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Research Article

Evaluación del proceso de secado solar de los culmos de *Guadua aculeata* Rupr. ex E. Fourn.

Evaluation of the solar drying process of *Guadua aculeata* Rupr. ex E. Fourn culms

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Abstract

The moisture content of freshly harvested bamboo culms is high, near 100 %, and it should be reduced by some drying process. A key step in the processing of culms, which has been under-appreciated by bamboo producers and users, is drying. Outdoor exposure is the most widely used drying method in Mexico; however, it is not very efficient, as it takes weeks to several months, depending on the environmental conditions. The objective of the present study was to evaluate the drying of *Guadua aculeata* culm sections (6 m long) in a solar tunnel dryer with a rectangular prism shape. The initial average moisture content was 106.72 %, and after a period of 80 days, a final average moisture content of 29.84 % was reached. The drying rate was above 1.0 % per day in the first 20 days, during which their moisture content was reduced by approximately 40 %. In the following 60 days, they lost on average 37.41 % of moisture, at a variable drying rate for each sample culm. The drying curve of the assessed method corresponds to an exponential function. Under the experimental drying conditions, it was determined that 6 m long sections of culms with an average diameter of 12.42 cm can reach an average *MC* below 18 % in 109 days, thus becoming suitable for use as structural elements.

Key words: Giant bamboo, moisture content, drying curve, exponential function, solar tunnel dryer, drying rate.

Resumen

El contenido de humedad de los culmos de bambú recién cosechados es de alrededor de 100 %, el cual se considera alto, por lo que debe reducirse mediante algún proceso de secado. Un paso clave en el procesamiento de los culmos es el secado, que ha sido poco valorado por los productores y usuarios de bambú. La exposición al aire libre es el método más utilizado en México, pero poco eficiente, ya que tarda desde semanas hasta varios meses en función de las condiciones ambientales. El objetivo del presente estudio fue evaluar el secado de secciones de culmos (6 m de longitud) de *Guadua aculeata* en un secador solar tipo túnel, con forma de prisma rectangular. El contenido de humedad inicial promedio fue de 106.72 %, en 80 días se alcanzó un contenido de humedad final promedio de 29.84 %. La tasa de secado fue superior a 1.0 % por día durante los primeros 20 días, lapso en el cual redujeron aproximadamente 40 % de su contenido de humedad. En los siguientes 60 días, perdieron en promedio 37.41 % de humedad a una tasa de secado variable para cada culmo muestra. La curva de secado del método evaluado corresponde a una función exponencial. Bajo las condiciones experimentales de secado se determinó que las secciones de culmos de 6 m de longitud y diámetro promedio de 12.42 cm, pueden alcanzar un *CH* promedio menor a 18 % en un tiempo de 109 días, para posteriormente usarse como elementos estructurales.

Palabras clave: Bambú gigante, contenido de humedad, curva de secado, función exponencial, secador solar tipo túnel, tasa de secado.

Introduction

Bamboo is the generic name given to plants of the Poaceae family, Bambusoideae subfamily, distributed in practically all ecosystems of the world. Today, 121 genera and 1 662 species of bamboos are recognized (Canavan *et al.*, 2017). In Mexico, there are eight genera and 61 species of woody bamboo have been identified, 42 of which are endemic to Mexico (Ramírez-Ojeda *et al.*, 2021; Ruiz-Sánchez *et al.*, 2022); the subtribe Guaduinae is the most important culturally and economically, and the *Guadua* genus is the most representative (Londoño *et al.*, 2002), as due to its large dimensions (diameter and length) and excellent physical and mechanical properties, it has great economic potential, particularly for housing construction in tropical regions (Ordóñez *et al.*, 2013).

