ARTÍCULO DE INVESTIGACIÓN

Fiber morphology in fast growth *Gmelina arborea* plantations

Morfología de la fibra en plantaciones de rápido crecimiento de *Gmelina arborea*

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ABSTRACT

Gmelina arborea is planted in large areas of forest with the objective of producing solid wood using well known silvicultural techniques and taking advantage of the properties of the wood quality of fast-growing tree species managed in short rotation systems. The aim of this study was to analyze the morphology and dimension of fibers from the pith to the bark in trees from fast growth plantations in northern Costa Rica.

The results indicate that fiber morphology is irregular in both diameter and shape; with 1 to 4 septa, abundant crystals deposited in fiber lumina and minutely bordered pits with oblique and non-vestured apertures. Fiber length, width and cell wall thickness increased with tree age in the early stages. Lumen diameter was not correlated with tree age.

KEY WORDS:
Fiber width, lumen diameter, cell wall thickness, fiber length.

RESUMEN

Gmelina arborea se planta en grandes áreas de bosques con el objetivo de producir madera sólida mediante el uso de técnicas silvícolas bien conocidas, así como para aprovechar las ventajas de las propiedades de la calidad de la madera de especies arbóreas de rápido crecimiento y manejadas por sistemas de rotación corta. El objetivo de este estudio fue analizar la morfología y dimensión de las fibras, desde la médula hasta la corteza, en los árboles de rápido crecimiento de las plantaciones del norte de Costa Rica. Los resultados indican que la morfología de la fibra es irregular, tanto en diámetro como en forma; con 1 a 4 septa, cristales abundantes que se depositan en los lúmenes de la fibra y con hendiduras minuciosamente bordeadas con orificios no cubiertos y oblicuos. La longitud y ancho de la fibra y el grosor de la pared celular se incrementaron con la edad del árbol en las etapas tempranas. El diámetro del lumen no se correlacionó con la edad del árbol.

PALABRAS CLAVE:
Anchura de la fibra, diámetro del lumen, grosor de la pared celular, longitud de la fibra.

INTRODUCTION

Gmelina arborea was introduced in the Americas between 1970 and 1975, mainly in Brazil (Kailsh, 1975). This species was chosen for its resistance to pests and diseases, its fast growth and the suitability of its wood for pulp and raw

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material for solid products. Very soon after it was planted in the north of the Brazilian Amazon, it became evident that the trees grew very poorly at some sites (Hornick *et al.,* 1984). In other countries, *G. arborea* has been planted extensively to produce wood for solid products. In Costa Rica, *G. arborea* is the most important species for timber production, and approximately 65000 hectares have been planted in different ecological zones, from wet to dry (Moya, 2004) and under a variety of silvicultural management regimes (Meza, 1999).

In terms of the wood's anatomical composition, fibers are the predominant cell type and occupy 57-78% of the tissue volume (average: 76,6%). Several studies have shown that this percentage is not influenced by site, tree height, early and latewood, or radial distance from the pith (Hughes, 1968; Sosanwo and Lindberg, 1975; Akachuku and Burley, 1979; Frimpong-Mensah, 1992; Nobuchi *et al.,* 1997). The importance of fiber dimension in making paper is well documented: the Runkel coefficient indicates this relationship, but has the limitation of only taking cell wall thickness and lumen diameter into consideration (Sosanwo and Lindberg, 1975). Variations in other fiber dimensions, i.e., fiber length, wall area, cell wall thickness and lumen perimeter and their effect on the properties of paper are mentioned in the literature as well (Corsan, 2002). Fiber dimensions are also important in solid wood products. For example, in Chinese poplar (*Popular trichocarpa*) Bao and Liu (2001) detailed the relationship between fiber width, vessel percentage and other wood characteristics with the quality of veneer and plywood.

