EVALUATION OF DIFFERENT APPROACHES FOR THE DRYING OF LIGNOCELLULOSE RESIDUES

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The main objective of this study was to evaluate three methodological approaches for the drying (air drying, solar drying, and hot-air drying) of three lignocelluloses residues in Costa Rica, namely the empty fruit bunches of oil palm (EFB), pineapple plant leaves (PL) with different treatments on this leaf, and sawdust from *Gmelina arborea* (GAD). The initial moisture content (MC_i), the drying times, and the variation of moisture content (MC) with time were determined. A mathematical model of the relation between MC and drying time was also established. The results showed that the MC_i was the highest in PL (over 79%), followed by EFB (over 47%), and GAD (lower than 47%). Drying times were higher for air drying, followed by solar drying, and finally hot-air drying. PL showed the longest drying times, followed by GAD and EFB. However, it can be reduced by shortening strands, application of grooves in the cuticle, or crushing the leaf. The MC variation model revealed that the function was $Y = ax^3 + bx^2 + cx + d$ for all three drying techniques, and the weather conditions where the drying was tested. This model presents high coefficients of determination (over 0.97) and low percentage of errors (1.85-4.73%).

Keywords: Agriculture waste; Mathematical model; Costa Rica; Drying method

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INTRODUCTION

The generation of lignocellulose residues is a considerable problem in Costa Rica (Ulloa *et al*. 2004). Lignocellulose residues from agriculture and forestry constitute a high percentage. Particularly, the forestry industry produces 500,000 m^3 in residues (Barrantes and Castro 2009). The production of palm oil and pineapple has shown an upturn in the last few years. The production of oil generates a set of residues from which the empty fruit bunch (EFB) constitutes an average of 26% of the total weight from harvested palms. For instance, in the year 2003, the production was 800 tons, out of which 200 tons were unused waste. Furthermore, the production of pineapple offers potentially more favorable results towards the better use of its residues, considering that aside from the fruit, 133 tons/hectare were comprised by the other parts of the plant (leaves, trunk, and roots) providing the promising amount of 3600 tons/hectare of residues to be used (Ulloa *et al*. 2004).

Over the last few years, with problems associated with the environment and global warming in many regions of the world, better uses of residues have been developed in energy sources for the lumber industry transformation processes (sawdust), and in agricultural crop residues (Shuit *et al*. 2009; Velázquez 2006). Furthermore, for Costa Rica and several other developing countries, the use of these residues would constitute an innovative alternative for the secondary use of these kinds of materials. For the utilization of residues for mushroom production, biogas, and direct combustion for drying agricultural products, continuous feeding of animals and combining composted residues and inorganic fertilizers should be evaluated for mixed and plantation cropping systems (Thiagalingam and Sriskandarajah 1987).

Energy recovery from lignocellulose residues as secondary material brings about many advantages, such as having components from renewable sources with relatively low energy consumption to obtain them (McKendry 2002a). However, it is important to point out that one of the greatest limitations faced by these sectors is regarding the development of a system that truly uses those residues. This is because said materials are from a biological origin with inherent high moisture contents (McKendry 2002a). Hence, for future use, elimination of moisture or water is eminently necessary (McKendry 2002b).

To dry lignocellulose products, several techniques have been traditionally used, from very simple to very complex approaches. The first group is air drying, which does not require any specialized equipment (FPL 2010). Among the sophisticated techniques there are those that require specialized equipment such as rotating drums or conventional drying chambers with boilers (González *et al.* 2011). Solar drying is considered intermediate, or low technology development. It has some advantages, such as a shorter drying time and low moisture contents compared with air drying, in addition to the cost (Langrish and Walker 2006; Skaar 1972) and the minimum energy consumption (Sattar 1994) compared to hot air drying. Biomass drying has received wide interest from researchers worldwide, not just for residues mentioned in this study, but for many other kinds of residues (McKendry 2002b). Studies have covered, besides the design of excellent dryers, the development of very tight drying models and quite real drying kinetic curves (McKendry 2002a). However, the real drying techniques are more complex than those drying systems and models. For example, Muñoz and Moya (2008) found that the drying time was affected by the tree diameter. Wang *et al*. (2005) researched a drying experiment of pineapple leaf wet fibers with a hot airflow drying device, and they chose different drying characteristics, different air flow temperatures, and velocities. However, this research was carried out by chemical analysis for nutrient elements in a laboratory. In EFB residues, Shuit *et al.* (2009) found that fresh EFB became reduced in volume and weight by 85% and 50%, respectively, after ten weeks in composting.

In the case of Costa Rica, there are no official reports on whether lignocellulose residues are being used for energy-related purposes. Thus, methodology for their use is urgently required, and the drying of said residues constitutes a key problem to be solved. In addition, Costa Rican industries can no longer afford to go on without using residual products from their plantations or from crop processing. Therefore, this study has as its objective the presentation of a methodological approach for the drying of lignocellulose residues (empty fruit bunch, pineapple leaves from plants, and *Gmelina arborea* sawdust) according to three techniques: air drying, solar drying, and hot-air drying. This study gives information on the determination of drying times for each residue when different drying techniques are applied, and thus generate strategies for possible uses.