Within the *Guadua* taxon, one species that stands out for its anatomical, physical and mechanical characteristics is *Guadua aculeata* Rupr. ex E. Fourn. (*tarro*, *caña brava*), reaching 25 m in height and 18 cm in diameter at the base, with hollow internodes 20 to 30 cm long and a thickness of 2 cm (Cedeño and Irigoyen, 2011). The most commonly used part of the bamboo is the culm (main stem) of the plant, whose traditional shape is cylindrical; however, its diameter decreases with height. It is internally separated crosswise by solid nodes, and its internodes are hollow (Chaowana *et al.*, 2021). Anatomically, it consists of a cortex (cuticle), fibers and parenchyma cells. The proportions and dimensions of each component vary between species, within species, and within the same individual, this generates a great heterogeneity in their behavior during the transformation processes (Yuan *et al*., 2022).

The drying process is key to the industrial and commercial utilization of the culms, since it improves both their structural properties and their aesthetic appearance (Tang *et al*., 2012; Burger *et al.*, 2017; Wang *et al.*, 2019), expanding their area of application and improving their utilization value (Lv *et al*., 2022). However, producers, traders, and users of culms have not given it the required importance, as they consider it a natural process (Montoya and Jiménez, 2006) that can take weeks to several months to attain a moisture content close to 12 % (Liese and Tang, 2015), which is considered to be a percentage suitable for various uses.

Cracking and splitting along the fibers are the main flaws that occur during drying of culms (Lv *et al*., 2018a; Lv *et al*., 2021) as an effect of low transverse tensile strength due to a lack of radial cells (Liese and Tang, 2015; Lv *et al*., 2018b).

Up to the present day, little research has been done on the solar drying of bamboo culms (Ong, 1996; Montoya and Jiménez, 2006; Morales-Pinzón *et al.*, 2012; Vetter *et al*., 2015; Hossain *et al.*, 2021; Kaba *et al.*, 2022), in all of which sections less than 2 m long were utilized. Given the scarce importance that has hitherto been attached to the solar drying process of 6 m bamboo culms for structural use, the present study tests this drying method for this size of culms as a more efficient option than open air drying. The objective of this study was to evaluate the drying process of *Guadua aculeata* culms in an active solar tunnel dryer in the *Hueytamalco* region, state of *Puebla*, Mexico.

Materials and Methods

The collection of the material consisted in obtaining 6 m long pieces of mature culms, which diameter at breast height was measured at a height of 1.3 m above ground level, with a Forestry Suppliers® 5 m-long measuring tape, model 283D/5m-CSE, accurately graduated to the millimeter. The normal diameter at breast height of the culms ranged between 10.7 and 13.8 cm and averaged 12.4 cm. These pieces were obtained in natural stands of *G. aculeata* located in the *Las Margaritas* site in the *Hueytamalco* municipality, *Puebla*, Mexico, between the geographical coordinates 19°52' and 20°12' N, and 97°12' and 97°23' W, at an average altitude of 430 m.

A solar dryer built at the *Las Margaritas* Experimental Site of the *Instituto Nacional de Investigaciones Forestales*, *Agrícolas y Pecuarias* (INIFAP) was used to dry the culm sections.

The drying process was carried out from August to November 2018. The solar dryer used is of the tunnel type, in the form of a rectangular prism, it consists of a semi-parabolic roof and rectangular walls covered with polyethylene with ultraviolet protection, a PTR structure, and a concrete floor. The dryer has an internal solar collector with the shape of a false ceiling, built with smooth aluminum sheets painted matte black. The dimensions of the dryer are 10 m in length, 4 m in width, and 2.8 m in height (Figure 1). The main modifications made to the original design were the replacement of the fans with a single 20 cm-diameter wind extractor fan positioned on the rear wall and centered at the bottom, whose purpose is to extract the humid air from the interior and expel it out of the dryer.

