PROCESS OPTIMIZATION IN KRAFT PULPING, BLEACHING, AND BEATING OF *Leucaena diversifolia*

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A variety of the *Leucaena* genus, *Leucaena diversifolia*, was used for pulp and paper making by kraft and refining processes and a OD(EP)DP bleaching sequence. The same species has been suggested as an energy crop and, in fact, this species used shows a high gross heating value; besides, this variety of *Leucaena* has appropriate characteristics for pulp and paper making. The holocellulose content was higher than *Eucalyptus globulus*, and ash and lignin contents were comparable to other varieties of *Leucaena*. Pulps with a kappa number between 17 and 18, and 21.4 cP viscosity were obtained using an active alkali concentration of 31%. Also, paper sheets showed good strength properties, comparable or even greater than those obtained with *Eucalyptus* or others varieties of *Leucaena* at comparable refining degrees, between 30 and 40 ºSR. The pulp was successfully bleached in all cases with a kappa number below 1.5 in the EP stage and a value of brightness higher than 90%.

Keywords: Kraft pulp; Leucaena diversifolia; Paper; Pulp; Bleaching

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INTRODUCTION

The pulp and paper industry is facing an ever-increasing demand for high quality paper and paperboard, and this demand necessitates a search for new and hitherto unexploited sources of cellulosic fibers. Non-wood raw materials account for 5 to 7% of the total pulp and paper production worldwide. Production of pulp from non-wood and alternative wood resources has many advantages such as easy pulping capability, excellent fibers for the special types of paper, and high-quality bleached pulp. It can be used as an effective substitute, forever decreasing traditional forest wood resources (Jiménez et al. 2001). Besides this, in the last decade, a great deal of attention of the European agricultural research was focused on the search of new non-food and high-yield short-rotation crops having promise for industrial utilization (Shatalov and Pereira 2005). Thus, high-yield fiber plants offer enormous potential to provide a productive new resource for the pulp and fiber manufacturing sector (Mansfield and Weineisen 2007).

The search for non-conventional plant fiber species offers multiple challenges. Out of nearly 600 known species, less than a dozen are in commercial use for pulp production. These species, most frequently found in plantations in the different regions of the world, may not always be favorable with regard to fiber quality and wood composition as well as natural evolution and ease of hybridization (Khristova et al. 2006).

On this basis, *Leucaena diversifolia*, an example of an annually harvested high-yield and short-rotation fibers plant, was the raw material studied in this work, as a potential pulping raw material and alternative source of fibers. Interest in the variety "*L. diversifolia*" from the *Leucaena* genus, a leguminous tree, arises from the easy adaptability to Mediterranean ecological conditions (Rout et al. 1999; Ma et al. 2003), high biomass productivity, beneficial effects in the restoration of degraded soils (Vanlauwe et al. 1998; Sharma et al. 1998; Savale et al. 2007), protection against the effects of wind and erosion (Wills et al. 1989), reductions in the salinity of soils (Eastham et al. 1993), increases in the fertility of the soil by nitrogen fixation or contribution of nutrients (McKenzie et al. 2001; Mugwe et al. 2009), and suitability for intensive cultivation, combined with appropriate chemical composition for the pulp and paper industry.

The *Leucaena* genus has been used as a source of edible pods, animals fodder (Mugwe et al. 2009), poles for construction (Kuntashula and Mafongoya 2005), and shade in permanent plantations. *Leucaena* has traditionally been used as high quality forage for ruminants, but it has also been valued for fuelwood, charcoal, timber, and cellulosic pulpwood (Prasad et al. 2011). Green biomass of *Leucaena* has been recognized as an effective source of nutrients for lowland rice in Asia and more recently for maize and vegetables in eastern and southern Africa (Jama et al. 2000)