EXPERIMENTAL

Materials and Origin

Three different lignocellulose residues from agricultural and forestry activities were investigated for drying: pineapple leaves (PL) from plant, fibers from the empty fruit bunch of oil palm (EFB), and sawdust of *Gmelina arborea* (GAD). These residues were chosen as they are currently produced in considerable amounts, and not used by any industry in Costa Rica. PL came from 18-month-old, second harvest plants located in the southern area of Costa Rica. The EFB was collected in the central Pacific area of the country. Finally, GAD came from a sawmill located in the northern area of Costa Rica.

Material Characteristics

Pineapple leaves

Pineapple leaves were processed under two different methods considering the possibilities that currently exist to use them and process them. With the first method, the leaves were cut in strands of three different lengths (Fig. 1a). With the second method, pineapple plants were crushed in a shredder, or miller, commonly used for the extraction of sugar cane juice (Fig. 1b). In the first method, PL were separated from the base of the plant and cut in strands of three different lengths (Fig. 1a): 2 cm (2-strand), 6 cm (6-strand), and 10 cm (10-strand). For the 6-strand and 10-strand, the epidermis and cuticle layer (lower and upper) were maintained. However, for the 2-strand, two treatments were tested: (i) the epidermis and cuticle layer were maintained (2 strand without grooves) and (ii) grooves were opened in the underside to break the cuticle (2-strand with grooves) and determine how it affected the water flow during drying (Fig.1a). Leaves in the bromelia family have a layer of cells called the cuticle whose function is that of a protective tissue that avoids moisture loss from the leaf (Bartholomew *et al*. 2003). The grooves were drawn 5 mm apart with nails. For the second method (leaf shredding), plants were totally pulled up from the ground, their roots were eliminated, and then they went through a shredder or miller for sugar cane juice extraction. The shredder had a 34 KW, 1725 rpm motor for a linear speed of 90 m/min (Fig. 1b). The apparent density of PL for all of the conditions was 95 kg/m^3 in green conditions.

Sawdust

Sawdust was directly extracted from the sawdust evacuation systems of a circular saw (Fig. 1c). The distribution of the length and the percentage of the total weight of the sawdust was: particles larger than 6.7 mm (2%), between 4.00 and 6.70 mm (4%), between 2 and 4 mm (11%), between 1 and 2 mm (31%), between 0.43 and 1.00 mm (36%), between 0.25 and 0.43 mm (11%), and finally with 6% corresponding to particles smaller than 0.25 mm. This distribution of the particles produces an apparent density of 158 kg/m^3 in green conditions.

Empty Fruit Bunch

During the process of oil extraction, the EFB with the fruit was heated, and after being separated, the EFB was ground and milled to extract the oil adhering to it during the cooking process. Then, they were milled in length from 6 to 9 cm, which produced a separation of the vascular beams that comprise these types of monocotyledons, and therefore, this type of residue comes in a fibrous shape (Fig. 1c). The fiber length and its distribution were not possible because the milled material did not present vascular separation. The apparent density was 70 kg/m^3 in green conditions.

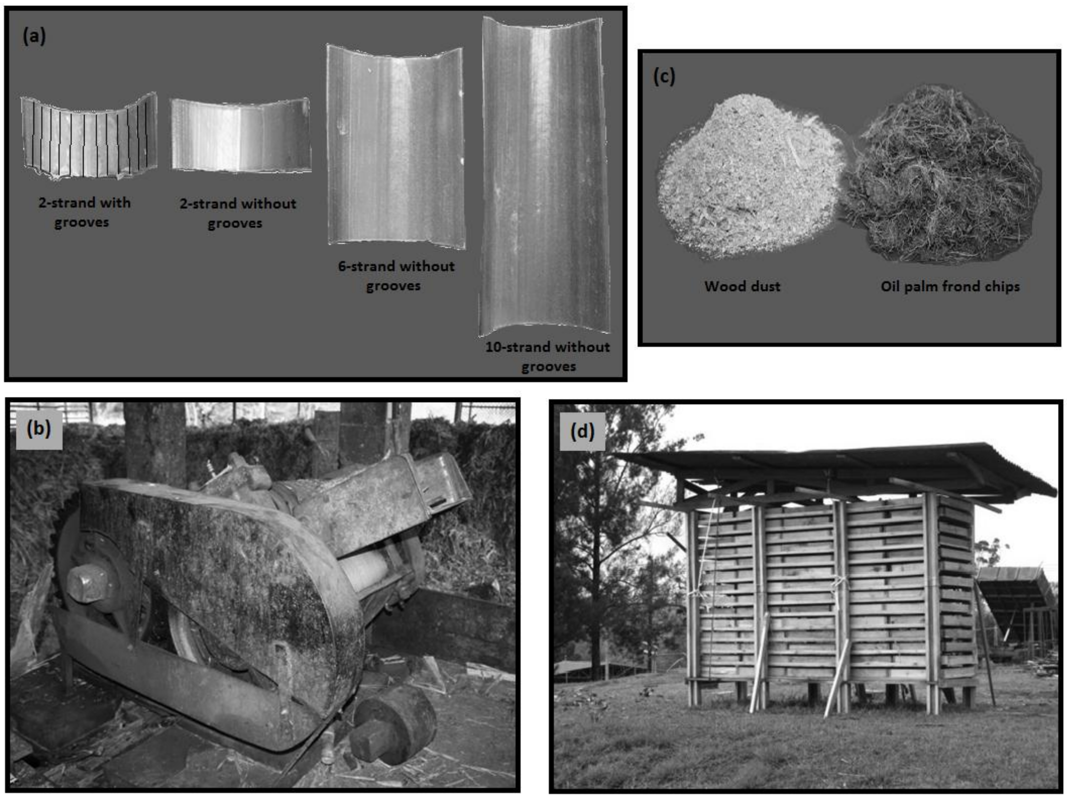

Fig. 1. Different lengths and treatment tested in pineapple leaves (a), shredder for sugar cane juice extraction used in pineapple leaves (b), shape of sawdust of *Gmelina arborea* and empty fruit bunches of oil palm (c), and wood trays used for stack of residues during air drying (d)