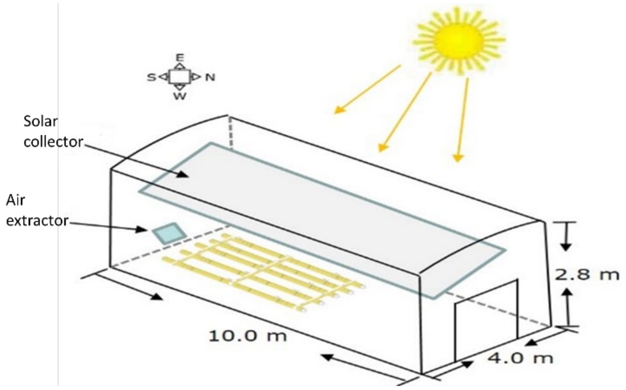

Figure 1. Diagram of the solar dryer used for the drying of *Guadua aculeata* Rupr. ex E. Fourn. culms.

The temperature and relative humidity were recorded with two HOBO® UX100-003 Data Loggers, with an error of 3.5 %; one was placed inside the dryer, and the other outside, at a height of 2 m from the ground, in order to record the external environment condition. Daily and monthly average solar radiation data were obtained from the Global Solar Atlas provided by the World Bank Group (Solargis, 2023) database for the geographic coordinates 20.000610, -97.307414 (20°00'02", -097°18'27"), corresponding to the location of the *Las Margaritas* Experimental Site facilities.

In order to assess the solar drying process, a pile was formed with 50 pieces each 6 m long, collected in a proportion of 80 % from the basal part and 20 % from the middle third of the total length of the culm. At the time of the felling, four 6.1 m pieces were selected to be used as drying samples, and from each piece two 5 cm long moisture probes were obtained, one from each end.

The pieces were stacked horizontally in five beds of 10 pieces each, and between them were placed, as separators, three 2.5 m long culms of a smaller diameter than those stacked, with a separation of 3 m approximately. Two drying samples were placed on each side of the pile, one at the bottom, and the other in the middle (Figure 2).

Figure 2. Stacking of *Guadua aculeata* Rupr. ex E. Fourn. culms inside the solar dryer.

The initial moisture content (*MC*) in green condition of the dried samples was determined using the gravimetric method, for which purpose the specimens were weighed on an Ohaus® PR Series Precision PR1602/E digital electronic balance with an accuracy of 0.01 g in order to determine their wet weight; then they were placed in a HDP 334 TECSA® laboratory oven, for drying at 103±2 °C for 24 hours, the period required to reach their dry weigh. The *MC* of each specimen was calculated as the weight loss, expressed as a percentage of its dry weight, by means of Equation 1 (International Organization for Standardization, 2019):

$$MC_i = \frac{IW_w - D_w}{D_w} 100 \qquad (1)$$

Where:

MC_i = Moisture content of each test specimen expressed as a percentage of its respective dry weight

IW_w = Initial wet weight of specimen before drying

D_w = Oven dry weight of the test specimen

The drying process was monitored by estimating the calculated dry weight (*CDW*) of the drying samples, using the average *MC* obtained from the aforementioned specimens and the weight of each sample at the time of the felling and cutting of the culm (Equation 2) (Simpson, 1991; Aquino-González *et al*., 2010):

$$CDW = \frac{IW_w}{MC_i + 100} 100 \qquad (2)$$

Where:

CDW = Calculated dry weight for the sample

IW_w = Initial wet weight of the drying sample

MC_i = Average moisture content of the test specimens, determined with the Equation (1)

The drying process was monitored using the gravimetric method, by estimating the weight loss of the drying samples, which were weighed every two days; the *MC* was determined by means of equation 3 (Baranski *et al*., 2021):

$$MC_{ds} = \frac{W_s - CDW}{CDW} 100 \qquad (3)$$

Where:

MC_{ds} = Moisture content of each drying sample at the time of weight recording through the drying process

W_s = Weight of samples at any time during the drying process

CDW = Calculated dry weight of the drying samples

The drying rate (*DR*) was determined with Equation (4), which describes the variation of moisture content measured at a time (*t*) with respect to the previous time (*t-1*) (Montero and Rozas, 2019):

$$DR = \frac{MC\Delta}{t\Delta} \qquad (4)$$

Where:

DR = Drying rate (% MC day^{-1})

