

# *Leucaena* species valoration for biomass and paper production in 1 and 2 year harvest

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## Abstract

In order to identify faster-growing non-woody species usable for biomass and paper production, four *Leucaena* species (*L. diversifolia*, *L. colinsii*, *L. salvadorensis* and three varieties of *L. leucocephala*) were tested. All the *Leucaena* species showed a good soil and climatic adaptation to Spain Southwest except for *L. salvadorensis*. Studied *Leucaena* species showed biomass productivity ranges from 67.14 to 9.44 t ha<sup>-1</sup> (o.d.b.) and 43.6 to 11.4 t ha<sup>-1</sup> under Mediterranean conditions for the first and second year sprouts, respectively. The quantity of solubles and extractives shows similar values when compared with wood materials. Relatively lower lignin content in *Leucaena* (from 15.7% to 21.4%) species has been found with respect to other vegetal species. The  $\alpha$ -cellulose contents (39.4–45.3%) are in the range of the normal values expected for the other non-wood raw materials.

The study confirms the feasibility of organocell yield pulping process to *Leucaena* species. Organocell process provides an efficient delignification (kappa number 12.4 and pulp yield 42.2%) for *L. leucocephala* and suitably physical characteristics of paper sheet (tensile index 20.3 kNm/kg for *L. diversifolia*).

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## 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 4% by wind erosion (Ananda and Herat, 2003). Land area globally affected by erosion is 1094 million ha (Mha) by water erosion and 549 Mha by wind erosion (Lal, 2003). Interactions between climate change and soil degradation are believed to be a primary cause of the frequent droughts, disastrous floods and related environmental problems (Tao et al., 2005).

Some of the main effects of soil degradation lead to reduce vegetative cover, decrease water quality, lower efficiency of use and management of water and increase risk from pests and diseases because of lowered biological control (Zalidis et al., 2000; Paz et al., 2006). Despite of several

solutions proposals and time and resources invested, it continues to be a substantial problem (Zalidis et al., 2000). There are many studies concerning bioremediation for highly polluted areas (Lombardi and Ramalho, 2003; Naidja et al., 2000). The possible solutions involve an agricultural sustainability that using natural resources to enhance progressively the productive capacity without jeopardizing future potential. For example, leguminous species or the ones vaccinated against bacteria have been proposed from the Bradyrhizobium, Rhizobium, Sinorhizobium and Mesorhizobium genera (Ulrich and Zaspel, 2000; Lafay and Burdon, 2001; Rodríguez-Echevarría et al., 2003), helping to the recovery of already degraded grounds because biological nitrogen fixing that happens while symbiosis between bacteria and plants is the main way of having nitrogen in the biosphere. Woody legumes can prevent erosion, increase soil fertility and facilitate the establishment and growth of other plant species (Cross and Schlesinger, 1999; Rodríguez-Echevarría et al., 2003).

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Under this perspective, the use of *Leucaena* species in soil restoration has been studied in several countries (Vanlauwe et al., 1998; Sharma et al., 1998; Santana et al., 2003). *Leucaena* species, a fast-growing leguminous shrub from Central America that is frequently used in agroforestry systems, can produce protein-rich foliage for livestock and pods bearing edible seeds. *Leucaena* species have been reported to grow on poor soils (Rout et al., 1999; Ma et al., 2003) where it has been found they provide an effective cover to prevent leaching of heavy metals from the mine tailings to the neighboring environments.

Moreover, these crops favorably affect another problem such as the surplus production of food generated by the European Union for last decade, and that make us to look for alternatives for the agriculture in order to be able to maintain the income for the exploitation of natural resources. Three different solutions have been proposed to this situation of surplus production (Montero de Espinosa, 1993): working on very high quality products, through selection of fast-growing species and high profitability (Fernández, 1996), the use of crops that help to recover the degraded environmental balance and leading agriculture to non-food uses (energy, paper, fabrics, chemical products, etc.).

The use of non-woody faster-growing species for papermaking may have a great advantage if they could provide a solution for environmental problems associated with the industrial use of those 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 of the use of wood *Leucaena* species for pulp and papermaking.

