J. Bamboo and Rattan, Vol.5, Nos. 1&2, pp. 3-13 (2006)

Silica content and its distribution in bamboo culms

Bieke Lybeer[1,2*], **Joris Van Acker**[2], and **Paul Goetghebeur**[1]

[1]*University College Ghent, Faculty of Biosciences, Voskenslaan 270,9000 Ghent, Belgium*
[2]*Ghent University, Laboratory of Wood Technology, Coupurelinks 653, B-9000 Ghent, Belgium*

Abstract: The amount of silica and its distribution in bamboo culms of different age classes from both temperate (*Phyllostachys viridiglaucescens* and *P. nigra*) and tropical species (*Gigantochloa levis* and *Dendrocalamus asper*) were analysed. Regardless of diameter class, height and age, silica accounted for 0.04 to 0.11 per cent of the dry weight for *Phyllostachys* spp. and 0.08 to 0.11 per cent for *G. levis* and *D. asper,* values much lower than reported in earlier studies. Silica was more concentrated in the epidermal layer, although *G. levis* and *D. asper* show its presence in the hypodermal cells also. The EDX maps showed an unequal distribution of silica in the epidermis of *Phyllostachys* spp. and higher silica concentrations in the epidermal cell wall.

Key words: Bamboo, silica content, silica distribution, SEM-EDX, processing.

INTRODUCTION

Numerous studies have shown that grasses accumulate silica in their tissues, and the highest content is deposited in leaves in majority of the species (Metcalfe, 1960; Motomura *et al*., 2004). Several authors have reported silica deposition in bamboo leaves and roots (Bennett and Sangster, 1981; Motomura *et al*., 2000, 2002; Lux *et al.,* 2003; Motomura *et al*., 2004). Silica, though not considered an essential element, indeed is important to the plant.

Silica is considered to increase the natural durability and strength (Sanyal *et al.*,1998) and to offer mechanical support (Lux *et al.,* 2003). However, one main constraint to efficient processing of timber as well as other woody materials is the presence of silica. Amorphous silica either as cell wall encrustation, impregnation or as translucent bodies can cause severe dulling of tools, which impedes the processing of materials.

In timber, silica is present in the form of crystals commonly associating with the

[*]To whom correspondence should be addressed; E.mail: bieke.lybeer@hogent.be

parenchyma cells, fibres and tyloses (Furuno and Côté, 1983). In bamboo culms, silica is found mainly in small epidermal cells (Liese, 1998). The aim of the present work is to examine the amount of silica and its distribution within the culms of *Phyllostachys nigra*, *P. viridiglaucescens*, *Dendrocalamus asper* and *Gigantochloa levis*.

MATERIALS AND METHODS

Bamboo

Samples from culms of different ages of *P. viridiglaucescens* and *P. nigra* were obtained from the Bambouseraie in Prafrance, France. Culms of the first year and second year development were harvested from the National Botanical Garden at Meise (*P. viridiglaucescens*) and from the University Botanical Garden at Ghent (*P. nigra*), Belgium. The tropical bamboo species *G. levis* and *D. asper* were sampled at a 4-year-old plantation in Real Quezon in the Philippines. All samples had been marked with the year of emergence giving precise ageing (Table 1).

Determination of silica content

Silica content was determined using the molybdenum blue method (Sulthoni, 1989; Motomura *et al*., 2000, 2002). Small blocks were cut from the middle part of the sampled internodes (Table 1) and were ground to powder. For some samples, powder

Table 1. Samples used for quantitative analysis: Sixth internode was used, except when mentioned differently

Species	Origin	Age (months)	Remarks
P. nigra	Ghent, Belgium	3*, 9*, 12*	
		1, 3, 9	Only epidermis
		24*	Internode 2 up to 22 and node 2/3 up to 18/19
	Prafrance, France	8, 32*, 56*, 104*	
		8, 32, 56, 104	Only epidermis
P. viridiglaucescens	Meise, Belgium	1, 3*, 9*, 12*	
		1, 3, 9, 12	Only epidermis
		24	Internode 2 up to 22 and node 2/3 up to 22/23
	Prafrance, France	8, 32, 56	Only epidermis
		8, 32*, 56*, 104*	
G. levis	Real Quezon, Philippines	8*, 21*, 40*	
D. asper	Real Quezon, Philippines	8*, 21*, 43*	

*Samples also studied by SEM-EDX.