References to the pulping of *L. diversifolia* are not readily found, however. Only three references of the same authors (Díaz et al. 2007; López et al. 2008; Alfaro et al. 2009) have been found. But the variety *Leucaena leucocephala* has been tested for pulp and papermaking by some authors by using a kraft process. Samples from 10 years old plants grown in Tanzania were studied to determine suitable kraft pulping conditions and pulp properties for paper production by Gillah and Ishengoma (1993). Also, kraft pulp from *L. leucocephala* with a kappa number of 28 was oxygen delignified and then bleached with chlorine and chlorine dioxide to a brightness level of 80% by the same authors (Gillah and Ishengoma 1995). Bhola and Sharma (1982) explored the feasibility of utilizing *L. leucocephala* grown in India for pulps suitable for papermaking, and pulp having a kappa number about 30 was bleached using chlorine and hypochlorite. Also, Sharma et al. (1984) determined the suitability of *L. leucocephala* for the production of dissolving pulp for rayon manufacture by water prehydrolysis sulfate process followed by the multistage bleaching. *L. leucocephala* has been introduced in Sudan, India, Syria, and Yemen, and it is considered promising, particularly in irrigated desert areas along the Nile. Kraft pulp was obtained by Khristova et al. (1988 and 2000), in Sudan, from 5 year old trees of *L. leucocephala*. Also, kraft pulp with ECF bleaching was obtained by Shibahare and Patel (2002) in India.

Studies about mechanical pulping of fibrous raw materials (*L. leucocephala*) indicate that by combination of basic raw material properties and suitable process conditions it is possible to produce high strength mechanical pulps from these nonconventional raw materials (Kulkarni et al. 1985). Majumder and Ghosh (1985) reported an easy delignification and bleaching of *L. leucocephala* pulp for cooking process under atmospheric conditions, and Jiménez et al. (2007) characterized the material, and pulp was obtained by an organosolv process (ethyleneglycol). The morphological, anatomical, and chemical characteristics of *L. leucocephala* were also studied by Malik et al. (2004) who showed that it can sustain an adequate supply of raw materials for the pulp and paper industry. Recently, Prasad et al. (2011) studied the effect of tree density on the growth, biomass partitioning, and wood productivity for pulpwood or solid biofuel.

Previous chemical analyses and kraft pulping evaluations of *Leucaena* genus (*L. leucocephala* principally) have shown good pulping properties and revealed the suitability of the species for paper, cellophane, and textile manufacture (Bola and Sharma 1982, Gillah and Ishengoma 1993, 1995, Khristova et al. 1988, Malik et al. 2004). *Leucaena* is among the best tropical hardwoods for paper and Rayon manufacture, as the pulp is high in holocellulose and low in silica, ash, lignin, alcohol-benzene solubles, and hot water solubles. The pulp yield is high (50 to 52%) and fibers are shorter than the softwood. The Runkel ratio is less than 1, making *Leucaena* a most suitable species for paper making (National Research Council 1984). On the other hand with *Leucaena* varieties, a screen yield of 49.5 to 50.6 % for one year old tree and 48.6 to 50.5 for two year old tree has been reported; the varities also exhibited good strength properties (PCARRD 1984). Then, the objective of this work is the study of kraft pulping, refining, and bleaching process to obtain pulp and paper from the *Leucaena diversifolia* variety.

MATERIALS AND METHODS

Raw Material. Provision and Characterization

A variety of *L. diversifolia* was used for field experiments. In this work, the material was harvested after 7 years of growth in plantations used to exploit experimental energy crops in Huelva (southwestern Spain). These plants were grown in a nursery, in 300 cm^3 pot holders; they were inured from bacterium *Rhizobium* and, when they were 3 months old, they were transplanted to the ground. Field experiments were carried out in two plots with a complete randomized block design with 4 replicates. No fertilization was added to the plots. The soil at the experimental site was sandy loam with a pH of 6 to 8 and having moderate to substantial depth.

For characterization of raw material, the following standard analytical procedures were used: hot water soluble (TAPPI T 207 cm-08, "Water Solubility of Wood and Pulp"), acetone extractives (TAPPI T 280 wd-06, "Acetone Extractives of Wood and Pulp"), holocellulose contents (Wise method 1946), and ashes (TAPPI T 244 cm-99, " Ash in Wood, Pulp, Paper, and Paperboard: Combustion at 525°C"). Also, the elemental composition (N, C, H, S, O) was determined using a Fisons EA 1108 Elemental Analyzer. Fiber length was determinated according TAPPI method T233 cm-06 (Fiber Length of Pulp by Classification).

The gross calorific values (constant volume) were determined according to “CEN/TS 14918:2005 (E) Solid biofuels—Method for the determination of calorific value” and UNE 164001 EX standards by using a Parr 6300 Automatic Isoperibol Calorimeter.