It should be noticed that paper production is responsible of most wood production all over the world. At the end of 20th century, almost 35% of wood world production was marketed to make paper or similar products and it is foreseen 50% growth for 2010. Ecological pressure for reduction of this consumption, could promote a strong development of non-conventional raw materials for pulp and paper production (Alaejos et al., 2004). Some studies carried out by FAO predict the increase of non-woody species consumption for pulp production all over the world. On 2010, a maximum of 20% over current paper production could be reached (Pande, 1998).

For pulp and papermaking, the method called the 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; Yawalata and Paszner,

2004). Moreover, valuable byproducts from hemicelluloses and sulphur-free lignin fragments useful for production of lignin-based adhesives and other products due to its high purity, low molecular weight and abundance of reactive groups can be obtained (Dapía et al., 2002; Pan et al., 2005).

The objectives of this study were to quantify the effects of four *Leucaena* species (*L. diversifolia*, *L. colinsii*, *L. salvadorensis* and three varieties of *L. leucocephala*) (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 and (c) on the physico-chemical characteristics of the pulp and paper obtained.

## 2. Experimental

### 2.1. Raw materials

Plants were obtained from seeds, for six varieties of *Leucaena*. *L. leucocephala* from Honduras (H), *L. leucocephala* from India (I), *L. leucocephala* var. K360 (K360), *L. salvadorensis*, *L. collinsii* and *L. diversifolia* were the varieties used in this experiment. These plants were grown in a nursery, in 300 cm<sup>3</sup> pot holders; they were inured from bacteria *Rhizobium* and, when they were 3 years old, they were changed to the ground in La Rábida (Huelva, southwestern Spain).

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<sup>2</sup> (9500 plants ha<sup>-1</sup>). Any fertilization was not added to plots. The soil at the experimental site was sandy loamy with a pH of 6–8 and having moderate to substantial depth.

Four samples, representing six *Leucaena* varieties aged from 1 to 2 years, and the sprouts again of the plant after the first year cut, were collected (pruning was always made during winter).

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. 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, pulp and paper sheets

*Leucaena* wood trimmings samples were milled to pass a 8 mm screen, 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.

Characterization of raw material involved the following parameters: hot water solubles (Tappi 257), 1% NaOH solubles (Tappi 212), ethanol–benzene extractives (Tappi 204),  $\alpha$ -cellulose (Tappi 203), holocellulose by the Wise et al. (1946) method. All treatments in this study were in a completely randomized design with five replications (variation coefficient less than 5%).

For determination of fiber length, 100 individual fibre were measured from each variety. Statistical analyses were performed using ANOVA and the differences among varieties were compared using Tukey's test. The means were separated on the basis of least significant difference at 0.05 probability level.

*Leucaena* wood trimmings were used for pulp and papermaking, but only wood was considered as it contained the bark, which was very thin and difficult to strip off also, it accounted for only 1–2% of the overall mass.

However, characterization experiments of pulp involved the following parameters: yield (Tappi 257), kappa number (Tappi 236) and viscosity (UNE 57-039). From paper sheets, grammage can be determined (UNE 57-014-74), tensile index (UNE 57-054 and UNE 57-028), burst index (UNE 57-058) and tear index (UNE 57-033).

### 2.3. Pulp and papermaking procedure

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. Finally, the liquor was quickly refrigerated by a internal heat exchanger, before opening the reactor. The initial liquor to solid ratio was 8:1 (dry wt. basis), the aqueous soda concentration in the cooking liquor was 21% in weight, the ethanol concentration was 30% in volume and the anthraquinone concentration was 0.05% in weight. The minidigester was then closed and simultaneously heated and actuated to assure good mixing and uniform swelling of the wood. 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 damaging the fibers, during 3 min (2500 rpm), washed on a sieve of 0.16 mm mesh, defibred and passed through a Strainer filter (0.4 mm mesh) in order to isolate the uncooked material.

Pulp preparation for making paper sheets is made disintegrating 30 g of pulp during 20 min at 2500 rpm, to a consistency of 1.5%.

Paper sheets were obtained in a sheet former ENJO-F-39.71. Once the sheets were obtained, they were pressed using PR.03(402) press, to reduce the moisture in the produced sheets. To definitively dry them, some plates and hoops were used in standard ambient conditions.

## 3. Results and discussion

### 3.1. Biomass production

All the *Leucaena* varieties showed a good soil and climatic adaptation to the zone, except for *L. salvadorensis* that suffers a great mortality. Biomass accumulation shows wide variations (Table 1).