Drying Techniques

Air drying

Air drying (AD) took place during the months of February and April at the Costa Rica Institute of Technology campus (Cartago, Costa Rica), at an altitude of 1380 meters above sea level. The temperature during those months was between 17.6 and 19.3 ºC, and the relative humidity was 88% and 89.9%; precipitation was between 0 to 50 mm/month, and the average wind speed varied between 12 and 13.8 km/h.

Solar drying

The solar drying (SD) was performed in a 6 m^3 solar dryer (Salas *et al*. 2008). The dryer had a temperature collector (iron sheet) whose function was to capture solar energy and turn it into heat. Then, this heat moved inside the dryer through fans that move hot air around materials to be dried. The average air speed in this dryer varied from 1.5 to 2.0 m/s (Salas *et al*. 2008). In addition, the chamber had an electronic device that measured the temperature, as well as the external and internal relative humidity conditions.

Hot-air drying

The hot-air drying (HAD) of the materials was carried out in an experimental 2 m^3 capacity NARDI dryer. In this dryer, the speed of air movement through materials was 2 to 2.5 m/s.

Stacking the Residues during Drying and Conditions of Drying test

For stacking the residues during drying, containers were designed (trays) that allowed air circulation both under and over the materials. The trays were built from wood with 19 mm x 19 mm mesh bottoms. The dimensions of the trays were 50 cm in length, 67 cm wide, and 7 cm high. The stacking was done in such a way as to ensure a space of 25.4 mm between trays to allow for air passage between them in all three drying processes. To this end, a wooden device was built where the trays were placed with the material. The dimensions of this pile device were 180 cm high, 85 cm wide, and 250 cm long, which were located sufficiently far from the walls for a good air circulation in the AD and HAD. Even though the devices were built to place the trays residues in the trays, their volume and weight varied with the type of drying. In AD only one device was placed with 75 trays (Fig. 1d), and for SD and HAD two devices were placed with 75 trays each, or 150 trays total. The amount of material to be dried in each tray varied according to the material to be dried; 3.35 kg of GAD per tray, 2.11 kg of EFB per tray, 2.24 kg of stranded PL per tray, and finally 2.06 kg of PL crushed per tray. All of these weights were determined with materials in green conditions.

AD and SD were performed simultaneously so that there were no variations caused by climate conditions between both types of drying. Said processes took place during the months of February and April, which correspond to the dry season in the area of Cartago, Costa Rica. HAD was programmed at 80ºC and 5% in equilibrium moisture content into the chamber. The external temperature average was 24ºC with a maximum of 27ºC, and a minimum of 15ºC. The relative humidity was about 90% with a maximum of 100% and a minimum of 39%. The internal conditions in the SD chamber were 52% average relative humidity, with maximum and minimum values of 71% and 19%, and an average temperature of 29ºC with 57ºC as the maximum and 20ºC as the minimum.

Humidity Control

For the control of moisture content (MC) variation in the different residue types, four dry samples were used for testing per material and per type of drying technique. Since a granulated material was being tested, a textile bag was used to avoid material loss and allow air circulation. These bags were placed in trays at different heights in the drying devices to be able to monitor the MC in different parts of the chamber (3 bags in each side of the devices at lower, upper, and middle heights). The samples were weighed at the beginning of each drying process and twice throughout the day in the case of AD and SD. For HAD, the MC control samples were weighed every two hours with a precision of ±0.05. Subsequently, at the end of the drying process, these samples were placed in an oven at 103ºC (± 1) for 24 hours. The MC of the samples was calculated according to Equation 1. All of the determinations for different residues were determined according to ASTM E1756 (Standard test method for determination of total solids in biomass).

$$Moisture\ content\ (\%) = \frac{green\ weight - oven\ dry\ weight}{green\ weight} x\, 100 \qquad (1)$$

Statistical Analysis and Mathematical Modeling

A descriptive analysis was performed (average, standard deviation, maximum, and minimum values) for all of the response variables. Also, variable compliance with normal distribution supposition, homogeneity of variance, as well as the non-presence of extreme data was analyzed. Subsequently, an analysis of variance (ANOVA) was applied to test the differences in MC_i, MC_f, and drying time between the different types of drying techniques for each residue. The mixed linear model was used in the analysis of variance of the wood properties. The model included the following sources of variation: type of drying (d) in three level (AD, SD, and HAD), type of residue (r) in three levels (GAD, EFB, and PL), and the interactions between the type of drying technique and the type of residue. Four dry samples were used for testing per residues and per type of drying (3 type of residue, 3 types of drying, and 4 dry samples = 36 samples). The GLM procedure from SAS (SAS Institute Inc. Cary, N.C) was applied to estimate the significance of the sources of variation. The existence of the significant differences between the averages from MC_i, MC_f, or drying time were verified through Tukey's test ($P<0.01$). The drying time was evaluated for the total drying time (at the moment it reaches total of drying) and the time when it reached 13% (moisture content corresponding to equilibrium moisture content in the air drying system).