Aliquots from the homogenized wood (without compounds that had been extracted by ethanol) were subjected to moisture determination (drying at 105 ºC to constant weight), quantitative acid hydrolysis with 5 mL of 72% sulfuric acid for an hour (TAPPI T 222 om-02 "Acid-insoluble lignin in wood"), and quantitative posthydrolysis with 4% sulfuric acid at 121 ºC and 2 atm during 60 min in order to ensure quantitative conversion of oligomers into monomers (Garrote et al. 2003). Before high-performance liquid chromatography (HPLC) analysis, the solid residue from posthydrolysis was recovered by filtration and considered as Klason lignin. The monosaccharides and acetic acid contained in hydrolysates were determined by HPLC in order to estimate (after corrections for stoichiometry and sugar decomposition) the contents in cellulose (as glucan), hemicelluloses (xylan + araban), and acetyl groups. Chromatographic determination was performed using an Agilent 1100 HPLC equipped with an ion-exchange resin BioRad Aminex HPX-87H column under the following conditions: mobile phase, 0.005 $mol \cdot L^{-1}$ of sulphuric acid; flow rate, 0.6 $mL \cdot min^{-1}$; and column temperature, 50°C. The volume injected was 20 μL.

Kraft Pulp Production and Characterization Pulp

Conventional kraft cooking was carried out in a rotary digester with electrical heating with four individual 2 L vessels. The time and temperature of the digester were monitored electronically, via computer. Monitoring was performed in these probability variables. Following cooking, the pulp was separated from the liquor and disintegrated, without breaking the fibers, during 10 min to 2000 rpm. Pulping yield (TAPPI T 257-02 "Sampling and preparing wood for analysis"), Kappa number (TAPPI T 236 om-06 "Kappa number of pulp"), and viscosity (TAPPI T 230 om-04 "Viscosity of pulp [capillary viscometer method]") were determined. The residual alkali was titrated according to TAPPI 625 wd-99 ("Analysis of soda and sulfate black liquor"). All cooks were performed aiming to produce pulp with kappa number in the range 17 to 18, which was achieved by keeping all parameters constant (sulfidity: 20 %; relation liquor/wood: 4/1; maximum temperature: 165 ºC; time until maximum temperature: 70 min.; time at maximum temperature: 60 min.). Only active alkali was varied in the cooking process (between 18 and 31% over dry matter).

Bleaching, Beating and Paper Sheets Characteristics

Bleaching of pulp was carried out to 90% ISO brightness with the sequence $OD_1(EP)D_2P$, whereby: O refers to a oxygen delignification; D_1 refers to a time of 60 min and a temperature (80 °C) chlorine dioxide stage; (EP) refers to a hydrogen peroxide stage with a time of 90 min and a temperature of 80 ºC; D_2 refers to conventional chlorine dioxide stage with a long time (120 min) and a temperature of 80 ºC; P refers to atmospheric peroxide stage for 120 min and a temperature of 80 ºC. General oxygen delignification and bleaching conditions are listed in Table 1.

For characterization of bleached pulp, the following standard analytical procedures were used: Kappa number (TAPPI T 236 om-06 "Kappa number of pulp"), viscosity (TAPPI T 230 om-04 "Viscosity of pulp [capillary viscometer method]"), forming handsheets for reflectance testing (TAPPI T 272 sp-08 "Forming Handsheets for Reflectance Testing of Pulp [Sheet Machine Procedure]"), diffuse brightness of pulp

(TAPPI T 525 om-06 "Diffuse Brightness of Paper, Paperboard and Pulp (*d*/0)"), brightness stability (TAPPI T 260 wd-98 (4 h, 105.8C, 0% HR) "Test to Evaluate the Aging Properties of Bleached Chemical Pulps"), and hexenuronic acid (HexA) content (TAPPI T282 pm-07 "Hexeneuronic Acid Content of Chemical Pulp"). The indirect analysis of TOC allowed for evaluation of the total yield of the bleached pulp, as described in Longue Júnior et al. (2005).