There was no statistical significant effect of the plot on dry woody biomass production, neither on the total dry biomass, so it was deleted from the analysis.

Above-ground biomass yield per hectare basis was significantly higher for *L. leucocephala* varieties. Among the five *Leucaena*, *L. leucocephala* (I) was the highest total dry biomass yielded (13.5 t ha<sup>-1</sup>); nevertheless, *L. leucocephala* (H) showed the highest wood dry basis biomass (9.4 t ha<sup>-1</sup>). *L. diversifolia* registered the second highest biomass yield (7.5 t ha<sup>-1</sup>) and *L. collinsii*, the lowest one. During the second year, contrary to expectations, *L. diversifolia* recorded the highest total and wood biomass yield but not significantly different from India and K360 *Leucaena* varieties.

The variety and kind of use (number of prunings) show significant differences regarding production, both for woody biomass ( $p < 0.001$ ) and for total biomass ( $p < 0.001$ ). It should be noted the great results for “variety \* kind of use”; that means a high capacity of sprouts after the pruning at the end of their second year of life. This effect is particularly important at *L. diversifolia* and for the three varieties of *L. leucocephala*, although for *L. collinsii* it turns out to be statistical indifferent.

Anyway, the obtained growth during the second year was always higher than the one obtained during the first year (Table 1).

The prunings of *L. leucocephala* varieties have similar diameter to a 2 years old plant, but they are 26–48% taller (Table 1). Pruning stimulates the growth in height (for slimmest plants) and the production of biomass by 72–97%. The 2 years old plants of *L. diversifolia* have a similar total and wood dry basis weight to the sprouts obtained after the first harvest. *L. collinsii* showed, again, the lowest biomass production but no differences on the plants' sizes were observed.

Highest biomass production for all the species during the second year was possibly due to the fact that the plants had been obtained in a nursery from seeds, taking them to plots later. Absolute growth is the variable that has been evaluated, so it seems logical to have a slower growth due to the transplant, till roots are spread through the

Table 1  
Biomass yielded and characteristics of fiber from *Leucaena* varieties during 2 years

Varieties	Year 1		Year 2		Year 1 sprouts	
	WD <sup>a</sup>	TD <sup>b</sup>	WD	TD	WD	TD
<i>L. diversifolia</i>	4.8 (0.9)	7.5 (1.5)	28.3 (5.3)	43.6 (8.2)	28.3 (10.1)	43.7 (15.6)
<i>L. collinsii</i>	3.0 (0.7)	3.1 (1.4)	11.1 (4.8)	11.4 (4.9)	9.2 (4.6)	9.4 (4.7)
<i>L. leucocephala</i> (H)	9.4 (1.3)	12.8 (1.8)	17.1 (2.1)	23.4 (2.9)	28.4 (2.3)	38.8 (3.2)
<i>L. leucocephala</i> (I)	9.1 (1.0)	13.5 (0.8)	20.8 (4.6)	30.9 (6.9)	45.1 (10.2)	67.1 (15.1)
<i>L. leucocephala</i> (K360)	7.8 (1.0)	12.3 (1.5)	16.1 (8.3)	25.6 (13.1)	31.5 (5.5)	50.0 (8.9)
	Height (m)	Diameter (cm)	Height (m)	Diameter (cm)	Height (m)	Diameter (cm)
<i>L. diversifolia</i>	2.82a	2.4a	4.23b	4.1b	3.48a	3.0a
<i>L. collinsii</i>	2.04a	1.9a	2.57a	2.3a	2.56a	2.2a
<i>L. leucocephala</i> (H)	2.87a	2.6a	2.64a	3.2a	4.08b	3.4a
<i>L. leucocephala</i> (I)	2.91a	2.8a	2.87a	3.4a	4.21b	3.6a
<i>L. leucocephala</i> (K360)	2.96a	2.4a	2.97a	2.8a	3.75b	3.2a

Standard deviation in parentheses. Values followed by the same letter in the same column do not differ significantly (Tukey's test,  $p < 0.05$ ).

<sup>a</sup> WD: wood dry basis biomass ( $\text{t ha}^{-1}$ ).

<sup>b</sup> TD: total dry basis biomass ( $\text{t ha}^{-1}$ ).

ground. At least, for *L. leucocephala*, it is usual to have a disacceleration in growth during 2 or 3 first years of life (Parrotta, 1992).