Table 2. Mean Si and SiO_2 contents (%) on a dry weight basis of sixth internode for the different species at different ages

Species	Origin	Age (months)	Si	SiO_2
P. nigra	Ghent, Belgium	3	0.066	0.142
		9	0.078	0.167
		12	0.071	0.152
		24	0.110	0.235
	Prafrance, France	8	0.081	0.173
		32	0.086	0.185
		56	0.058	0.124
		104	0.104	0.223
P. viridiglaucescens	Meise, Belgium	1	0.066	0.142
		3	0.042	0.089
		9	0.078	0.167
		12	0.061	0.131
		24	0.081	0.174
	Prafrance, France	8	0.081	0.173
		32	0.073	0.155
		56	0.098	0.209
		104	0.076	0.162
G. levis	Real Quezon, Philippines	8	0.081	0.173
		21	0.078	0.166
		40	0.080	0.171
D. asper	Real Quezon, Philippines	8	0.082	0.174
		21	0.082	0.174
		42	0.118	0.252

was obtained only from the epidermal layer (Table 1). Bamboo powder (0.5 g) was treated with 5 ml 10 per cent NaOH and pyrolysed at 700°C for 4 h. After cooling, the residue was dissolved in distilled water and transferred to a 250 ml volumetric flask. Then 5 ml of 12N HCl was added and the mixture was made up to volume. Twenty millilitres of the solution was transferred into a 50 ml volumetric flask and 2 ml of ammoniummolybdate reagent, ammoniumheptamolybdate tetrahydrate dissolved in 50 ml water with 5 ml 95-97% H_2SO_4 and diluted to 100 ml with distilled water was added. After shaking, 2 ml of tartaric acid solution, 5 ml of 10 N H_2SO_4 and 2 ml of reducing reagent (a solution of 30 g $Na_2S_2O_5$ and 3 g Na_2SO_3 in 200 ml distilled water and a solution of 0.5 g metol (p-methylaminophenolsulfate) in 25 ml distilled water mixed together and made up to 250 ml with distilled water) were added. The resultant solution was made up to 50 ml with distilled water and the absorbance at 828 nm was measured. The Si content was calculated on a dry weight basis by comparing the absorbance with silicon dioxide standard solution. The SiO_2 content was calculated by multiplying the Si content with 2.139.

Microscopy and X-ray analysis

Air-dried bamboo samples were smoothened using razor blade. The samples were fixed on stubs using adhesive tape, and gold coated in a coater (Balzers SCD 030) before being examined under a SEM (FEI Quanta 200 F) equipped with an EDXA system (Genesis 4000) at 20 kV.

RESULTS

Silica content in bamboo culms

Table 2 shows the mean values of percentage of Si and SiO_2 on a dry weight basis for the different species at different ages. Samples of sixth internode of *P. nigra* and *P. viridiglaucescens* contained 0.06 to 0.11 per cent and 0.04 to 0.10 per cent Si on dry