Table 1. Bleaching Conditions for *Leucaena diversifolia* Pulp

	O	D	EP	D2			P		
				a	b	c	a	b	c
Consistency, %	10	10	10	10			10		
Temperature, ºC	100	80	80	80			80		
Time, Min.	60	60	90	120			120		
Kappa factor (KF)	-	0.24	-	-	-	-	-	-	-
NaOH, % o.d.p	2	-	0.5	-	-	-	0.2		
H_2SO_4, % o.d.p	-	1.4	-	0.15	0.075	-	-	-	-
$MgSO_4$, % o.d.p	0.15	-	0.15	-	-	-	-	-	-
O_2, % o.d.p.	2	-	-	-	-	-	-	-	-
ClO_2 expressed as Cl_2, % o.d.p.	-	2.41	-	0.3	0.6	0.9	-	-	-
H_2O_2, % o.d.p.	-	-	0.5	-	-	-	0.2		
Final pH	11.6	2.8	11.2	4.3	4.4	4.7	10.0	9.6	10.1
o.d.p.: oven dry pulp									

Bleached and unbleached pulp samples were refined in a PFI mill for between zero and 4500 revolutions. Paper sheets were prepared with an ENJO-F-39.71 sheet machine according to TAPPI T 205 sp-02 ("Forming handsheets for physical tests of pulp"). The laboratory handsheets were conditioned at a temperature of 23 ± 1 ºC and relative humidity of 50 ± 1 % and tested for grammage (TAPPI T 220 sp-01 "Physical testing of pulp handsheets"), burst index (TAPPI T 403 om-02 "Bursting strength of paper"), tear index (TAPPI T 414 om-04 "Internal tearing resistance of paper [Elmendorf-type method]"), tensile index (TAPPI T 494 om-01 "Tensile breaking properties of paper and paperboard [using constant rate of elongation apparatus]"), Schopper Riegler degree (ISO 5267/1 "Pulps -- Determination of drainability -- Part 1: Schopper-Riegler method"), and ISO brightness (TAPPI T 525 om-06 "Diffuse brightness of paper, paperboard and pulp [d/0 degree]") (TAPPI 2007).

RESULTS AND DISCUSSION

Raw Material Characteristics

The soluble content of *L. diversifolia* is known to be lower than that of many other raw materials (hot water soluble: 4.8 %) and higher than wood species (López et al. 2008). The wood density is 549 kg/m^3 similar to other species such as *L. leucocephala* (Bhola and Sharma 1982). Specifically, the content of extractives compounds in *L. diversifolia* is 1.1 %, lower than those found for eucalyptus wood, with a value of 2.09 %, and the results (4.4%) reported by other authors (López et al. 2008). These compounds could cause problems related to pitch deposits in the manufacturing of pulp, could cause problems by adhering to machinery, and could reduce the quality of pulp (Gutiérrez et al. 2003).

Previous results and results from other authors about chemical characterization of *L. diversifolia* are shown in Table 2. *Eucalyptus globulus* was included as a reference species. The holocellulose content in *L. diversifolia* is in the range of other *Leucaena* varieties (between 11% and -6.2% higher) and higher (8.8%) than results reported for *Eucalyptus globulus*.

Table 2. Chemical Composition of *Leucaena diversifolia* and other Raw Materials

	L. leucocephala					*L. diversifolia*			*Eucalyptus globulus*
	a	*b*	*c*	*d*	*e*	*f*	*g*	*This work*	*h*
Holocellulose, %	70.6	76.58		76.58	68.34	76.3	65.8	72.8	66.9
Klason lignin, %	24.1	19.55	21.49	26.12	18.4	24.8	24.8	23.7	22.9
Glucan, %	37.2	58.7	41.79	n.d.	-	38	-	32.2	46.8-53.4
Xylan, %	17.1	-	-	-	-	15.7	-	15.5	14.2-16.6
Araban, %	1.0	-	-	-	-	1.5	-	1.0	0.4-0.54
Acetyl groups, %	1.8	-	-	-	-	3.3	-	2.1	3.56
Acetone extractives, %	1.1	2.55	1.64	3.26	8.19	-	1.7	3.9	2.09
Ash, %	1.3	0.85	0.95	0.8	2.23	1.59 (i)	-	1.4	0.4(i)
Gross heating value, MJ/kg, o.d.b.	18.945					19.148 (i)	18.840	19.083	17.000 (j)

(a) Feria et al (2011) b. Malik *et al.* (2004) c. Majumder and Ghosh(1985) d. Bhola and Sharma (1982) e. Jiménez, L (2007) f. López et al (2010b) g. López et al (2010a) h. Garrote G (2003) i. Feria et al (2009) j. Telmo et al (2010). Percentages on dry basis.