The relationship between the MC and the drying time was modeled applying a polynomial dependency (Equation 2), through a regression analysis. To carry out these analyses, the SAS 8.1 statistical program for Windows was used (SAS Institute Inc. Cary, NC),

$$Moisture\ content\ (\%) = a*(\text{time in h})^3 + b*(\text{time in h})^2 + c*(\text{time in h}) + d \qquad (2)$$

where *a*, *b*, *c*, and *d* are coefficients of the model.

RESULTS AND DISCUSSION

Moisture Content of Lignocellulose Residues

The MCi for each type of residue varied from 41.8% to 47.1% for GAD, from 51.0% to 53.9% for EFB, and from 87.6% to 79.9% for PL (Table 1). The highest MC_i values were shown by PL in the different drying conditions, followed by EFB, and the lowest MCi value was found in GAD, with a MC_i lower than 47% (Table 1). Regarding the MC_i for each type of residue, it was not found statistically different (value p>0.05) in the different drying techniques used. The PL in general, show a similar MC_i when they were cut into different strand lengths (Table 1). When being grooved to break the cuticle in the PL, the MCi remained statistically the same (value p>0.05) as when not being grooved. But, when the PLs were shredded, the MC_i is statistically lower (value p<0.05) than the PL with or without grooves for all drying techniques (Fig. 2a).

Table 1. Initial and Final Moisture Content and Drying Time for Three Different Lignocellulose Residues Treated by Three Different Kinds of Drying Techniques

Residues		Type of drying	Initial moisture content (%)	Final moisture content (%)	Drying time (hours)	Drying Time reached 13% in MC
Gmelina arborea sawdust		Air	47.1A ± 7.1	13.0A ± 1.2	220^{A}	220^{A}
		Solar	41.9A ± 3.5	4.9B ± 0.7	150^{B}	106^{B}
		Hot air	46.4A ± 2.2	6.6B ± 0.4	35^{C}	28^{C}
Empty fruit bunch		Air	51.0A ± 0.6	6.1A ± 0.6	147^{A}	114^{A}
		Solar	53.9A ± 4.4	7.9A ± 4.3	106^{B}	68^{B}
		Hot air	52.8A ± 2.0	5.9A ± 1.8	32^{C}	27^{C}
Pineapple leaves	2-strand with Grooves	Air	87.4A ± 0.3	5.4A ± 1.8	222^{A}	166^{A}
		Solar	87.0A ± 0.4	2.2B ± 1.6	125^{B}	65^{B}
		Hot air	86.4A ± 0.3	4.8AB ± 1.0	26^{C}	21^{C}
	2-strand without grooves	Air	86.8A ± 0.5	5.7A ± 0.9	222^{A}	171^{A}
		Solar	86.7A ± 0.2	2.8B ± 1.6	125^{B}	62^{B}
		Hot air	86.1A ± 0.4	3.2B ± 1.0	33^{C}	26^{C}
	6-strand without grooves	Air	86.5A ± 1.2	6.9A ± 2.2	314^{A}	242^{A}
		Solar	86.1A ± 0.6	5.7A ± 0.6	167^{B}	70^{B}
		Hot air	86.4A ± 0.4	5.5A ± 2.0	50^{C}	45^{C}
	10-strand without grooves	Air	87.6A ± 0.2	7.7A ± 1.3	342^{A}	277^{A}
		Solar	85.9A ± 0.3	7.9A ± 1.4	167^{B}	134^{B}
		Hot air	86.6A ± 0.8	8.7A ± 1.4	50^{C}	47^{C}
	Leaves shredding	Air	79.9A ± 1.0	4.8A ± 0.4	123^{A}	79^{A}
		Solar	80.7A ± 0.7	2.6A ± 1.4	77^{B}	60^{B}
		Hot air	80.5A ± 1.1	4.8A ± 3.2	35^{C}	21^{C}

Legend: Note: the values after ± are standard deviation and different letters between different drying methods are statistically different at 99%.

Regarding the MC_f, it was found that it varied from 2.3 to 14.0%. The lowest value was found in the SD of the 2-strand with grooves in the PL and the highest for GAD in the AD (Table 1). The different techniques of drying were applied to these residues and resulted in a MC_f that was statistically the same for EFB (6.6% on average), in the PL cut into 6-strand and 10-strand, and when the leaves were shredded. A statistical difference was found in the 2-strand with and without grooves in the PL. AD resulted in a MC_f statistically higher (value p<0.05) than SD, but statistically the same as HAD (value p>0.05) for the 2-strand with grooves in PL. Also, AD resulted in a MC_f

statistically higher (value $p<0.05$) than SD and HAD, these two being statistically the same in the case of the 2-strand with grooves in the PL (Table 1).

Regarding PL, there was no significant difference whether it was grooved or shredded (value $p>0.05$) compared to PL with no treatment (Fig. 2b); however, when the leaf was cut into 2-strand, 6-strand, and 10-strand without any treatment, the MC_f increased with the length increment (Fig. 2c).