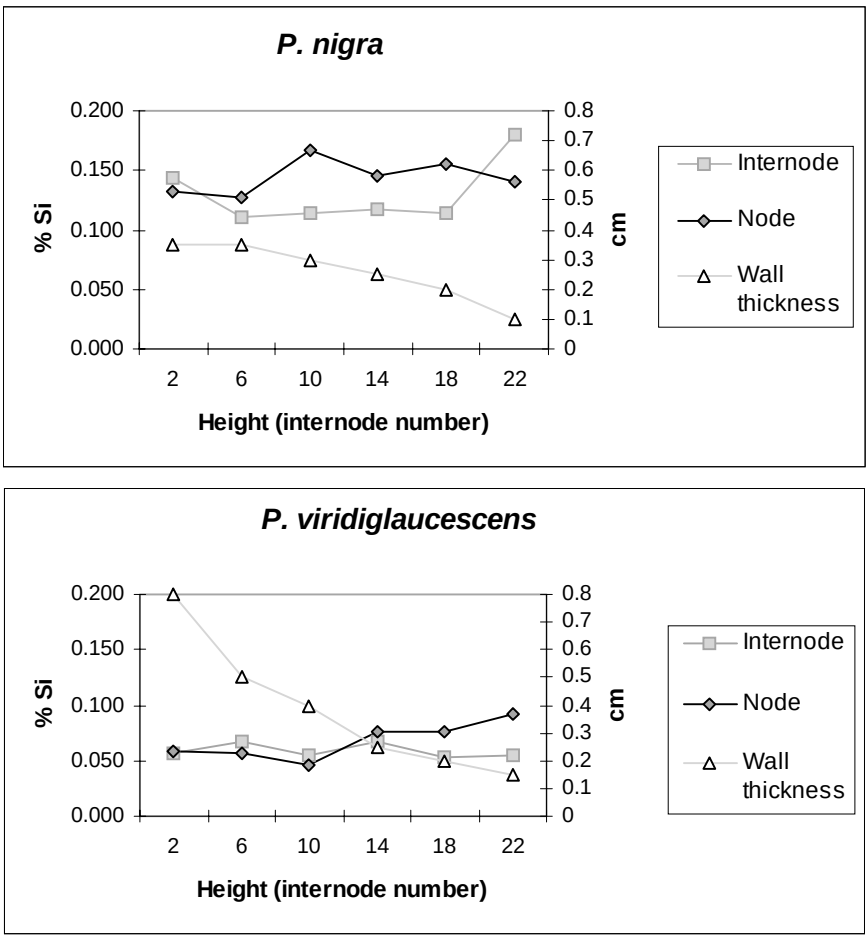

Figure 1. Comparison of Si content between internode and node of a 24-month-old culm of *P. nigra* and of *P. viridiglaucescens*

Table 3. Si content (%) on a dry weight basis of sixth internode of *P. nigra* culms

Origin	Age (months)	Only epidermis	Whole culm wall
Ghent	3	0.085	0.066
	9	0.116	0.078
Prafrance	8	0.155	0.081
	32	0.233	0.086
	56	0.181	0.058
	104	0.163	0.104

weight basis, respectively. The tropical bamboo species *D. asper* and *G. levis* contained around 0.08 per cent and 0.08 to 0.11 per cent Si, respectively. The difference between the species was not statistically significant and within a species there was no significant difference between different ages. Furthermore, no significant difference could be demonstrated between the culms grown in Belgium and France. Less than two per cent ($r^2 = 0.017$) of the variation in Si content could be explained by the variation in culm wall thickness. So, no significant correlation was evident between culm wall thickness and Si content between species at different ages.

Table 3 illustrates that Si content was high in the epidermis as compared to the whole culm wall showing that Si is more concentrated in the former. When comparing the Si

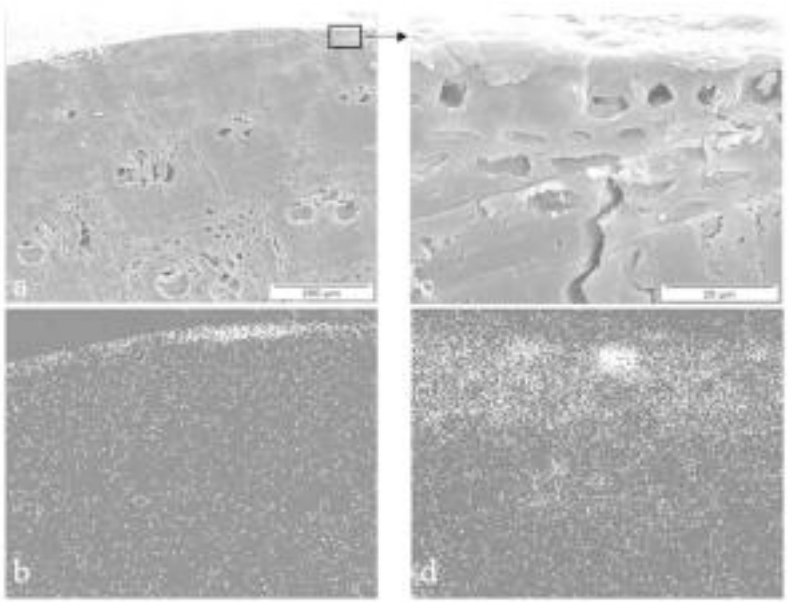

Figure 2. SEM micrographs (above) and EDX maps of the same area (below) of *P. nigra* (24-month-old, internode 20); bright abundant white dots indicate the location of Si; (a-b): Si is deposited in the epidermis and is not equally distributed. Some cells contain more Si than others and some cells do not contain any Si at all. (c-d): detail of the epidermis of (a-b) showing that Si is mainly concentrated in the outer epidermal cell wall.

content of the nodes with that of the internodes (Fig.1), the content is found slightly higher in the former. However, this is not true for all measured nodes and internodes. As indicated by *t*-test, the Si content is not significantly higher in the nodes. Figure 1 illustrates that internode of upper height levels has thinner culm wall. However, only in the culm of *P. nigra* the Si content was higher in upper internodes .