The Klason lignin values were slightly higher than *Eucalyptus globulus* and lower than lignin contents in previous works (López et al. 2010a,b) concerning *Leucaena* diversifolia (only 3 years old when harvested). Xylan, araban, and acetyl groups values were found to be similar to those found for other *Leucaena* varieties and eucalyptus wood, and ash content was found to be lower than those found for similar species of *Leucaena* (7.1 %) (Feria et al. 2011).

The gross heating value for *Leucaena diversifolia* was similar to that of *L. leucocephala* (0.7%) (Feria et al. 2011) and other solid biofuels such as willow and poplar from one-year-old plants, never more than 20 MJ/kg (Klasnja et al. 2002). The heating value of the genus *Leucaena* was found to be higher than other species such as *Populus euramericana* or *Eucalyptus globulus* (between 18.8 MJ/kg and 17.0 MJ/kg) (Telmo et al. 2010).

Kraft Pulps Cooking, and Beating

Table 3 shows the results for kappa number, total pulp yield, pulp yield (without reject), final pH, and residual alkali for experiments at different active alkali concentrations. All other variables of cooking were constant. The attainment of a selected kappa number and efficiency in cooking process were the two objectives of the experimental design, also preserving yield and moderate consumption of reagents.

Table 3. Characterization of Kraft Pulp from *Leucaena diversifolia*

Active Alkali, % NaOH	Kappa Number	Yield, %		Residual liquor (NaOH)	
		Total	Without reject	pH	AEr, g/L
18,0	39,8	51,4	48,8	12,4	2,2
23,0	25,2	47,0	45,9	12,8	7,8
25,0	23,7	46,5	46,0	13,0	11,1
27,0	20,1	45,4	44,9	13,1	13,8
29,0	18,7	43,8	43,4	13,2	16,9
31,0	17,5	43,4	43,0	13,2	20,1
AEr: residual effective alkali					

An increase in active alkali concentration is always accompanied by a decrease in Kappa number and process yield, and an increase in the pH and residual active alkali of the black liquor from pulp process, indicating an excess of unreacted reagent. These data show that the process could be improved, with lower reagent consumption at greater operating temperatures or times. In this study, it is explained how, by appropriate setting of the operating temperature and time, a Kappa number between 17 and 18 with an active alkali concentration of 31% was obtained, giving a pulp yield of 43.4%.

The active alkali levels used and the results of the purified yield and residual alkali were represented and set by second degree polynomial equations (figures not shown). So from the results, one can obtain a *L. diversifolia* kraft pulp with a Kappa number of 18, with an active alkali concentration of 30.9%, keeping the other conditions constant (sulfidity: 30%; ratio liquor/wood: 4/1; maximum temperature: 165 ºC; ramp time: 70 min. and operating time at maximum temperature: 60 min.). Under these conditions, a pulp may be obtained that reaches the maximum area of purified yield (42.8%), and whose residual alkali values appear among the lowest within the rank of results (20.0 g/L).

The pulp obtained using 30.9% active alkali showed 21.4 cP viscosity, 29.8% ISO brightness, and a hexenuronic acid concentration 28.3 mmol/kg.

In order to evaluate the potentiality of this cellulosic pulp obtained from *L. diversifolia*, it was subjected to a refining study. The beatability is an important quality parameter for market kraft pulps and is usually measured as a number of revolutions required in a PFI mill to beat a pulp to a certain drainage degree. Beatability and physical properties of paper (tensile index, burst index, tear index, etc.) are correlated not only with the morphological properties of fibres, but also with their chemical composition and structure (Seth and Page 1988; Lindstrom 1992). Figure 1 shows evolution of Schopper Riegler degree (ºSR), tensile index, burst index and tear index of the paper sheets with the number of revolutions in PFI.