The distribution, shape and dimension of the fibers in the wood of *Gmelina arborea* have been described in detail by Pearson and Brown (1932) based on a macroscopic examination of two Indian samples. They observed that the fibers were non-libriform, septate, with long tapering and numerous simple or bordered pits. Other studies report the anatomical features; mainly variation in fiber length (Hughes and Esan, 1969; Akachuku and Burley, 1979; Ohbayashi and Shiokura, 1989a; Frimpong-Mensah, 1992). The cell and lumen diameter, and cell wall have been studied as well, by Frimpong-Mensah (1992) for example, and they found that cell wall thickness was significantly correlated with cambial age. Hughes and Esan (1969) found strong correlations between fiber length and tree age with distance from the pith in 9-year-old trees in Nigeria. Also in Nigeria, for 7-year-old trees, it was found that fiber length was different at four sites (Akachuku and Burley, 1979). In contrast, Frimpong-Mensah (1992) found no variation in fiber length with cambial age in 20-year-old *Gmelina arborea* trees in Ghana. Growth rate affects fiber dimensions too. Ohbayashy and Shiokura (1989b) carried out a study on fiber length in 15-year-old trees and found that a high growth rate was strongly correlated with short fiber length.

OBJECTIVE

The objective of the present research was to study the variation in shape and size of wood fibers in *Gmelina arborea* trees under fast growth conditions in Costa Rica.

MATERIALS AND METHODS

Sampled areas: *G. arborea* plantations were selected in different regions of Costa Rica (Fig. 1), where mean annual precipitation varies between 1700 and 5000 mm, temperatures range from 20 to 28 °C, and there is a moderate to short dry season (3 to 1 dry months).

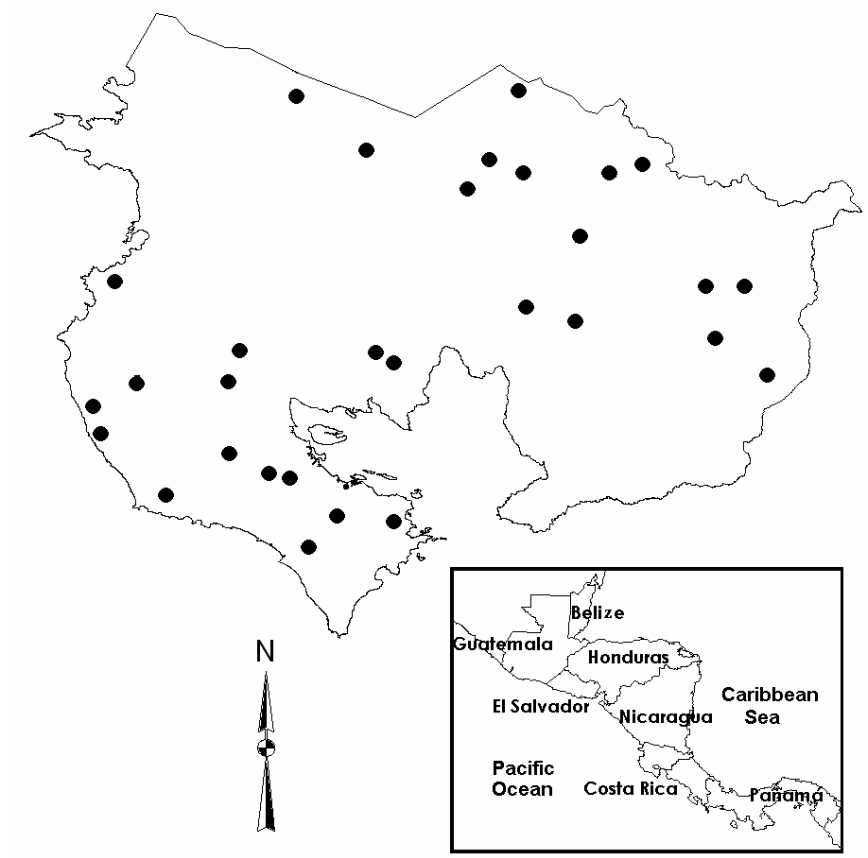

Figure 1. Location of the plantations sampled in northern Costa Rica

Plot establishment and tree selection: A total of 30 plots (400 m^2 each) were established in 9- to 12-year-old plantations. The coordinates of each plot were recorded with a Global Positioning System (GPS). On each plot, the diameter at breast height (DBH), total and crown height were measured. One tree with an average DBH, a straight stem, and no disease or pest symptoms was selected on each plot (Table 1).