Residues come from plants where water is necessary for the cellulose formation, which makes water a natural plant component (McKendry 2002a). But the amount of water for necessary growth varies with the type of plant (John and Thomas 2008). This can be proven in the results obtained with the three types of investigated residues. PL, being a plant with a fibrous beam, has fewer fiber bundles inside its structure and greater parenchyma tissue (Bismarck *et al*. 2005). The tissue where water is maintained produces a higher MC_i, whereas EFB, being a member of the Arecaceae family, has a structure of vascular beams with a moderate parenchymal tissue (Weiner and Liese 1990). Wood, on the other hand, features a fibrous cellular tissue in its structure (Skaar 1972), and therefore it has fewer spaces to store water, thus showing a lower MC than the other residues.

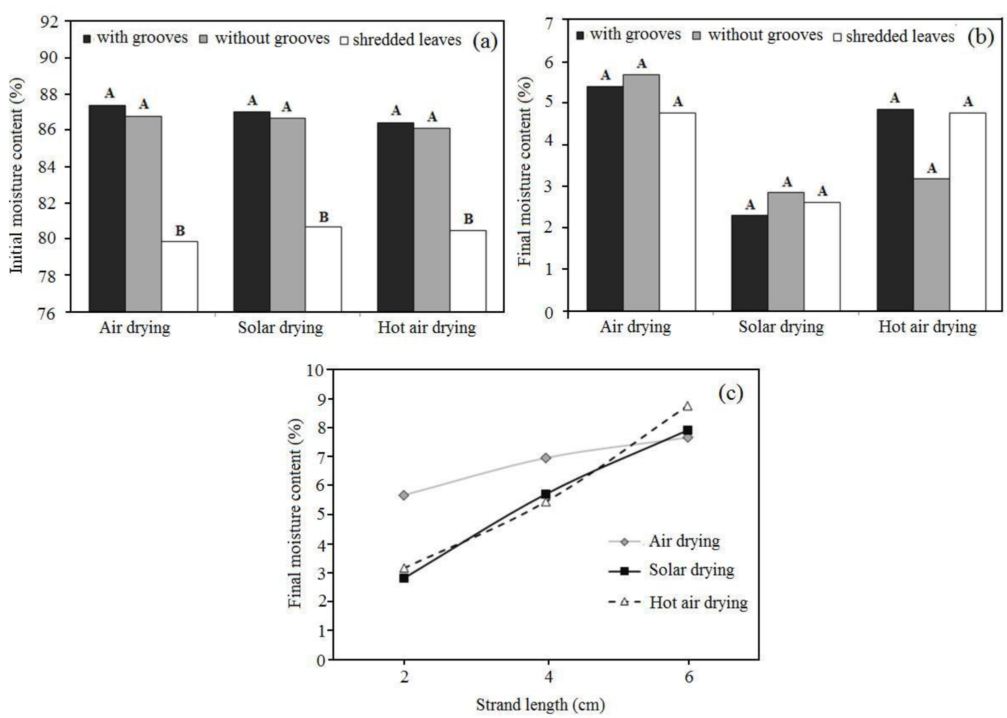

Fig. 2. Initial (a) and final moisture content (b) of pineapple leaves with and without grooves, crushing of leaves, and variation of final moisture content for different strand length (c). Legend: different letters between different drying methods in (a) and (b) are statistically different at 99%

When comparing these results to other studies on EFB, Ratnasingam *et al.* (2008) reports an MC of 67%, a value higher than the one obtained in this study (53.9%). Furthermore, in EFB drying studies using overheated steam, a 50% MC is reported (Shuit *et al.* 2009); this is higher than the present study as well. This difference in MC_i

(approximately 33%) is due to the fact that in previous studies, samples were collected from the fruit of the palm and immediately measured, whereas in this study, EFB was ground and then sampled after being milled.

In the case of PL, studies report a MC_i of 86% (Py *et al*. 1987), a value similar to the one obtained in the present study for PL without any treatment on the cuticle layer. For GAD, Muñoz and Moya (2008) report MC_i values of 170% on over-dried weight (approximate value between 60 and 70% on green weight base) for solid wood of *G. arborea*, this value being higher than the one found for GAD of the same species in this study. The difference can be explained by the fact that during the logging process, hardwood turns into a granulated material separated by the high speed of the tools, which aids in the humidity elimination at that moment, and therefore, in the reduction of MC between hardwood and granulated material. The lowest MC_i in shredder PL with respect to the strand PL of different lengths (Table 1) is attributed to the plant being crushed and shredded, and during this process a portion of water in the plant is lost or eliminated.

Regarding the MC_f, for all types of drying, values lower than 8% were reached with the exception of air-dried GAD, where the highest MC_f was reached (Table 1). This difference can be explained as the equilibrium moisture content (EMC) of each type of drying is different. HAD presented EMC conditions of 4%, while SD presented an EFB of approximately 8% for the site where it took place, whereas the environmental conditions for AD were between 13 and 16% of EMC. In the cellular structure and chemical constituents of wood or sawdust, a balance is established with the EMC of the environment, reaching, in this case, a MC_f on a dry base approximately similar to the environmental EMC. In the case of PL or EFB, the MC_f was lower than 8% for this type of drying technique; however, if the MC_f calculated on an over-dried weight was used instead of a green weight, as in this study, then the MC_f obtained was similar to GAD of 12.4% and 50% for EFB and PL, respectively. These results show that for PL and EFB, the rate of drying is very low in relation to the green weight, and thus low MC_f is to be expected.

