping process for *Leucaena* varieties. MD-organocell pulping provides an efficient delignification. In this process, the operation temperature, among studied, has a positive effect pulp measured properties. Large amounts of lignin from 83.24 to 95.05% of the initial content are removed during the pulping process, depending on the *Leucaena* variety.

In summary, the physico-chemical parameters evaluated, both in raw material and pulp obtained, for the second year are, in general, lightly suitable than that obtained for the first one. However, wood dry biomass values obtained are higher for resproutings than that obtained for the second year.

Acknowledgements

The authors acknowledge financial support from the CICYT (Science and Technology Inter Ministerial Commission, Spanish Government)-FEDER, (project numbers PPQ2001-2489-C03-02 and -03, PPQ2003-03913-C02-02 and CTQ2004-06564-C04-04/PPQ) and Junta de Andalucia, Conserjería de Agricultura y Pesca Project C01-121.

References

Alonso, L., 1976. In: INIA (Ed.), Análisis químico de maderas de diferentes especies forestales. Ministerio de Agricultura, Madrid, Spain.

Antunes, A., Amaral, E., Belgacem, M.N., 2000. *Cynara cardunculus* L.: chemical composition and soda-anthraquinone cooking. Ind. Crops Prod. 12 (2), 85–91.

Browning, B.L., 1967. Methods of Wood Chemistry. John Wiley & Sons, New York, USA.

Burleigh, J.R., Yamoah, C.F., 1997. Site factors associated with the performance of *Leucaena leucocephala* (Lam.) de Wit and *Sesbania sesban* (L.) Merill in pure and mixed stands in the northern highlands of Rwanda. Agrofor. Syst. 37, 121–131.

Cordeiro, N., Belgacem, M.N., Torresa, I.C., Mourad, J.C.V.P., 2004. Chemical composition and pulping of banana pseudo-stems. Ind. Crops Prod. 19 (2), 147–154.

Díaz, M.J., Eugenio, M.E., López, F., Alaejos, J., 2005. Paper from olive tree residues. Ind. Crops Prod. 21 (2), 211–221.

Duhoux, E., Dommergues, Y., 1985. In: Ssali, H., Keya, S.O. (Eds.), The Use of Nitrogen Fixing Trees in Forestry and Soil Restoration in the Tropics. Biological Nitrogen Fixation in Africa, Nairobi Mircen, Kenya, pp. 384–400.

Felker, P., Sorensson, C.T., Ueckert, D., Jacoby, P., Singer, E., Ohm, R., 1999. Growth, cold-hardiness, protein content, and digestibility of 70 *Leucaena* seedlots on three sites in Texas, USA. Agrofor. Syst. 42, 159–179.

Gilarranz, M.A., Rodríguez, F., Santos, A., Oliet, M., Garcia-Ochoa, F., Tijero, J., 1999. Kinetics of *Eucalyptus globulus* delignification in a methanol-water medium. Ind. Eng. Chem. Res. 38 (9), 3324–3332.

ICRAF (International Centre for Research in Agroforestry), 2002. Soil fertility degradation in sub-Saharan Africa: leveraging lasting solutions to a long-term problem. Conclusions from a Workshop held at the Rockefeller Foundation Bellagio Study and Conference Centre, March, Monterrey, Mexico, pp. 10–15.

Jiménez, L., López, F., Ferrer, J.L., Herranz, J.L., 1993. Evaluation of agricultural residues for paper manufacture. Tappi J. 76 (3), 169–173.

Kauter, D., Lewandowski, I., Claupeina, W., 2003. Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel usea review of the physiological basis and management influences. Biomass Bioenergy 24 (6), 411–427.

Khristova, P., Kordsachia, O., Patt, R., Khider, T., Karrar, I., 2002. Alkaline pulping with additives of kenaf from Sudan. Ind. Crops Prod. 15 (3), 229–235.

Kumar, B.M., Kumar, S.S., Fisher, R.F., 1998. Intercropping teak with *Leucaena* increases tree growth and modifies soil characteristics. Agrofor. Syst. 42, 81–89.

Law, K.N., Kokta, B.V., Mao, C.B., 2001. Fibre morphology and soda-sulphite pulping of switchgrass. Bioresour. Technol. 77 (1), 1–7.

Leung, W.C., Wong, M.F., Chua, H., Lo, W., Yu, P.H.F., Leung, C.K., 2000. Removal and recovery of heavy metals by bacteria isolated from activated sludge treating industrial effluents and municipal wastewaters. Water Sci. Technol. 41 (12), 233–240.

Lombardi, S.C., Ramalho, A.L., 2003. Properties of complexes of galactomannan of *Leucaena leucocephala* and Al^{3+}, Cu^{2+} and Pb^{2+}. Bioresour. Technol. 89 (1), 63–73.

Ma, Y., Dickinson, N.M., Wong, M.H., 2003. Interactions between earthworms, trees, soil nutrition and metal mobility in amended Pb/Zn mine tailings from Guangdong, China. Soil Biol. Biochem. 35 (10), 1369–1379.

Naidja, A., Huang, P.M., Bollag, J.M., 2000. Enzyme–clay interactions and their impact on transformations of natural and anthropogenic organic compounds in soil. J. Environ. Qual. 29 (3), 677–691.

Oggiano, N., Angelini, L.G., Cappelletto, P., 1997. Pulping and paper properties of some fibre crops. Ind. Crops Prod. 7 (1), 59–67.

Parajó, J.C., Vázquez, D., Alonso, J.L., Santos, V., 1993. Optimization of catalysed acetosolv fractionation of pine wood. Holzforschung 47, 188–196.

Parrotta, J.A., 1992. *Leucaena leucocephala* (Lam.) de Wit *Leucaena*, tantan. SO-ITFSM-52. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA.

Pascucci, P.R., Kowalak, A.D., 1999. Metal distribution in complexes with *Chlorella vulgaris* in seawater and wastewater. Water Environ. Res. 71 (6), 1165–1170.

Rout, G.R., Samantaray, S., Das, P., 1999. Chromium, nickel and zinc tolerance in *Leucaena leucocephala* (K8). Sivae Genet. 48, 3–4.

Sharma, N.K., Singh, P.N., Tyagi, P.C., Mohan, S.C., 1998. Effect of *Leucaena* mulch on soil-water use and wheat yield. Agric. Water Manage. 35 (3), 191–200.

Shatalov, A.A., Pereira, H.A.A., 2004. *Arundo donax* L. reed: new perspectives for pulping and bleaching. Part 3. Ethanol-reinforced alkaline pulping. Tappi J. 3 (2), 27–31.

Sun, R.C., Tomkinson, J., 2004. Separation and characterization of cellulose from wheat straw. Sci. Technol. 39 (2), 391–411.

Van den Born, G.J., de Haan, B.J., Pearce, D.W. Howarth, A., 2000. Technical Report on Soil Degradation, RIVM Report 481505018.

Vanlauwe, B., Sanginga, N., Merckx, R., 1998. Recovery of *Leucaena* and *Dactyladenia* residue 15N in alley cropping systems. Soil Sci. Am. J. 62, 454–460.

Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P., Santas, R., 2004. Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. Ind. Crops Prod. 19 (83), 245–254.

Wise, L.E., Marphy, M., D'Adieco, M., 1946. Chlorite holocellulose, its fractionation and bearing on summative wood analysis and on studies on the hemicelluloses. Paper Trade J. 122 (2), 35–43.

Zalidis, G., Stamatiadis, S., Takavakoglou, V., Eskridge, K., Misopolinos, N., 2000. Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agric. Ecosyst. Environ. 88 (2), 137–146.