Wood samples: Each sampled tree was marked on the side facing north and a stem section (3,0 cm thickness) was cut at DBH. A 1,0 mm wide, 2,0 mm thick slice was cut from pith to bark. Each growth ring was separated using a razor blade. We decided to only use the beginning part of the annual ring – which is similar to earlywood in temperate species – given that the profile patterns of fiber dimensions are more or less stable from the beginning of the ring to 50% (Moya, 2005). This part of the ring was macerated using Franklin's method (Ruzin, 1999).

Fiber morphology: Fiber shape and inclusions were identified under a light microscope. In addition, 6 block samples

Table 1. Description of plantation samples

Plantation sampled	Stand density (n ha^{-1})	Diameter at breast height (cm)	Average growth rate (cm $year^{-1}$)	Total height (m)	Crown height (m)	Age (years)
1	159	38,0	4,22	15,5	11,0	9
2	300	31,5	3,94	22,0	11,0	8
3	191	33,2	3,32	18,5	11,2	10
4	223	32,0	4,00	23,5	14,5	8
5	127	30,7	3,41	18,0	13,0	9
6	659	25,0	3,13	19,0	6,0	8
7	477	28,5	3,56	22,5	14,0	8
8	350	25,2	3,15	21,4	14,0	8
9	446	30,0	3,75	23,2	16,0	8
10	505	28,3	2,83	24,0	18,0	10
11	732	24,0	2,67	21,8	15,0	9
12	1032	21,5	2,69	21,5	17,5	8
13	764	21,0	1,91	19,1	11,6	11
14	891	24,1	2,41	15,0	12,0	10
15	1496	24,3	2,03	20,0	13,8	12
16	318	31,9	3,19	20,8	11,0	10
17	350	29,8	2,71	19,5	12,5	11
18	223	32,5	2,71	24,7	13,5	12
19	344	30,5	3,05	24,0	11,0	10
20	250	33,2	2,77	27,1	17,1	12
21	509	19,7	1,79	19,5	13,2	11
22	477	22,5	2,50	23,3	13,4	9
23	477	23,4	2,34	17,8	13,5	10
24	605	23,5	2,61	18,5	7,7	9
25	509	23,9	2,99	22,1	15,1	8
26	827	20,5	2,05	18,7	13,0	10
27	732	18,8	2,09	19,0	9,5	9
28	836	20,5	2,05	22,1	14,2	10
29	796	20,7	2,07	18,3	9,1	10
30	1025	20,2	2,24	22,0	13,0	9

(5 x 5 x 5 mm) were cut from six different trees. They were dried at 80°C and coated with platinum for later observation with the scanning electronic microscope (SEM) at the Electronic Microscopy Unit of the University of Costa Rica.

Fiber dimensions: Initially, a sample of 30 fibers was evaluated to determine the number of replicates it would be necessary to measure to obtain fiber length, width and lumen diameter. Thirty coefficients of variation (CV) were calculated for the first fiber measured to the last one. A scatter plot was then graphed with the CV values and the measurements. The number of fibers to measure was determined as the point where the coefficient stabilized. It was necessary to measure 25 fibers for fiber width and lumen diameter, and 24 fibers for length. Each annual ring was macerated and three glass slides of the macerate prepared for observation. Eight fibers were measured for length and five fibers for diameter by observing them under magnifying lenses at 250x and 1000x, respectively, on each glass slide. Fiber wall thickness was calculated by substracting lumen diameter from fiber width.

Data analysis: Different models were tested for the analysis of variation in fiber dimension from pith to bark, setting tree age as the independent variable and fiber dimension as the dependent variable. An analysis of variance (ANOVA) was carried out using the SAS program (SAS Institute, 1997).

RESULTS

A total of 1 to 4 septa per fiber were found in the wood samples (Figs. 2a and 2b). Non-septate fibers were observed as well, though there were few of these. Crystals were found in several sections of the lumen or in each septum of the septa, when present (Figs. 2a and 2b). The fibers were irregular in both diameter and shape (Fig. 2b), with one- or two-sided, long tapering and circular forked ends (Figs. 2c and 2d). Few pits were found along the fiber walls and there was a mean of 20 mm between pits (Fig. 3a). Minutely bordered pits, with borders less than 2 mm in diameter (Fig. 3b), oblique, longitudinal apertures (Fig. 3c) and lacking vesturing (Fig. 3d) were observed in the wood samples.