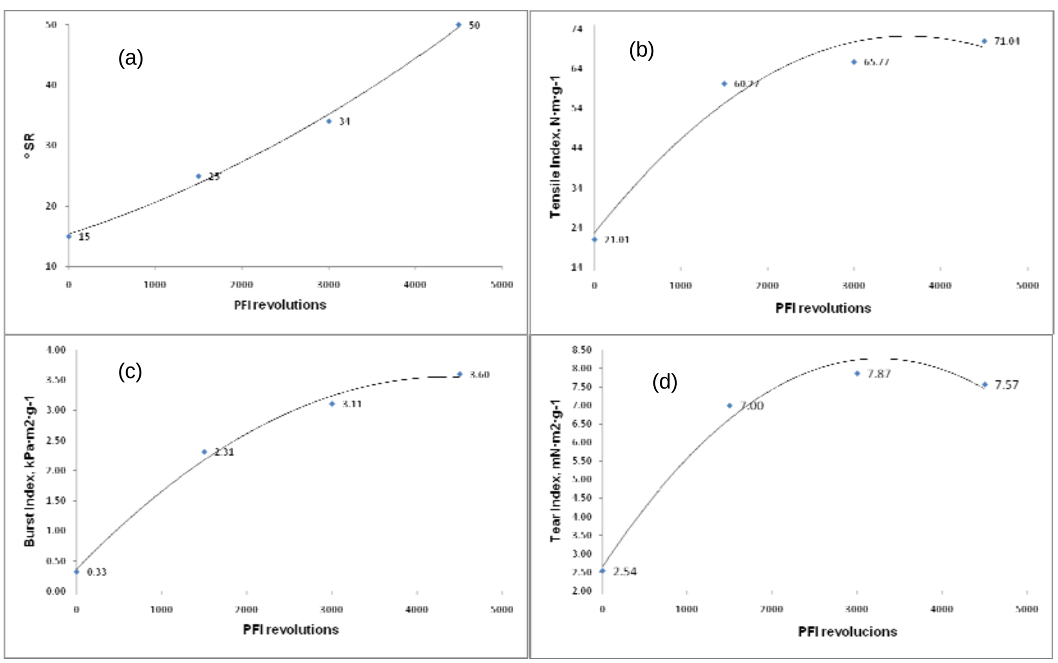

Figure 1. Physical properties of *Leucaena diversifolia* unbleached kraft pulp as a function of refining

The increase in the refining degree Schopper-Riegler (ºSR) was more pronounced at the beginning (66.7% increase between 0 and 1500 revolutions versus increments of 36% between 1500 and 3000 revolutions and 47.1% between 3000 and 4500 revolutions). The pulp obtained from *Leucaena diversifolia* showed better fitness for the refining (lower energy consumption) than the cellulosic pulps of eucalyptus studied by other authors. When compared to the refining results of kraft pulp (Mutjé et al. 2005), it is observed that, in order to obtain a Schopper-Riegler degree of 26.5 ºSR, the refining should be performed at 3000 rev. of the PFI mill, with a percentage increase in the refining slightly degree better as well (126.7% versus 140.9% in eucalyptus between 0 and 3000 revolutions). The results were much better in comparison to other material such as *L. leucocephala* (Gillah and Ishengoma1993), where the Schopper-Riegler degree ranges between 18ºSR (not beated) and 23.5 ºSR (2000 revolutions PFI).

Regarding the strength rates, the kraft pulp from *L. diversifolia* was developed favorably. Great increments were achieved in the three rates studied at 3000 revolutions in the PFI mill: The tensile index increased 209.8% up to values above 7.87 Nm/g, the burst index increased by 852.4%, and the tear index increased by 209.8%. As shown in Fig. 1, tensile index and burst index kept increasing along with the refining degree, although less pronounced, until they reached values above 71 N m/g and 3.6 kPa m^2/g respectively. However, the tear index showed maximum values in the region between 1500 and 3000 PFI revolutions, which suggests that one should not refine these pulps beyond that point.