Distribution of silica in bamboo culms

The culm walls of *P. nigra* observed under SEM-EDX displayed more concentration of Si in the epidermis (Fig. 2). Mapping indicated unequal accumulation of Si in different regions of the epidermis including some parts without Si at all. X-ray

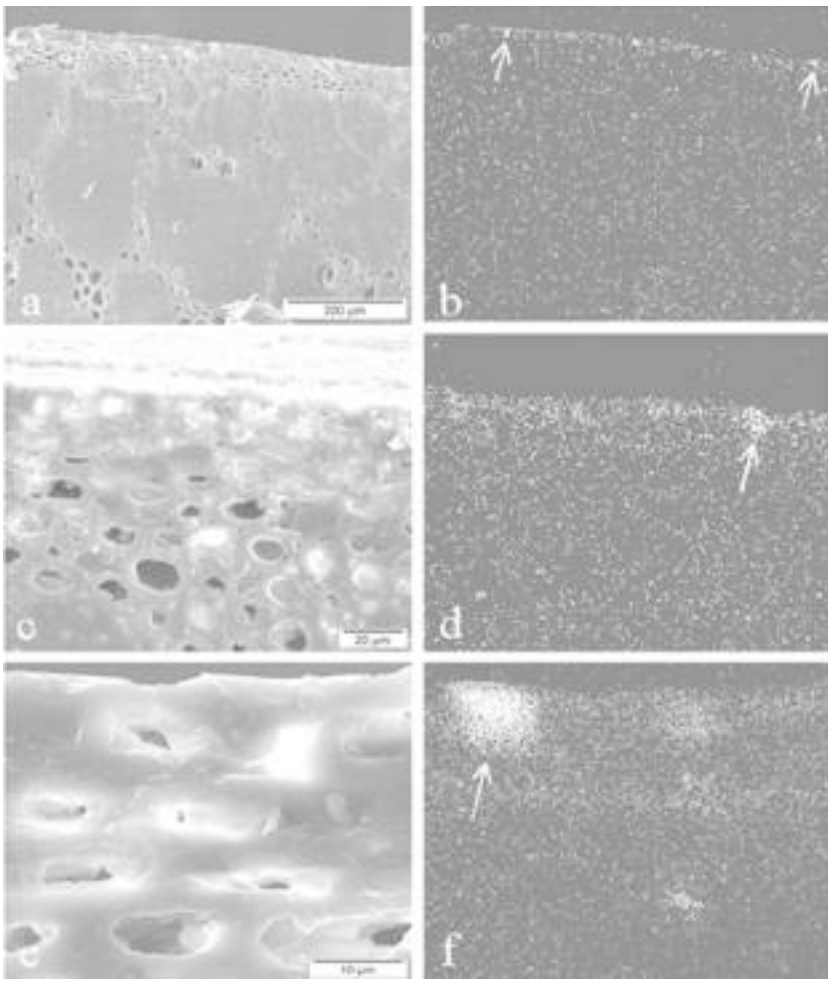

Figure 3. SEM micrographs (left) and EDX maps of the same area (right) of *P. viridiglaucescens*; bright abundant white dots indicate the location of Si; (a-b): 9-month-old, (c-d): 56-month-old, (e-f): 3-month-old. The arrows indicate silica cells in the epidermis.