Dimension fibers: The mean fiber length of *G. arborea* wood samples was 1,29 mm, fiber width was 30,67 mm, cell wall thickness was 4,01 mm, and lumen diameter was 22,64 mm (Table 2). Fiber length tended to increase with tree age (Fig. 4a), varying from 0,75 to 1,75 mm

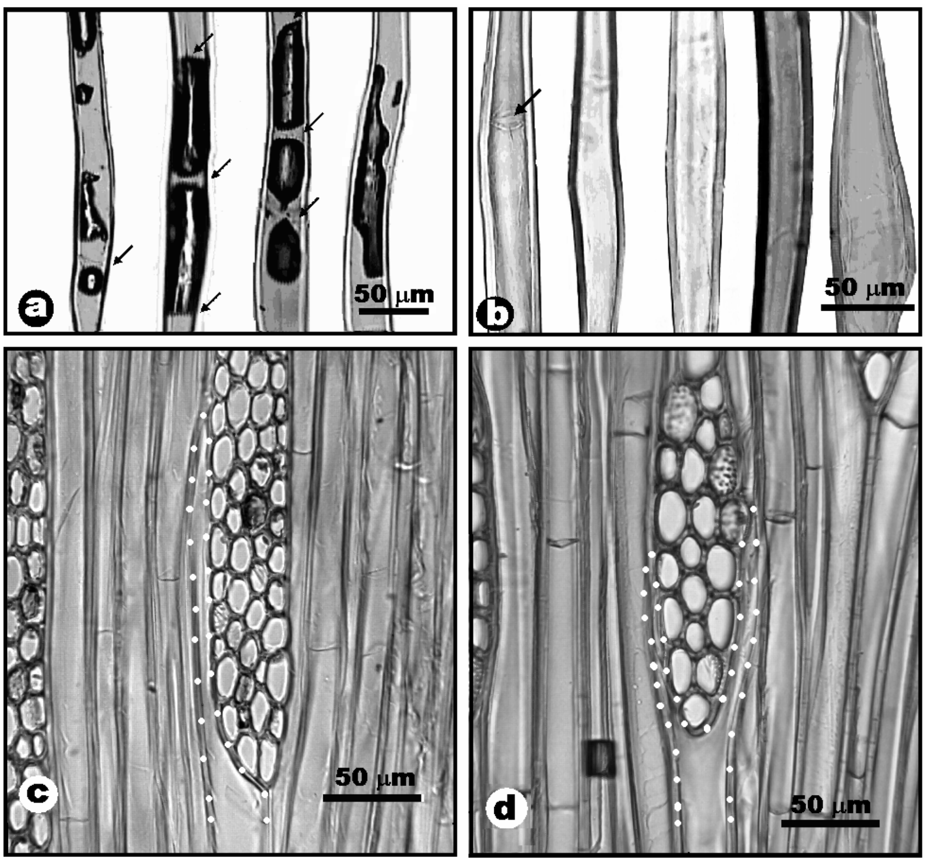

Figure 2. *Gmelina arborea* fibers. a) Crystals both in the lumen and between septa, b) Cell with an irregular diameter (arrow indicates septum), c) One-sided forked ends (delineated by white dots), d) Two-sided forked ends (dashed line showing indicates end of fiber)