These results are very interesting when compared to those obtained from a reference material such as eucalyptus. In the study performed by Khristova et al. (2006), in which alkaline cellulosic pulps (kraft, kraft-AQ, soda-AQ, ASA and ASAM) of 4 varieties from Sudan (*Eucalyptus camaldulensis, E. citriodora, E. microtheca*, and *E. tereticornis*) were analysed, the following results were obtained: Tensile index at a refining degree of 30ºSR was between 61.7 N m/g and 85 N m/g; burst index was between 3.1 kPa m^2/g and 5.6 kPa m^2/g; and tear index was between 6.9 mN m^2/g and 10.4 mN m^2/g. In the work of Area et al. (2010) concerning kraft pulps treated with chelants agents of *Eucalyptus grandis*, the strength properties at 30 ºSR (aproximately), were between 85.2 N m/g and 103 N m/g for tensile index; 5.3 kPa m^2/g and 7.1 kPa m^2/g for burst index; and 7.8 mN m^2/g and 9.9 mN m^2/g for tear index. In the work of Colodette et al. (2002) conerning kraft pulp of *Eucalyptus grandis* (beating at 40 W h, 3000 PFI aproximately and Kappa numbers 16 to 17) using high and low residual alkali (14-18 g/L and 3-4 g/L) and high and low temperatures (170ºC and 160ºC), values for tensile index, burst index, and tear index falling between 95.6 N m /g and 112.1 N m/g; 6.1 kPa m^2/g and 7.9 kPa m^2/ g; 9.2 mN m^2/g and 11.2 mN m^2/g respectively, were achieved. In the work of Mutje et al. (2005) concerning refining a comercial eucalyptus kraft pulp to 26.5ºSR, values of tensile index: 76.7 N m/g and burst index: 7.8 kPa m^2/g were obtained. In the work of Gillah and Ishengoma (1993), values for tensile index of 84.1 N m/g and tear index of 11.8 N m^2/g for eucalyptus Kraft pulp (1000 revolutions PFI) were reported.

The characteristics of the paper sheets obtained from kraft pulps from *L. diversifolia* were also better than those obtained by other authors from other varieties of *Leucaena* genus by kraft, soda and organosolv processes. For unbeaten pulps of *L. leucocephala* (Bhola and Sharma 1982; Jimenez et al. 2007), and three years old varieties of *L. diversifolia* (López et al. 2010b), the results of tensile index, burst index, and tear index, range between: 10.8 N m/g and 34.6 N m/g; 0.32 kPa m^2/g and 1.32 kPa m^2/g; and 0.24 mN m^2/g and 5.87 mN m^2/g, respectively. When compared, less favorably, to the minimum values of the specified intervals, the results of the paper sheets of kraft pulp from *L. diversifolia* obtained in this study were 94.5%, 2%, and 95.8% better. The results obtained by Jimenez et al. (2007) and Bhola and Sharma (1982) from pulps beated of *L. leucocephala* to maximum revolutions were similar in tensile index (between 53 N m/g and 84 N m/g). The results were much lower in tear index (between 8.18 mN m^2/g and 10.10 mN m^2/g). The results obtained by Gillah and Ishengoma (1993) from pulps kraft of *L. leucocephala* grown in Morogoro (Tanzania) beaten in a PFI mill between 0 and 4000 revolutions show tensile index (42.7 to 106.7 N m/g) and tear index (6.7 to 8.4 mN m^2/g) values, slightly higher than those obtained in this work.

Although a sheet of paper can be formed by simple felting, such a sheet has little commercial interest because of its lack of strength. The properties of different types of paper depends on the process equipment, additives, and mixtures of pulp from different types of raw material. It is known (Paperonweb 2011) that the properties for typical applications of bleached paper (bond office, coated paper, test liner and newsprint) are: tensile index (40 to 175 N m/g), burst index (1.2 to 4.3 kPa m2/g), and tear index (6.25 to 9.7 mN m2/g). Based on these numbers, *Leucaena* unbleached and bleached pulp are suitable for different kinds of paper.

Pulp Bleaching

The previously indicated kraft pulp with a Kappa number of 18 and an active alkali concentration of 30.9% was selected for bleaching tests. The sequence utilized was selected among a wide experimental design with the objective of obtaining cellulosic pulp with the same brightness degree (90 to 91% ISO). Variations in process conditions from the different steps shown in Table 1 have been adopted to achieve this target. Three different concentrations of chemicals (ClO_2 expressed as Cl_2, kg/t, 0.3, 0.6, and 0.9%) were used in the D_2 step. The pulp was sucessfully bleached in all cases with a kappa number lower than 1.5 after the stage (EP) and a value of brightness greater than 90% ISO (90.1%, 91.1% and 91.7%, respectively). Brightness reversion was decreasing as the chlorine dioxide amount increased over stage D_2, but below 2% in all cases, which indicates that good brightness "quality" of the pulps was obtained.