In the case of *L. leucocephala*, it can be seen that a pruning every 2 years does not cause an important increase in the annual growth ratio, while if they are pruned when they are 1 year old, the grown sprout during that second year notably increases the production, reaching 50 t/ha/year. This result is one of the highest found (Parrotta, 1992; Faria-Marmol and Morillo, 1997; Sánchez et al., 2003). For this specie, prunings can be done every three months (Zárate, 1987), but they are used to produce forage. If the objective was to produce wood, periods between prunings would be longer, 6 or 12 months, even being able to make a double use of forage and wood. Faria-Marmol and Morillo (1997) remark that the first pruning, 5 or 6 months after the sowing, is a good time to choose the most productive individuals. On the other hand, *L. diversifolia*, showed good performance for both pruning periods (1 and 2 years), even a better performance than *L. leucocephala* for wood use. Nevertheless, the initial growth from the sowing turned out to be less vigorous than last one. *L. diversifolia* has been used as an alternative to *L. leucocephala* in high elevations (700–2500 m) in their natural habitat, if there are no frost. Moreover, as it has less mimosine on leaves it is better for forage use. On the other hand, *L. collinsii* did not reached productive levels like the other two species of the same genus.

Annual production of dry material obtained during test make equal to highest productions obtained from other alternative crops like kenaf, *Miscanthus* o *Sorghum* (Montero de Espinosa, 1993; Junta de Extremadura, 1996) in Spain and exceed the ones obtained for tree species like poplar trees, robinia, willow trees, eucalyptus or ailanthus, that never exceed 20 t/ha/year (poplar trees) (Hernández et al., 1996). As they are nitrogen fixing from the atmosphere (e.g. 110 kgN/ha for *L. leucocephala*, Parrotta, 1992) and they have multiple use (e.g. forage production

up to 15 t/ha/year for *L. leucocephala* y *L. diversifolia*), they are an interesting alternative for as a crop for soil recovery with industrial and livestock use.

### 3.2. Physico-chemical characteristics of raw materials

The physico-chemical characterization for *Leucaena* varieties for first year (and year 1 sprouts) and second year (Table 2) are shown. Higher fiber length values for *L. leucocephala* varieties with respect to other *Leucaenas* is observed. However, no statistical significant differences in fiber lengths has been found among the others *Leucaena* varieties with except to the lower values found for *L. collinsii*.

If they are analyzed as a whole, the characteristics related to the predictable yield in cellulosic pulp (hot water and 1% NaOH solubles and ethanol–benzene extractives) mean a higher potential for second year pruning if they reduce hot water solubles between 15.6% and 48% and 1% NaOH solubles between 3% and 24%. The highest value in 1% NaOH solubles, for the second year, among *Leucaena* varieties, has been found for *L. collinsii*. Ethanol–benzene extractives follow the same performance that for K360 variety (54% reduction) and *L. diversifolia* (13.6% reduction), even though do not vary or slightly increase for the other three varieties.

The holocellulose content of the *Leucaena* varieties under investigation was higher than 68%, with respect to o.d. material, meaning a cellulose/hemicellulose ratio was higher than 1.2, which is common to other vegetal species. This ratio is very important if one considers the capital role that hemicelluloses play in papermaking (Cordeiro et al., 2004). High values in content holocellulose (higher than 75%) have found for *L. collinsii*, *L. diversifolia* and *L. leucocephala* (I) in first year and *L. diversifolia*, *L. leucocephala* (I) and *L. leucocephala* K360 in second year. It can be seen a reduction in holocellulose content in second year pruning in comparison to the first one (more sprouts) for *L. diver-*