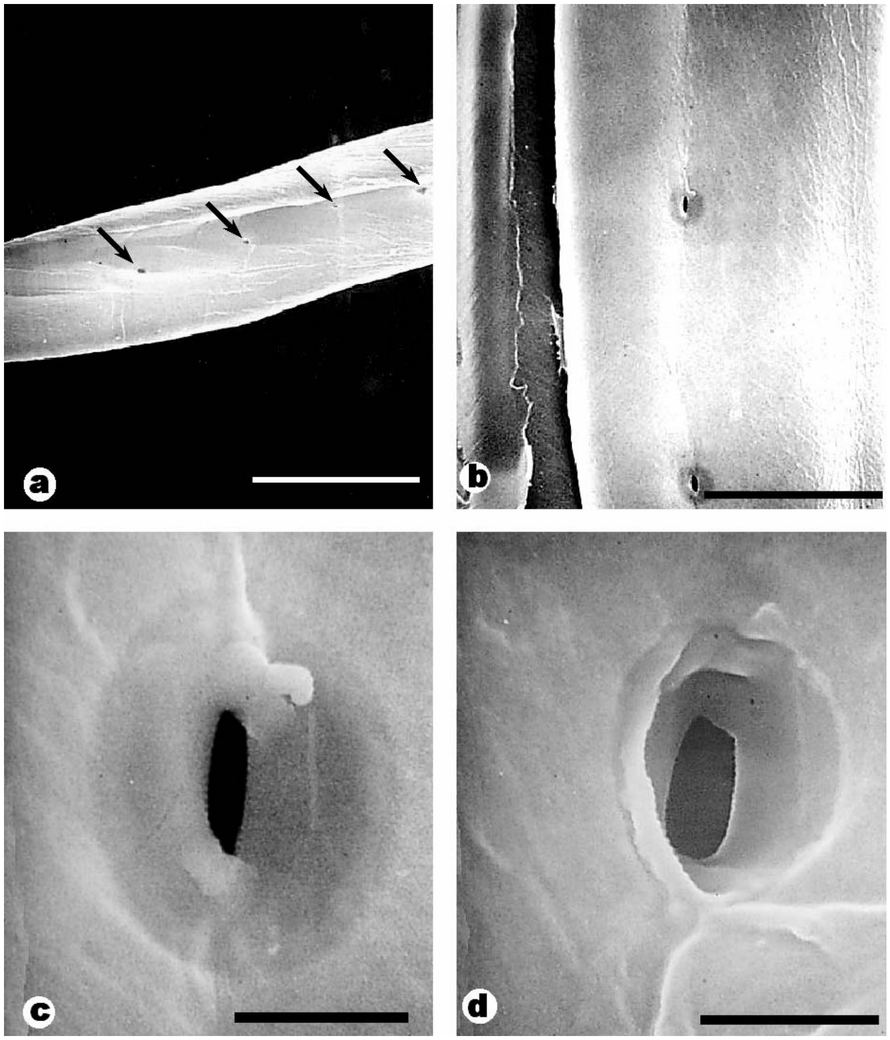

Figure 3. *Gmelina arborea* pits in the cell wall. a) Pit (arrow) arrangement, b) Oblique aperture in longitudinal direction. Fig. 3c-d. Bordered pit. Scale bar 3a = 30 μm; 3b = 10 μm; 3c and 3d = 1,5 μm.

(Table 2), but increased rapidly with tree age up to the 6th year. After this, fiber dimension decreased drastically and reached a plateau. The model tested for predicting fiber length from tree age had a high correlation coefficient (Table 3). Fiber wall thickness increased with tree age (Fig. 4b), varying from 1,74 to 5,83 mm (Table 2), with an increase of 45% between the 1st and 12th year (Table 3). Fiber width increased with tree age from 24,89 to 37,27 mm; however the correlation coefficient decreased and was more variable within each growing year. The greatest increase

Table 2. Fiber dimension of *Gmelina arborea* from fast growth plantations in Costa Rica

Fiber dimension	Minimum	Maximum	Mean	Number of Samples	Standard deviation	Coefficient of variation
Fiber length (mm)	0,75	1,75	1,29	7125	0,210	16,26
Cell wall thickness (μm)	1,74	5,83	4,02	7125	0,636	15,84
Fiber width (μm)	24,89	37,27	30,67	7125	2,400	7,72
Lumen diameter (μm)	17,57	28,38	22,64	7125	2,159	9,54

occurred between the 1st and 6th year of growth and after the 6th year fiber width rate of change decreased or remained constant (Fig. 4c). Average lumen diameter was not strongly correlated with tree age, and variation within each growing year was high (Fig. 4d, Table 3).