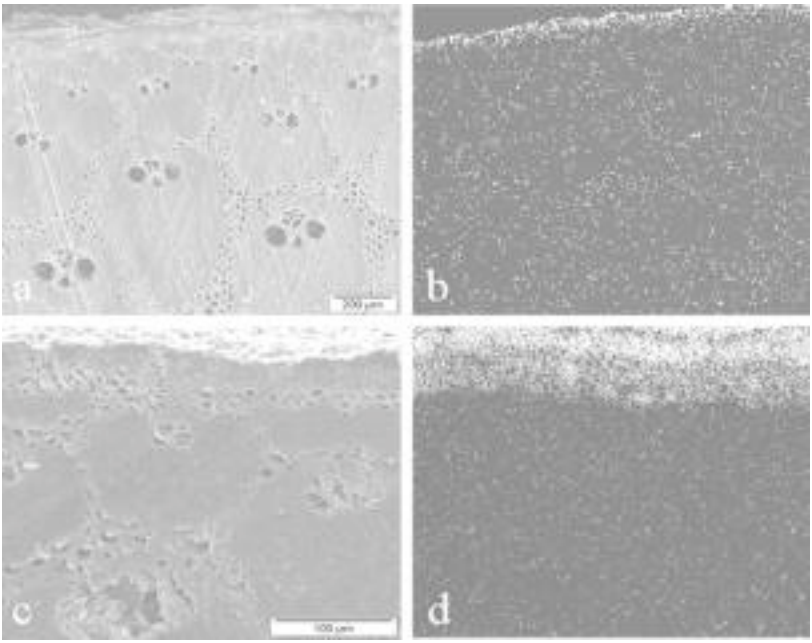

Figure 4. SEM micrographs (left) and EDX maps of the same area (right) of *G. levis*; bright abundant white dots indicate the location of Si; (a-b): 21-month-old, (c-d): 40-month-old. Si is equally distributed in the epidermis and hypodermis.

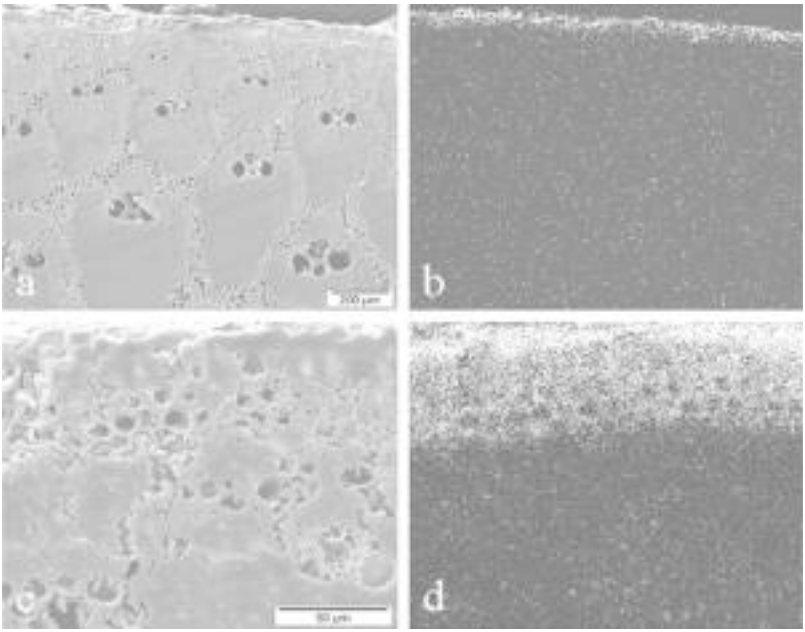

Figure 5. SEM micrographs (left) and EDX maps of the same area (right) of *D. asper* (8-month-old); bright abundant white dots indicate the location of Si. (a-b): Si is located in the epidermis and hypodermis cells and is equally distributed. (c-d): Details of the epidermis and hypodermis cells showing that Si is mainly concentrated in the outer epidermal cell wall.

microanalysis of some epidermal cells showed Si signal in the cell walls, with the highest values found in the outer wall of epidermal cells (Figs. 2c, d). Figure 3 shows SEM micrographs and EDX maps of Si distribution in *P. viridiglaucescens* culms indicating absence of appreciable amount, although some cells have higher Si concentration. Si is exclusively accumulated in the epidermal layer and no Si signal was detected in other tissues. No difference in Si concentration was observed between culms of different ages (Fig. 3).

The tropical species, *G. levis* and *D. asper,* had Si deposited in both epidermal and hypodermal cells (Figs. 4, 5). In contrast to *P. nigra* and *P. viridiglaucescens*, the Si maps indicate a more uniform distribution of Si with higher accumulation in epidermal cells than in hypodermal cells. The highest Si signal was detected in the outer epidermal cell wall as illustrated in the EDX mapping of Si in *D. asper* (Fig. 5d).