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

	Fiber length (mm)	Hot water solubles (%)	1% NaOH solubles (%)	Ethanol–benzene extractives (%)	Holocellulose (%)	Lignin (%)	$\alpha$ -Cellulose (%)
<i>First year and sprouts with 1 year</i>							
<i>L. diversifolia</i>	0.81a	3.2	17.4	4.4	77.9	19.0	40.1
<i>L. collinsii</i>	0.69b	4.3	21.9	4.6	80.8	17.0	43.8
<i>L. leucocephala</i> (H)	0.84a	5.0	20.3	6.1	74.1	19.4	41.2
<i>L. leucocephala</i> (I)	0.89a	4.0	18.4	4.6	75.9	21.4	44.4
<i>L. leucocephala</i> (K360)	0.77a	6.8	23.4	8.2	68.3	18.4	39.4
<i>Second year</i>							
<i>L. diversifolia</i>	0.82a	2.7	15.9	3.8	75.2	21.0	41.6
<i>L. collinsii</i>	0.68b	3.2	20.0	5.8	69.0	18.5	39.7
<i>L. leucocephala</i> (H)	0.86a	2.6	18.7	6.4	69.0	19.1	39.6
<i>L. leucocephala</i> (I)	0.92a	2.5	17.9	5.8	76.4	17.7	44.6
<i>L. leucocephala</i> (K360)	0.78ab	4.3	17.7	3.8	79.7	15.7	45.3

\*Percentages with respect to initial raw material (100 kg o.d.b.). Values followed by the same letter in the same column do not differ significantly (Tukey's test,  $p < 0.05$ ).

*sifolia* (–3.5%), *L. collinsii* (–14.6%) and *L. leucocephala* (H) (–6.7%), but an increase of  $\alpha$ -cellulose/holocellulose ratio of 6.7%, 5.7% and 3.1%, respectively. That means a higher development in the cellulose fraction of the long chain and a predictable better evolution of mechanical characteristics of paper sheets for these varieties.

The lignin content shows a similar effect. The lignin/holocellulose ratio increases from 4.1% to 21.6% for the three varieties (*L. diversifolia*, *L. collinsii* and *L. leucocephala* (H)) and decreases for the other two ones. That implies a higher lignification of the vegetable.

Table 3 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 and

their values are relatively lower when they were compared with non-wood and some other annual plants, although ethanol–benzene extractives are slightly higher than most of considered materials. Pulp yield is negatively correlated with the extractives content (ethanol–benzene and water solubles), therefore a greater pulp yield could be supposed for these varieties.

Relatively lower lignin content in *Leucaena* species has been found with respect to other vegetal species (Table 3 and Ververis et al., 2004). Low values lignin content have been found in *L. collinsii* and *L. 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. *L. leucocephala* (I) had the highest lignin content followed by *L. leucocephala* (H) and *L. diversifolia*.

Table 3  
Chemical characterization of some raw material (bibliographic references)

Raw material	Holocellulose (%)	Lignin (%)	$\alpha$ -Cellulose (%)	Hot water solubles (%)	ethanol–benzene extractables (%)	1% NaOH solubles (%)	References
<i>Wood materials</i>							
<i>Eucalyptus globulus</i>	80.5	20.0	52.8	2.8	1.2	12.4	Alonso (1976)
<i>Eucalyptus globulus</i>	79.5	21.2		2.9	1.4	12.8	Gilarranz et al. (1999)
<i>Eucalyptus globulus</i>	72.6	22.9	46.6				Parajó et al., 2004; Garrote and Parajó (2002)
<i>Beech (Fagus sylvatica)</i>	62.11	23.7	38.6		0.49		Dapía et al. (2002)
<i>Pinus pinaster</i>	60.5	30.2	42.9				Parajó et al. (1993)
<i>Pinus pinea</i>	69.6	26.2	55.9	2.0	2.6	8.0	Alonso (1976)
<i>Aspen wood</i>	68.3	21.4	47	0.39	0.64		Abad et al. (2000) Yañez et al. (2000)
<i>Non-wood materials</i>							
<i>Cannabis sativa</i> L. (hemp).		21.8	37.3				Antunes et al. (2000)
<i>Cynara cardunculus</i> L.	63.4	19.6	38.0	13.0	5.0		Antunes et al. (2000)
<i>Gossypium hirsutum</i> L. (cotton)	72.9	21.5	42.3	3.3	1.4	20.3	Jiménez et al. (1993)
<i>Hibiscus cannabinus</i> L.(kenaf)				6.7	2.0	26.1	Khristova et al. (2002)
<i>Panicum virgatum</i> L. (switchgrass)	78.5	18.1		15.1	3.7	45.4	Law et al. (2001)
<i>Panicum virgatum</i> L. (switchgrass)	81.0	19.5		12.4	1.7	27.9	Law et al. (2001)
<i>Triticum</i> sp. (wheat straw)	70.7	21.7	41.3		2.5		Sun and Tomkinson (2004)
<i>Olea europaea</i> (olive)	69.1	17.6	41.0	17.3	12.2	30.0	Díaz et al. (2005)