$MC\Delta$ = Moisture content variation (%)

$t\Delta$ = Time between measurements (day)

Drying curve for evaluating the solar drying of culms

The moisture content (*MC*, %) and drying time (*t*, hours) recorded in the samples were the variables used to generate the curve that characterizes the process of solar drying of the culms in the study area. A previous analysis that consisted in evaluating the fit of various forms of exponential models referred to by Mehta *et al.* (2022) and Rezaei *et al.* (2022) led to the selection of the model whose mathematical structure is shown in Equation (5).

$$MC = \alpha \times exp(-\beta \times t) \qquad (5)$$

Where:

MC = Moisture content

α and β = Regression coefficients to be estimated

exp = Exponential function

t = Drying time in hours

According to Hox *et al*. (2017), Equation (5) was regression-adjusted using the mixed-effects modeling technique, with the nlme package of the R statistical software (R Core Team, 2022), version 4.2.3. The following goodness-of-fit statistics were determined: Coefficient of determination adjusted by the number of parameters (R^2_{adj}), Root mean square error (*RMSE*), Akaike Information Criterion (*AIC*), Bayesian information criterion (*BIC*), and the logarithm of likelihood (*logLik)*.

Results

Climatological analysis of the study area

The average monthly solar radiation during the study was 3 433, 3 729, and 3 382 Wh m^{-2} for September, October and November, respectively. The maximum temperature values recorded in the interior were 46.9 °C and minimum temperatures of 18.8 °C; while outside the maximum was 39.6 °C and the minimum was 18.8 °C, the average ambient and inside temperature differential being 11 °C between 12:00 and 14:00 h, with a maximum difference of 13 °C observed at approximately 13:00 h. In relation to relative humidity, the minimum value was 31.8 % and the maximum value 91 % inside the dryer; in the outside environment, the minimum value was 53.6 %, and the maximum value was 89 %.

Solar drying curve of culms

The drying process of *G. aculeata* was monitored during a period of 1 920 hours (80 days); the initial average *MC* of the drying samples was 106.71 %, and the average observed *MC* reached at day 80 was 29.84 %, which is within the range of the *MC* corresponding to the fiber saturation point (Liese and Tang, 2015). Figure 3 shows the average fitted drying curve and the respective standard deviations represented by the exponential Equation (4), whose highly significant regression coefficients values —with a probability level of 95 %— were α=95.02205 and β=0.00064 (α=0.05, *p* value=2e-16), along with the observed drying trends. The values obtained for the goodness-of-fit statistics of the model were 0.9856, 2.4996, 985.80, 1005.41, and -486.90 for R^2_{adj}, *RMSE*, *AIC*, *BIC*, and *logLik*, respectively.