DISCUSSION

From the point of view of utilization, Si content over 0.3 per cent can reduce the production rate due to frequent replacement of cutting tools (Haygreen and Bowyer, 1987). However, Thibaut *et al.* (2004) give much lower values of Si (0.014%) below which there is no influence of Si on tool wear. In bamboo culms, Si is considered to be an important constituent of the epidermis with values between 1.5 per cent (*Bambusa vulgaris*) and 6.4 per cent (*Schizostachyum lumampao*) (Liese, 1998). Ueda (1960) reported that in *P. edulis* most Si is concentrated in the exodermis (4.20-5.10%), with average of 0.29-0.33 per cent for the whole culm. Istas and Raekelboom (1962) mention values between 0.07 and 4.7 per cent for *B. vulgaris*, between 0.59 and 1.83 per cent for *O. abyssinica*, around 0.16 per cent for *Arundinaria alpina* and between 0.19 and 0.49 per cent for *Gigantochloa aspera*. Van Acker *et al.* (2000) report values of 0.066 per cent in the lower part and 0.082 per cent in the upper part of *P. praecox* culms and values of 0.12 per cent in the lower part and 0.36 per cent in the upper part of *P. nigra* culms. The results of the present study indicate lower values between 0.04 and 0.11 per cent for *P. nigra* and *P. viridiglaucescens* and between 0.08 and 0.11 per cent for *G. levis* and *D. asper*. The molybdenum blue method, as applied in this study, can be used to detect small amounts of Si present (Bennett and Reed, 1971). The minimal detectable concentration is about 1 µg/g, which is much lower than the values obtained in this study (mg/g) and the study of Van Acker *et al.* (2000). So, it seems that the low values are not an artefact of the technique used. It is, however, impossible to compare the method used here with the methods used in the cited literature, as they do not mention which technique is applied to determine the Si content. More work is required on the Si content in bamboo species to understand the great differences between the values. It would be helpful to cross-check the values by using different methods (*e.g.*, ICP and MS). Furthermore, environmental conditions (*e.g.*, soil) should be taken into account when comparing the Si content.

The tropical species *G. levis* and *D. asper* contain, in contrast to the *Phyllostachys* spp., Si in the hypodermis also. So, it would be logical to assume that the tropical species have higher Si content. Nevertheless, the values obtained do not indicate a significantly higher Si content for the tropical species. According to the EDX-maps, the amount of Si measured is dependent on the part used for the analysis as some parts of the epidermis contain hardly any Si at all. This might partly explain the discrepancy in values obtained for replicate samples of the same culm and also that between the values reported for *P. nigra* by Van Acker *et al.* (2000) and the values reported in this study.

Tamolang *et al.* (1980) reported increasing Si content toward the top in tropical species. However, in the present study this trend was not observed, although it can be expected as the upper internodes are smaller and have relatively higher proportion of epidermis by volume than the lower culm parts. Significant difference was not found in Si content between the nodes and internodes but usually, the content was somewhat higher in the nodes. Liese (1998) has mentioned that the culm tissue itself contains hardly any Si and the nodes only small amounts. However, it is not clear from the statement whether it refers to the whole node or only the nodal tissue without the epidermis. The latter would explain the somewhat higher Si content of the nodes as observed here.

Schmitt *et al.* (2002) localized Si polymers as extracellular deposits within the epidermal cell wall of *Sasa palmata* and *Sinoarundinaria* spp. Young internodes showed distinct Si deposition in epidermal wall regions underneath the cuticle. In the outer wall regions granular deposits of Si were found in increasing amounts during maturation but were only present in inner wall regions in late development stages. The EDX maps show that higher concentrations can be found in the outer wall of epidermis cells.

The culms examined for this purpose in the present study correspond to the late developmental stages as studied by Schmitt *et al.* (2002). Gritsch *et al.* (2004) showed in a study on *Guadua angustifolia* that there are a large number of Si cells concentrated on the outer epidermal layer, but they also observed Si bodies embedded amongst fibres in the periphery of the vascular bundles and in the intercellular spaces between parenchyma cells in the ground tissue. According to their SEM/EDX observations, the concentration of Si bodies in the middle of the culm wall seemed to increase with maturity. However, the Si content was not quantified to prove these observations. As no Si bodies are present in the middle culm wall of the species studied here, their concentration cannot increase. In *Gigantochloa scortechinii*, the Si content increased from 2.1 per cent in the 1-year-old culm to 2.6 per cent (2-year-old) and 3 per cent in 3-year-old culms (Yussof *et al.*, 1994). Such an increasing trend with age was not observed in this study.

CONCLUSION

Precise knowledge of Si deposition and its amount in the culm could give a good estimate of its possible impact on the processing of bamboo. The present study concludes that Si content is less than 0.3 per cent. Thus, in terms of utilization, the Si should have no adverse influence on the production rate of these species. Furthermore, as Si is located only in the epidermis and hypodermis, removing the outer layers should solve the problem.

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