Drying Times and Reduction of Moisture Content in Relation to Drying Time

As was expected, the drying times (total and reach 13% in MC) for all three types of residues were longer in AD, followed by SD, and finally HAD. For AD, the drying time in the 2-strand and 10-strand in PL produced longer drying times, but when PL was processed by the shredder, the air drying time was reduced (Table 1). It was observed that when PL were grooved, the water flowed through the cuticle; it did not affect the air drying time compared to samples without grooves. In the case of GAD, air drying times were longer than for EFB, and EFB time was similar to those in the cut PL (Table 1). For AD, the shortest time was found in the shredded PL (Table 1).

SD showed the same behavior as AD, but if the PL were shredded, the drying time will be shortened (Table 1). The grooves of the cuticle did not increase or reduce the drying time of PL (Table 1). The GAD drying time in SD was longer than the drying time for EFB. For HAD, the drying time for 2-strand with grooves in PL was shorter in relation to other strand lengths (2 cm, 6 cm, and 10 cm), and very similar to the one obtained when PL was shredded (Table 1). Also, an increase in the cut strand length increased the drying time in HAD. The GAD drying time was longer than EFB's; it was similar to the times obtained for PL with grooves and the hours of the shredded PL, but it still had a shorter drying time in relation to PL cut in 2-strand, 6-strand, and 10-strand. The EFB was the residue that showed the shortest drying time for HAD (Table 1).

It was observed that the drying time was related to the temperature in all of the three drying techniques. The shortest time was that for HAD, followed by SD, and finally AD (Table 1). The difference in the drying times can be explained by the fact that at higher temperatures, the MC was quickly reduced as a consequence of a higher evaporation of moisture, and a higher water movement speed inside the material, whereas for lower temperatures there was little evaporation and a lower water movement speed inside the materials. According to this, it is to be expected that AD had the longest drying time for all residues. Also SD had lower temperatures than HAD, and therefore a longer drying time.

A relationship between longer drying times and high MC_i was also observed. PL with high MCi values presented the longest drying time out of all of the drying techniques (Table 1). However, this behavior was different for EFB. These differences may be explained by the morphology of particles comprising each type of residue. The EFB has an apparent density of 70 kg/m^3 and GAD has a density of 158 kg/m^3. The lowest density allows a higher circulation of air, which does not happen with sawdust, a much denser, granulated material.

Longer drying times for PL can be attributed to specialized tissues that avoid moisture loss, like the cuticle, which is a water resistant and a protective tissue (Bartholomew *et al*. 2003). This tissue is accountable for the slow loss of moisture during the drying process of PL, for a longer drying time. It is there to favor water elimination in the case of PL, and consequently it is necessary to make modifications such as the following:

1. Grooves or incisions on the leaf cuticle that will aid in water elimination from the surface by reducing the waterproof barrier. However, for low temperatures and slow drying, as happening in AD or SD, these kinds of incisions apparently did not favor the drying times because no statistical differences were found between leaves with or without grooves. On the other hand, for conventional drying, grooves on PL reduced drying time by 7 hours in relation to leaves of the same size without grooves (Table 1).
2. Reducing the strand leaf length; obtained results showed that by reducing the strand length, drying time was also reduced (Table 1) because water flowed easily lengthwise, thus avoiding water trying to go through the cuticle.
3. Shredding in PL; this procedure produced a fully ripped cuticle, thus considerably reducing drying time (Table 1). With the exception of the 2-strand with grooves in PL in HAD, which presented a shorter drying time than that of the shredded PL. Hence, this treatment obtained the best results for PL in MC_f as well as drying times.

Mathematical Modeling of the MC Variation in Relation to Time

The MC reduction with time depends on drying conditions. The reduction was different in each of the tested materials and type of drying (Fig. 3). A lower drying rate was shown in low-temperature drying (AD), but it increased when the temperature was increased, such as for SD and HAD. Among them, SD had the lowest temperature, and therefore, a lower drying rate for moisture compared to HAD. The highest reduction in the drying time was achieved by EFB, followed by GAD, and then PL (Fig. 3).