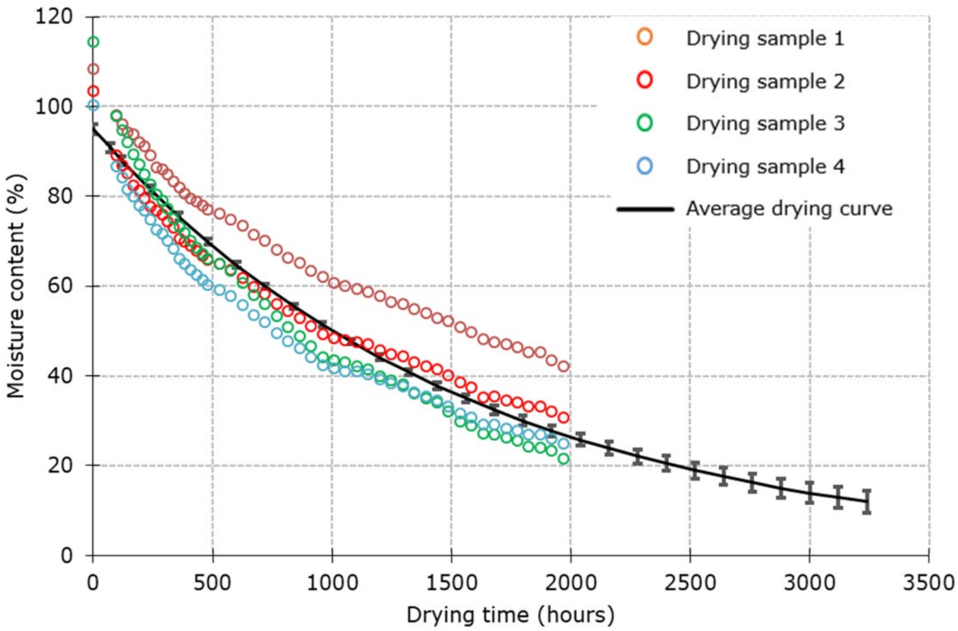

Figure 3. Observed graphical behavior of the solar drying process of culms and trend of the average drying curve based on exponential expression.

In order to estimate the drying time (t) in hours required for an *MC* value of interest considered suitable for the intended use of the culms, it was necessary to find the value of t in Equation (5), which gave rise to the Equation (6). However, in order to estimate the drying time in days, the result of Equation 5 should be divided by 24.

$$t = -\frac{ln\left(\frac{MC}{\alpha}\right)}{\beta} \qquad (6)$$

Where:

t = Drying time (hours)

ln = Natural logarithm

MC = Moisture content (%)

α and β = Regression coefficients used to generate the drying curve

Drying rate of *Guadua aculeata* in a solar dryer

The moisture loss per day, as well as throughout the drying period, was different in each of the sample culms. Figure 4 illustrates the behavior of the two samples that had the slowest and fastest drying rates during the drying process. In both cases, it can be seen that at the beginning of the process, when their moisture contents were high, more than 1.0 % moisture was lost per day. Drying sample 1, with an initial *MC* of 108.36 %, exhibited a maximum moisture loss rate of 1.86 % per day and maintained the drying rate above 1.0 % for the first 16 days, until it reached approximately 78 % moisture. From that point on, the rate decreased, ranging between 1.0 and 0.6 % until day 40, when it reached a *MC* of 60 %, after which the drying rate remained below 0.6 % every 24 hours.