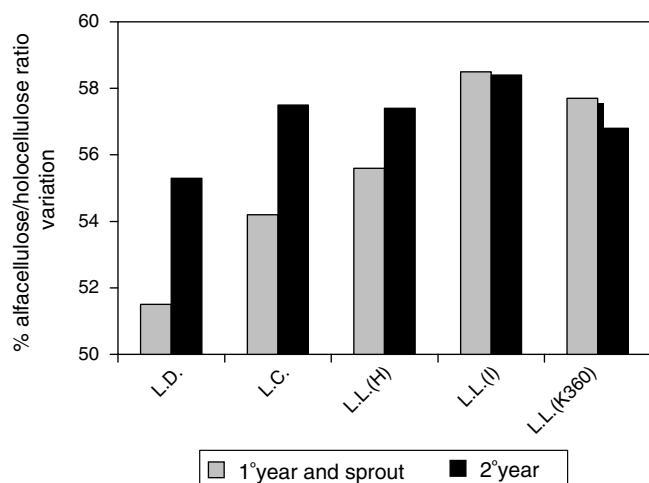


Fig. 1. % Alfacellulose/holocellulose ratio variation in *Leucaena* species. L.D.: *Leucaena diversifolia*, L.C.: *Leucaena colinsii*, L.L. (H), L.L. (I) and L.L. (K360): *Leucaena leucocephala* from Honduras, India and K360 varieties.

On the other hand, holocellulose contents, like the ones on K360 variety or on the one coming from India, are ones of the highest compared to raw materials shown in Table 3.

The  $\alpha$ -cellulose contents found in *Leucaena* species are in the range of the normal values expected for other non-wood raw materials and lower than those found for wood-based materials.

There is no one variety of among the ones considered with an overall best value for physico-chemical characteristics in first year. Holocellulose, lignin and  $\alpha$ -cellulose contents are better in their K360 variety harvested in second year. If it is considered  $\alpha$ -cellulose/holocellulose ratio evolution, highest growth between first and second year is for *L. diversifolia*, although higher values of that ratio belong to *L. leucocephala* (I) (Fig. 1).

### 3.3. Characteristics of pulp and paper sheets

Industrial use has been considered by means of cellulose pulp and paper production through tests described on section called “experimental”.

In Table 4, the values found for the physico-chemical characterization of the pulps and paper sheets obtained for the different varieties of *Leucaena*, in the first year (and sprouts, after prunings, with 1 year) and second year, are shown.

These results are comparable to other alternative crops and better to other tree species like eucalyptus. Many information exists about the state of the art. For example, with respect to eucalyptus, Botello et al. (1999) reports a yield of 50.5 under ethanol process. In several articles appear kappa numbers between 20 and 110 (Lora, 1992; Pascoal Neto and Robert, 1992). Pereira et al. (1986) reports rupture length values between 1.4 and 1.7 km for ethanol pulping of eucalyptus globulus and 1.3 for kraft pulping process without refining (tensile index: 13–17 kNm/kg approximately).

It can be seen an important increase on cellulose pulp yield from 2 years old raw material when compared to 1 year old ones (even considering sprouts), from 10.9% in the case of *L. leucocephala* from India to 19.5% for *L. leucocephala* improved with K360. Lowest yields in every pruning are on *L. colinsii* as it could be foreseen observing the 1% NaOH solubles contents. If variations on cellulosic pulp yield/ha on the first year is 4.7 t of pulp/ha for *L. colinsii*, 22.9 t of pulp/ha from *L. leucocephala* (I) and 5.0 t of pulp/ha from *L. colinsii* to 13.1 t of pulp/ha from *L. diversifolia* in second year.

In Table 4, higher values of kappa number for the second year in *L. diversifolia* and *L. collinsii*, similar values in all *L. leucocephala* varieties in both years and lower values for the first year in *L. diversifolia* and *L. collinsii* have been found. Cellulose pulps from *L. leucocephala* varieties would be more easily bleached.