The sequence OD_1EPD_2P with a 0.3% ClO_2 expresed as Cl_2 in D_2 step (final Brightness of 90.1% ISO), was selected for full characterization, and beated pulp and paper sheets were prepared. The yield of bleaching process was 96.0%, kappa number < 1, viscosity: 9.45 cP, brightness reversion: 1.7%, and hexenuronic acids content: 3.05 mmol/kg.

In part, brightness reversion of bleached pulps is due to the presence of hexenuronic acid (in our case, the hexenuronic acid content was decreased a 89.2% with respect to unbleached pulp). The elimination of these acids increases the stability of pulp brightness, as some authors have stated (Buchert et al. 1997; Vuorinen et al. 1996).

Reagent consumption was practically 100% in stages O, D_1, EP, and D_2. However, consumption at the final stage with hydrogen peroxide was about 80%, which indicates that the load of this reagent could be reduced at the final stage of bleaching.

Viscosity values decreased at the successive stages, between 21.4 cP in brown pulp and 9.45 cP in bleached pulp, which is consistent with the cellulose degradation characteristic of the bleaching sequencies. In this case, the results of yield TOC (8.18

kg/ton), indicate that cellulose degradation was relatively low, below 1% cellulose, although, on the other hand, significant decreases were observed in tensile index (17.03 N m/g to 69.83 N m/g for 0-4000 PFI revolutions) and burst index (0.50 kPa m^2/g to 3.80 kPa m^2/g for 0-4000 PFI revolutions). However, the results of tear index were similar to those from the unbleached pulp (2.51 mN m^2/g to 7.43 mN m^2/g fo 0-3000 PFI revolutions).

The results obtained for other varieties of *Leucaena* genus that involved bleaching and beating (Gillah 1995; Bhola and Sharma 1982) showed values of tensile index between 49.5 N m/g and 78.23 N m/g, burst index between 2.93 kPa m^2/g and 4.77 kPa m^2/g, and tear index between 7.96 mN m^2/g and 9.46 mN m^2/g.

These results are appropriate for pulp and paper making, although they are somewhat lower than those obtained by others authors from a raw material like eucalyptus. Santiago and Pascoal Neto (2008) achieved values of tensile index between 80 N m/g and 85 N m/g, burst index between 4 kPa m^2/g and 6 kPa m^2/g, and tear index between 8 mN m^2/g and 10 mN m^2/g from eucalyptus pulps obtained through modified kraft processes (SR = 30 ºSR).

In this study the brightness was lower than 90 to 91% ISO, between 88.9% and 87.5% (Khristova et al. 2006), for bleached kraft and ASAM pulps of *Eucalyptus citriodora* (30 ºSR), with reported values of tensile index, burst index, and tear index of 70.2 and 78.3 N m/g; 4.4 and 4.8 kPa m^2/g; and 8.1 and 7.9 mN m^2/g respectively. However, Garcia et al. (2010) reported similar values of strength for kraft pulp from *Eucalyptus grandis* (Schopper Riegler degree = 30 aproximately) bleached with 6 different sequences (brightness of 90.0% ISO aproximately): tensile index between 51.9 N m/g and 66.5 N m/g, burst index between 2.1 kPa m^2/g and 2.6 kPa m^2/g, and tear index between 8.9 mN m^2/g and 10.2 mN m^2/g.

CONCLUSIONS

1. The species *Leucaena diversifolia* has been suggested as energy crops and, in fact, this species used shows a high gross heating value; besides, this variety of *Leucaena* has appropriate characteristics for pulp and paper making. The holocellulose content was found to be higher than that of *Eucalyptus globulus*, and ash and lignin contents were comparable to other varieties of *Leucaena*.
2. Pulps with a Kappa number between 17 and 18, and 21.4 cP viscosity were obtained using an active alkali concentration of 31% and gave a pulp yield of 43.4%. Also, paper sheets showed good strength properties, comparable to or even greater than those obtained with *Eucalyptus* or other varieties of *Leucaena* at comparable refining degrees, between 30 and 40 ºSR. The pulp was sucessfully bleached in all cases with a Kappa number below 1.5 in EP stage and a value of brightness bigger than 90%. It is recommended that pulp prepared in this manner from *Leucaena diversifolia* be used for wrapping paper, bags, and paperboard to satisfy the local demand.

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