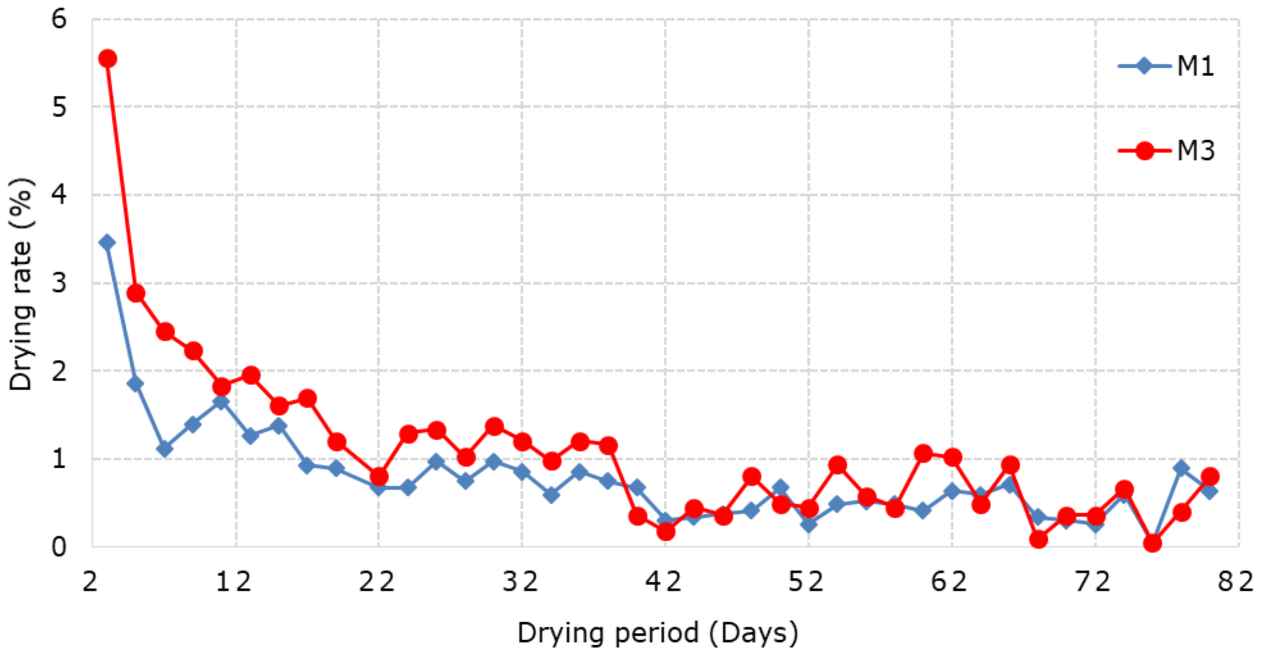

Figure 4. Drying rate of two bamboo samples with solar drying, every 24 hours.

Drying sample 3 had an initial *MC* of 114.52 %, it started with a moisture loss of 2.9 % every 24 hours, with a constant drying rate above 1.5 %, until the *MC* was reduced to approximately 66 % in the first 17 days; subsequently, the drying rate was maintained above 1.0 % until the *MC* reached 44 % after 38 days; from this point on, the average drying rate was constant at 0.5 % every 24 hours.

Discussion

The initial *MC* on a dry basis of the different bamboo species cited in the specialized literature is above 100 %, although there are variations depending on the species, growth area, and cutting season (Hossain *et al*., 2021). For the *G. aculeata* culms studied, the average initial *MC* was 106 %, which is higher than the value recorded by Wang *et al.* (2019) for *Phyllostachys heterocycla* fo. *pubescens* (Pradelle) D. C. McClint., of 90 %. Even though there is a clear difference in *MC* between the different heights of a bamboo culm, Hartono *et al.* (2022) document average moisture contents of 223.4 % in the lower part of the culms of *Bambusa vulgaris* var. *vittata* Rivière & C. Rivière. As for the drying process, according to Tang *et al.* (2012), bamboos with solid culms are easier to dry than species with hollow culms, such as *G. aculeata*. Montoya and Jiménez (2006) indicate that the drying period depends on species-inherent factors such as culm diameter, wall thickness, initial moisture content, age, position in culm height, length of the sample to be dried, and growth site.

A fundamental factor to be considered in determining the drying time of bamboo culms is the length of the pieces, longer pieces require longer periods because the movement of moisture through the anatomical structure of bamboos only occurs in the longitudinal direction. In the absence of anatomical elements in the transverse direction such as vessels or parenchyma, moisture movement in this direction is secondary (Huang *et al*., 2015; Lv *et al*., 2021). Thus, Morales-Pinzón *et al.* (2012) dried 6 m-long preserved sections and needed at least four months to attain a *MC* of 19 to 27 %.

In order to dry in a solar dryer 2.5 m-long culms of three bamboo species with an average initial *MC* of 60 % to 14 %, Hossain *et al.* (2021) required 30 days for *Bambusa balcooa* Roxb., 27 days for *Bambusa vulgaris* Schrad. ex J. C. Wendl., and 24 days for *Schizostachyum* Nees*.* While, in order to conduct studies on drying of 4 m long *Yushania alpinia* (K. Schum.) W. C. Lin culms stacked horizontally under a shed without exposure to humidity, rain, or sunlight, Kaba *et al.* (2022) took 97 days to dry from an initial *MC* of 110.81 % to a final moisture of 13.90 %. In another study on air drying and shed drying, by Yan *et al.* (2022), it is reported that 6 m long sections of *Phyllostachys edulis* (Carrière) J. Houz. culms with an initial *MC* of 76 % attained a final *MC* of 11 % after six months.