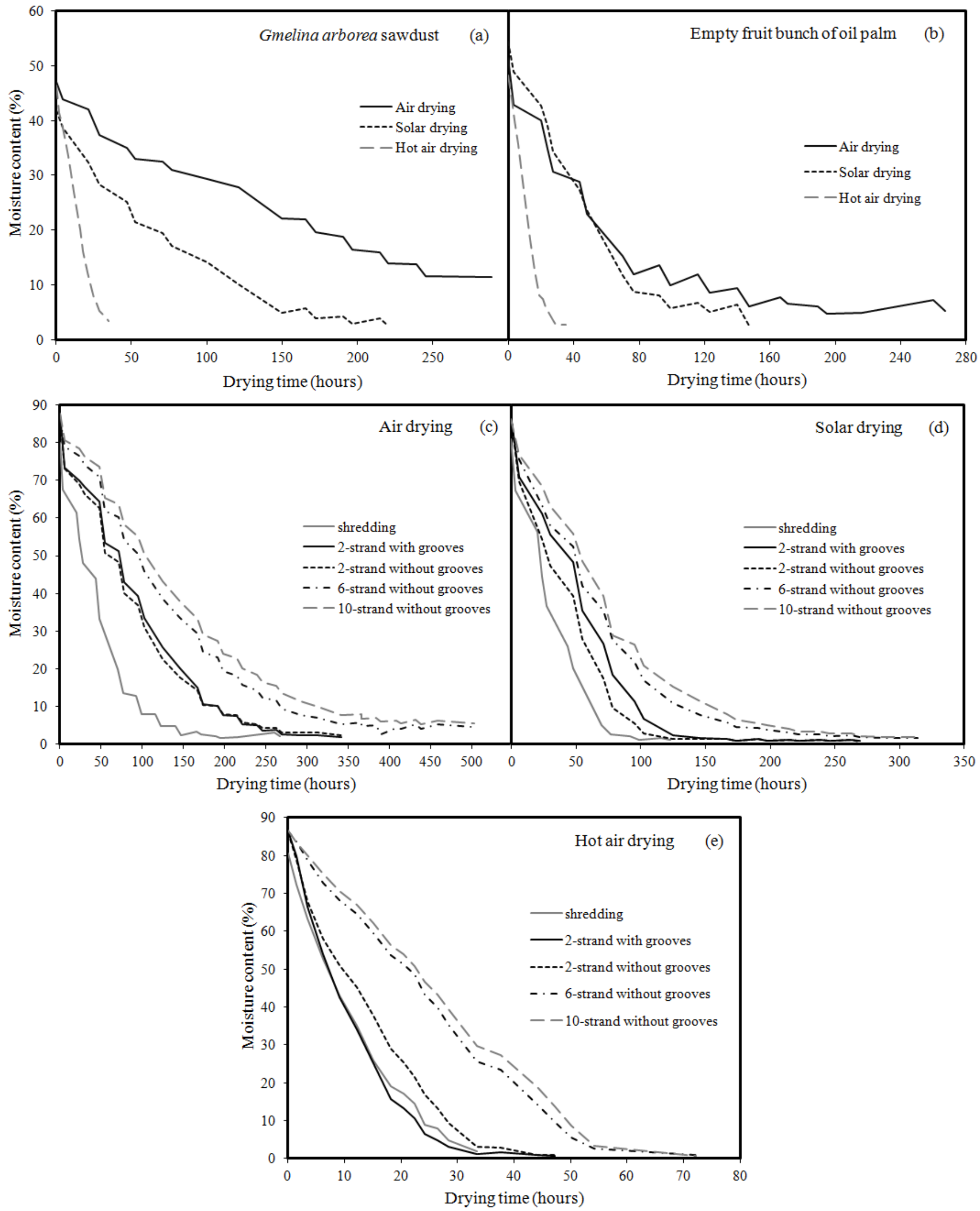

Fig. 3. Variation of moisture content during three different drying methods for *Gmelina arborea* sawdust (a) y empty fruit bunch (b) and pineapple leaves with different treatments during air dry (c) solar dry (d) and hot air dry (e)

For the different kinds of residue, it was found that the MC can be modeled with respect to time with a polynomial function having the following form: $MC = ax^3 + bx^2 + cx + d$. In Table 2, the different coefficients of the model are shown; the determination coefficients (R^2) as well as the percentage error for the different agro-forestry residues. In general, the different residues showed high R^2 (more than 0.97) with the exception of GAD in AD, which presented a value of 0.90 only. The percentage error of the residue models varied from 1.85% to 4.73%. The highest values were those for shredded PL in HAD and in 2-strand without grooves in PL cuts in SD, with an error of 4.73% and 3.84%, respectively. On the other hand, the lowest percentage errors were for GAD and 6-strand for HAD, which presented 1.86% and 1.85%, respectively.

Previous results showed that the proposed model ($MC = ax^3 + bx^2 + cx + d$) provided the best curve fitting for all three drying techniques. In this regard, Diamante *et al*. (2010), adjusting a mathematical model for the MC in relation to time for kiwi and apricots, established polynomial models similar to the one presented in this study. They describe their advantage in the following terms: "the proposed equation uses three constants that can easily be obtained through polynomial regression using statistical packages or even a programmable calculator. This is quite useful for researchers in developing countries with limited computer facilities. It should be noted however, that there is no theoretical base for a good equation curve fitting".

The decrease in the MC for solid wood has been modeled (De Souza *et al*. 1995) using an exponential relationship ($MC = a * \varepsilon^{-t*b}$), known as the Henderson and Pabis model. For instance, Moya *et al*. (2012), for *G. arborea* solid wood, reported the following model: $y = 69.19e^{-0.009x}$, with a coefficient of determination of 0.88 and an error of 35%, for HAD, a model different than the one found in this study for sawdust of the same species with a coefficient of determination of 0.99 and an error of 1.86%.

An important study in pineapple (Wang *et al*. 2005) found that the relationship between the MC and the time can be modeled by $MC = a*\varepsilon^{-t*b}$. However, these studies were carried out with a different part of the pineapple plant or different drying methods. Wang *et al*. (2005) dried fibers extracted from PL with a hot airflow drying device. Meanwhile, Wang *et al*. (2005) studied pineapple peel by varying the temperature and material thickness, and they utilized hot airflow drying again.