DISCUSSION

Septate fibers have been previously reported for *Gmelina arborea* by Pearson and Brown (1932), and Hughes and Esan (1969). These are fibers that contain a septum or a thin transverse wall across the lumen, which is present in dicotyledonous plants and is formed during cell wall maturation, in which cells lose their cytoplasmic contents and lignification processes are absent (Itabashi *et al.,* 1999). Septa were not observed in all fibers and their variable occurrence (from 1 to 4 septa per fiber) is suspected to be influenced by anatomical features such as tree age or the proximity of other woody cells (Itabashi *et al.,* 1999); possible causes that are beyond the scope of the present research.

Table 3. Parameter values and regression statistics for the best allometric models developed for fiber dimensions of *G. arborea* from fast growth plantations in Costa Rica

Fiber dimension	a	b	c	Coefficient correlation	RMSE	P Value
Fiber length[1]	0,8306	0,1327	-0,0068	0,6801	0,119	<0,0001
Cell wall Thickness[1]	3,0136	0,2416	-0,0079	0,4976	0,4524	<0,0001
Fiber width[1]	27,3030	0,7984	-0,0505	0,2772	2,0483	<0,0001
Lumen diameter[2]	22,0810	0,1043	-	0,0160	2,1415	00185

[1] Quadratic model: Y = a + b*age + c*(age)^2
[2] Linear model: Y = a + b*age
RMSE: Root Mean Square Error

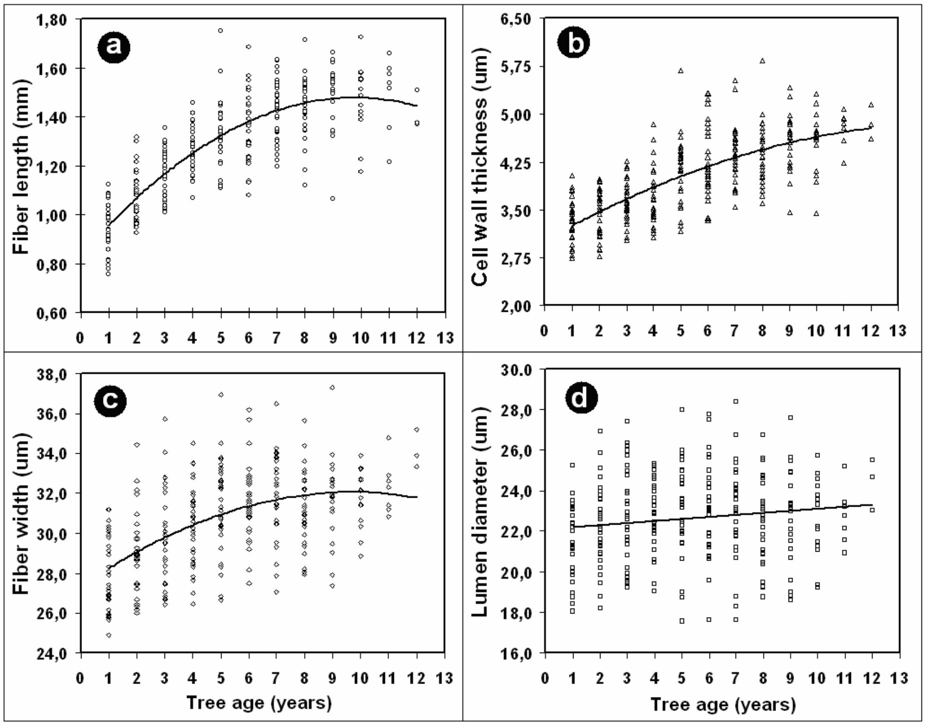

Figure 4. Variation in the fiber dimension of *Gmelina arborea* from a fast growth plantation in Costa Rica

Crystal deposition within the fiber lumen on secondary xylem has been reported for *G. arborea*. Deshpande and Vishwakarma (1992), and Rao and Dave (1984) carried out a detailed analysis of the occurrence of crystals at fusiform and at radial/axial parenchyma cells in the secondary phloem and primary xylem of *G. arborea*. According to those authors, the crystals are formed by deposits of calcium oxalate, which result from the high metabolic rate generated by a physiologically active vascular cambium. According to our results, it can be concluded that the crystals in the secondary xylem correspond to those deposited in the fusiform initial cells of the vascular cambium.