In the present study, we started with an average *MC* of 106.71 % and required 80 days to reach a final *MC* of 29.84 %. However, with the exponential function generated, 4.7 months are estimated to be required to attain a final *MC* of 11 to 12 %; this proves, by comparison, that solar drying is 22 % faster than traditional drying, with a low proportion of defects due to cracking, and improves the quality of the product (Chen *et al.*, 2023).

When the fitted exponential function is utilized, a period of 109 days is estimated to be required for the drying of 6 m-long canes of *G. aculeata* (Seduvi, 2017) at a *MC* value of less than 18 %, a percentage suggested for use in structural design. This is similar to the 106-day period calculated by Montoya and Jiménez (2006) in *Pereira*, *Colombia*, for *Guadua angustifolia* Kunth to attain a moisture content of 17.5 %;

their study used the exponential function $MC = 132.42 \times \exp(-0.0188 \times t)$ with an R^2 of 0.969. In this sense, Vetter *et al.* (2015) states that drying of bamboo culms in their round form requires long periods of time; this is an indispensable condition to achieve the minimum of defects due to cracking, which, according to Chen *et al*. (2023) usually occur at the nodes, at the internodes and at both ends of the sections of the culms.

The drying rate at which the *G. aculeata* culms lost moisture during the solar drying process was above 1.0 % per day during the first 20 days, going from an initial moisture content of 106.71 % to an average moisture content of 67 %, i. e., on average they lost approximately 40 % moisture. After this period, the drying rate was variable, averaging a 37.41 % loss over the next 60 days, with an average rate of 0.62 % per day, although some drying samples reached a daily drying rate of close to 1.0 % during this second period. The values obtained for the drying rate are higher than those recorded by Yan *et al.* (2022) for the open-air and shed drying of *Phyllostachys edulis* culms, which exhibited a daily drying rate of 0.50 % when reducing its *MC* from 76 to 35 % in 81 days and of 0.22 % when going from 35 to 11 % in a period of 108 days. However, although these are average drying rates, the height of the culm from which the section to be dried is obtained must be considered in the process, since pieces from the middle part have a higher drying rate than those coming from the lower part, as shown in the results of the two samples analyzed in relation to the drying rate, sample 1 was obtained from the basal part and exhibited a lower drying rate than sample 3, which was taken from the second third of the culm; this is due to the chemical, physical and anatomical structure differences that exist in bamboo culms (Tang *et al.*, 2012; Chaowana *et al*., 2021), as well as to the greater wall thickness of the lower section of the culm (Vetter *et al.*, 2015; Chen *et al.*, 2023).

Conclusions

The evaluation of the solar drying process of commercial *Guadua aculeata* culms from *Hueytamalco*, *Puebla*, Mexico, using sections of 6 m in length, allows us to conclude that the drying time of *Guadua aculeata* culms under solar drying conditions in *Hueytamalco*, *Puebla*, can be estimated with the equation: $t = -\frac{ln\left(\frac{MC}{95.02205}\right)}{0.00064}$. Using the adjusted exponential equation, a period 109 days is estimated to be required to dry *G. aculeata* culms to a moisture content of 18 %, which is the percentage suggested for structural use. The *G. aculeata* culms exhibit a drying rate of over 1 % during the first 20 days of processing, and of 0.62 % on average during the remaining 60 days.

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Conflict of interest

The authors declare that they have no conflict of interest in the conduction of this research. Juan Carlos Tamarit-Urias declares not to have participated in the editorial process of the document.

Contribution by author

Juan Carlos Tamarit-Urias: conceptualization and organization of the research, collection of information in the field, creation of databases, statistical analysis, drafting and editing of the document; Juan Quintanar-Olguin: research conceptualization, data curation, drafting and editing of the paper with emphasis on literature review; Casimiro Ordóñez-Prado and Martha Elena Fuentes-López: fund raising, editing of the document; Melchor Rodríguez-Acosta: fieldwork data collection and editing of the document.

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