PL shows certain similarities with many vegetables. For this type of product in general, it is pointed out that the time variation with respect to drying can be modeled by the "Page Model" (Tunde-Akintunde and Ajala 2010). However, in spite of its similarity, the drying variation model is different from the Page model. The said difference can once more be attributed to the PL cuticle, which does not allow for water to be eliminated easily, and therefore, a different variation model may be applied.

Table 2. Coefficient of Model ($MC = ax^3 + bx^2 + cx + d$), Determination Coefficient, and Error of Mathematical Model for Drying of Different Lignocelluloses Residues

Lignocellulose residues		Type of drying	Coefficient of model				Determination coefficient (R^2)	Error (%)
			a	b	c	d		
Gmelina arborea sawdust		Air	-0.0000* (± 0.0000)	0.0006** (± 0.0002)	-0.21** (± 0.02)	41.02** (± 0.74)	0.9579	1.99
		Solar	-0.0000^{NS} (± 0.0000)	0.0015** (± 0.0003)	-0.41** (± 0.03)	40.73** (± 0.71)	0.9760	2.06
		Hot air	0.0010** (± 0.0002)	-0.0311* (± 0.0129)	-1.37** (± 0.19)	45.52** (± 0.72)	0.9854	1.86
Empty fruit bunch		Air	-0.0000** (± 0.000)	0.0033** (± 0.0002)	-0.65** (± 0.03)	48.19** (± 0.74)	0.9709	2.42
		Solar	-0.0000^{NS} (± 0.0000)	0.0039** (± 0.0011)	-0.82** (± 0.07)	50.28** (± 1.05)	0.9826	2.29
		Hot air	-0.0005^{NS} (± 0.0004)	0.0221^{NS} (± 0.0201)	-2.65** (± 0.30)	48.96** (± 1.13)	0.9691	2.91
Pineapple leaves	2-strand with grooves	Air	-0.0000^{NS} (± 0.0000)	0.0012** (± 0.0002)	-0.60** (± 0.03)	84.21** (±1.19)	0.9815	3.79
		Solar	-0.0000** (± 0.0000)	0.0057** (± 0.0003)	-1.22** (± 0.04)	84.99** (± 1.17)	0.9834	3.50
		Hot air	-0.0010** (± 0.0002)	0.1365** (± 0.0113)	-5.98** (± 0.21)	86.79** (± 1.01)	0.9900	2.93
	2-strand without grooves	Air	-0.0000** (± 0.0000)	0.0017** (± 0.0002)	-0.66** (± 0.03)	83.90** (± 0.95)	0.9873	3.04
		Solar	-0.0000** (± 0.0000)	0.0075** (± 0.0004)	-1.39** (± 0.04)	83.19** (± 1.28)	0.9781	3.84
		Hot air	-0.0000^{NS} (± 0.0001)	0.0456** (± 0.0099)	-3.83** (± 0.19)	83.42** (± 0.89)	0.9916	2.58
	6-strand without grooves	Air	-0.0000** (± 0.0000)	0.0009** (± 0.0000)	-0.49** (± 0.01)	87.13** (± 0.76)	0.9892	2.80
		Solar	-0.0000** (± 0.0000)	0.0039** (± 0.0002)	-0.98** (± 0.03)	84.67** (± 0.90)	0.9890	2.79
		Hot air	0.0002** (± 0.0000)	-0.0123** (± 0.0026)	-1.57** (± 0.07)	85.01** (± 0.56)	0.9956	1.85
	10-strand without grooves	Air	-0.0000** (± 0.0000)	0.0007** (± 0.0000)	-0.44** (± 0.01)	88.32** (± 0.67)	0.9916	2.47
		Solar	-0.0000** (± 0.0000)	0.0027** (± 0.0002)	-0.82** (± 0.02)	85.43** (± 0.72)	0.9937	2.24
		Hot air	0.0002** (± 0.0000)	-0.0150** (± 0.0028)	-1.37** (± 0.08)	85.28** (± 0.61)	0.9947	1.99
	leaf crushing	Air	-0.0000** (± 0.0000)	0.0058** (± 0.0003)	-1.16** (± 0.04)	77.65** (± 0.97)	0.9845	3.16
		Solar	0.0000* (± 0.0000)	0.0024^{NS} (± 0.0019)	-1.31** (± 0.09)	79.32** (± 1.22)	0.9892	3.12
		Hot air	0.0007^{NS} (± 0.0008)	0.0126^{NS} (± 0.04)	-3.55** (± 0.55)	78.81** (± 1.81)	0.9722	4.73

Legend: **statistically different at 99%, * statistically different at 95% and NS=not statistically different.

CONCLUSIONS

1. Out of the residues investigated, EFB presented the shortest drying times (with the exception of ground PL in AD and SD) for the three types of drying techniques applied, turning it into a material with great potential for future uses, such as fuel for heat production.
2. By reducing the length of the PL, there was a higher water flow in a longitudinal direction, which resulted in a shorter drying time; specifically leaves cut in 2-strands length had the shortest drying times. Furthermore, by applying some kind of treatment to the PL, such as grooves to the cuticle or shredding of the leaves, the drying times were reduced.
3. For the MC variation modeling, it was found that the 3 degree polynomial model ($MC = ax^3 + bx^2 + cx + d$) provided the best curve fitting for residues in all three drying processes. The application of this experimental model can be used to predict drying curves for GAD, PL, and EFB.

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