The *L. leucocephala* K360 shows best developments for tensile and burst indexes of paper sheets obtained from 1 year old raw material or 1 year old sprouts, although they show an important reduction of tensile index when using raw material from second year up to –25%. Therefore, results obtained in holocellulose contents, *L. colinsii*, *L. diversifolia* and *L. leucocephala* (Honduras) show best viscosity values in both prunings. Moreover, *L. colinsii* and

Table 4

Physico-chemical characterization of the first year (and sprouts, after prunings, with 1 year) and the second year *Leucaena* varieties pulp obtained

	Yield (%)	Kappa number	Viscosity (cm <sup>3</sup> /g)	Tensile index (kNm/kg)	Burst index (Nm <sup>2</sup> /kg)	Tear index (mN/m <sup>2</sup> )
<i>First year and sprouts with 1 year</i>						
<i>L. leucocephala</i> Honduras	40.1	12.1	632	12.5	0.54	0.66
<i>L. leucocephala</i> India	42.2	12.4	509	12.6	0.45	0.61
<i>L. leucocephala</i> K360	39.5	14.5	597	14.7	0.57	0.76
<i>L. colinsii</i>	38.4	10.8	764	13.2	0.47	0.80
<i>L. diversifolia</i>	41.0	10.7	725	13.8	0.56	0.85
<i>Second year</i>						
<i>L. leucocephala</i> Honduras	45.8	15.0	769	12.6	0.60	0.81
<i>L. leucocephala</i> India	46.8	13.0	636	16.0	0.71	1.24
<i>L. leucocephala</i> K360	47.2	12.0	679	11.7	0.47	0.92
<i>L. colinsii</i>	44.7	18.7	697	19.7	1.02	1.30
<i>L. diversifolia</i>	46.4	17.4	881	20.3	0.80	1.20

*L. diversifolia* have best resistance indexes in second year. *L. diversifolia* is the most appropriate one when looking at paper characteristics development and viscosity from raw material pruned during on second year, having increases around 30% on tensile, burst and tear indexes when compared to paper obtained from 1 year old raw material or 1 year old sprouts.

#### 4. Conclusions

*Leucaena* species showed a good soil and climatic adaptation to Southwestern of Spain. We should remark the high production of dry wood and biomass in 1 year old sprouts that were yielded after 1 year of growth (from  $9.4 \text{ t ha}^{-1}$  – *L. colinsii* – to  $67.1 \text{ t ha}^{-1}$  – *L. leucocephala* from India – dry total biomass), in comparison to productions after 2 years of growth (between  $11.4 \text{ t ha}^{-1}$  – *L. colinsii* – and  $43.6 \text{ t ha}^{-1}$  – *L. diversifolia*). These productions are comparable to other alternative crops such as kenaf, *Miscanthus* o *Sorghum* in Spain and better to other tree species like poplar tree, *robinia*, willow tree, *eucalyptus* or *ailanthus*.

No statistical significant differences in fibre lengths have been found for *Leucaena* species (0.77–0.92 mm) except for the lower values found for *L. colinsii* (0.69 mm).

The quantity of hot water and 1% NaOH solubles and ethanol–benzene extractives shows similar values when compared with wood materials and their values are relatively lower than they were compared with non-wood and some other annual plants. Relatively lower lignin content in *Leucaena* (15.7–21.4%) species has been found with respect to other vegetal species. The  $\alpha$ -cellulose contents found in *Leucaena* species are in the range of the normal values expected for the other non-wood raw materials and lower than those found for wood-based materials.

The high holocellulose content (higher than 75%), on prunings of *L. diversifolia*, the highest increase of  $\alpha$ -cellulose/holocellulose ratio between first and second pruning and the smaller content of 1% NaOH solubles and ethanol–benzene extractives during second pruning mark *L. diversifolia* as the most interesting specie for their paper use; nevertheless, the higher biomass yielded and content in  $\alpha$ -cellulose 1 year harvest and sprouts mark *L. leucocephala* from India as the most interesting raw material.

On the whole, *L. diversifolia* is the best specie *Leucaena* because of its physical characteristics of paper sheets (tensile index  $20.3 \text{ kNm/kg}$ , burst index  $0.80 \text{ Nm}^2/\text{kg}$  and tear index  $1.20 \text{ mN/m}^2$ ), and viscosity ( $881 \text{ cm}^3/\text{g}$ ) for second year harvest. Nevertheless, *L. leucocephala* from India is the most interesting specie because of its bleaching aptitude (kappa number 12.4) y mayor cellulosic pulp yield in first harvest (42.2%).

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