The irregular diameter and shape of fibers in *G. arborea* could have originated in the cambial zone. Rao and Dave (1985), and Dove and Rao (1982) have studied the causes of the wide variation in size, shape, and arrangement of the fusiform cells in the vascular cambium and primary/secondary xylem of *G. arborea*. Vascular cambium activity in primary xylem was intense; the fusiform initials were long, radially flattened and tangentially tapering with overlapping ends. Multiple division types (periclinal, anticlinal, pseudotransverse) were observed within radial and circumferential increments.

According to our results, trees from fast growth plantations are expected to have the greatest variation in shape and fiber diameter. On the other hand, the presence of circular forked ends usually occurs when those cell tips enclose a ray, and forking appears during the elongation period of the fusiform cell in the cambial zone (Rao and Dave, 1985). This type of cell end is considered abnormal because once arrested at vertical ends, cell growth may take place at the lateral walls.

Pearson and Brown (1932) described numerous and simple or bordered pits in *G. arborea* from India, whereas in our study only bordered pits were found.

The average and variation range for the fiber dimensions obtained in the present study coincide with those of previous studies of Nigerian wood in India by Pearson and Brown (1932). Akachuku and Burley (1979) recorded fiber lengths of 0,80 to 1,47 mm in Ghana; Ohbayashi and Shiokura (1989a) found that fiber length was 0,5 mm near the pith and 1,4 to 1,6 near the bark in Malaysia, and Nobuchi *et al.* (1997) have reported less variation in fiber width, as supported by this research. However, Frimpong-Mensah (1992) reported fiber lengths of 0,7 to 1,09 mm and wall thickness ranging from 2,70 to 3,38 mm for 16-year-old trees in Japan; all of which are lower than our values.

G. arborea trees increase fiber length, cell wall thickness and fiber width as they get older. This is a result of the many molecular and physiological changes that occur in the vascular cambium during the aging process (Plomion *et al.,* 2001). The cells produced in the primary xylem divide less frequently, thus allowing more time for the fusiform initial section to elongate longitudinally and transversally (Horacek *et al.,* 1999).

At 6 years of age an inflection in the allometric model for length, width and fiber wall thickness suggests the beginning of a transition between juvenile and mature wood. In *Gmelina arborea* this transition was previously identified at 4,0-9,0 cm from the pith by Ohbayashi and Shiokura (1989a). If the annual increment (CAI) in DBH *G. arborea* trees is 2,0 cm year^{-1} in Costa Rica (Moya, 2004), the juvenile period of this species can be set at 5-6 years old, when the inflection occurs in the fiber dimension curve. It is necessary, however, to confirm this result for older trees. Hughes and Esan (1969) found strong correlations between fiber length, tree age and distance from the pith at 1,0 mm intervals from pith to bark in 9-year-old trees in Nigeria. Akachuku and Burley (1979) found that fiber length increased until 6,0-8,0 cm from pith to bark in 51-year-old Nigerian trees. In contrast, Frimpong-Mensah (1992) found no variation in fiber length with cambial age in 20-year-old *G. arborea* trees in Ghana.

The average fiber diameter increased with tree age (Fig. 4c) but there was no variation in lumen diameter with tree age (Fig. 4d), and according to this result, the increase in fiber diameter was mainly the result of the increase in cell wall thickness (Fig. 4b) and not that of lumen diameter (Fig. 4b).

CONCLUSIONS

Characteristics were found in G. arborea fibers from fast growth plantations, which have not been reported in the literature to date, i.e. the presence of minutely bordered pits and the lack of regular morphology related to its width and tips. Fiber length and width increased with increasing tree age. However, these fiber dimensions increased rapidly with tree age up to the 6th year, after which the rate of increase slowed down (and decreased) drastically until it reached a plateau. Wall thickness was associated with tree age but no inflection in the rate of increase for the length or width of the fiber. The best allometric models were the linear model for lumen diameter and the quadratic model for width, length, and fiber wall thickness.

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