Energy Balance for Three Lignocellulosic Residues Using Different Drying Techniques

Roger Moya,[a]* Carolina Tenorio,[a] and Brian Bond [b]

The main goal of this research was to establish the energy balance from the drying of oil palm empty fruit bunches (EFB), pineapple plant leaves (PL), and sawdust from *Gmelina arborea* (GAD). Three drying techniques (air, solar, and hot air drying) were tested. The initial moisture content (MCi), drying time, moisture content (MC) variation with time, transformation energy, transportation and drying energy, drying critical point, and the energy balance were measured. MCi was higher for PL (over 79%), followed by EFB (over 47%), and GAD (under 47%). Drying time varied from 27 to 342 hours depending on the technique used. PL presented the longest drying time, followed by GAD, and finally EFB. The transformation energy input was only applied to PL, and the values ranged from 0.041 to 0.09 kWh/kg. Energy used for transportation ranged from 0.051 to 0.090 kWh/kg. Energy consumption ranged from 0.20 to 1.90 kWh/kg, and its mathematical model regarding MC was $\beta_1 MC^3+\beta_2 MC^2+\beta_3 MC+\beta_4$ (polynomial) or $\beta_1 \ln(MC)+\beta_2$ (logarithmic). A critical value of MC was found, where an inflection of energy consumption occurs during the drying process for all residues. The critical MC for GAD was 10%. For EFB it varied from 11 to 13%. For PL it varied from 4% to 13%. The best energy balance was obtained for GAD and EFB (4.0 to 4.5 kWh/kg) when MC was less than 10%. The best energy balance for PL was obtained when MC varied from 30 to 40%.

Keywords: Energy input; Caloric power; Energy gain; Bioenergy

Contact information: a: Instituto Tecnológico de Costa Rica, Escuela de Ingeniería Forestal, P.O. Box: 159-7050 Cartago-Costa Rica, Phone: (506) 2550-2433 / Fax: (506) 2591-3315; b: Department of Sustainable Biomaterials, Virginia Tech, Blacksburg, VA USA.
** Corresponding author: rmoya@itcr.ac.cr*

INTRODUCTION

It is estimated that around 11,764 tons of waste are produced in Costa Rica daily, of which 86% (10,122 ton/day) are agro-industrial residues and only a small percentage of these residues are utilized (GFA Consulting Group 2010). Due to problems associated with the environment and global warming, many regions of the world have developed better uses for residues from the lumber industry (sawdust) and agricultural crops (Askew and Holmes 2001; Offerman *et al.* 2011; Shuit *et al*. 2009). Using these lignocellulosic residues as energy-generating materials is beneficial, since renewable residues are used to produce energy (Offerman *et al*. 2011). However, it is often necessary to implement a pre-treatment step for biomass in order to reduce its high moisture content (Ulloa *et al*. 2004; McKendry 2002).

Biomass drying has attracted the interest of researchers worldwide (Fagernäsa *et al*. 2010). Much of this research has focused on the design of dryers, the development of mathematical drying models, and kinetic curves (White *et al*. 2011). However, the actual process of drying these materials is more complex than what has been modeled. For example, the energy expenditures for the pretreatment of materials to facilitate drying have not been considered. Also, it has been mentioned that an increasing drying temperature increases the drying rate and decreases the drying time (Chen *et al.* 2012, Artiaga *et al*. 2005).

In Costa Rica, the cost of 1 kWh of industrial use is equivalent to 0.16 United States Dollars (USD) (La Gaceta 2012), and this cost represents a high proportion in the total cost of drying process. Energy can also be spent to reduce the size of residues for faster drying (Anttila *et al*. 2011). The most efficient material for providing energy is one that has the best energy balance, which can be defined as the difference between energy gained (energy input) and energy expended during pre-treatment and processing of waste (energy consumption or energy used). Also, there is the lack of knowledge on the energy potential and the energy balance when drying residues come from different agricultural crops. Therefore, the objective of this study was to establish the energy balance for three types of lignocellulosic residues generated in Costa Rica (empty fruit bunches, pineapple plant leaves, and *Gmelina arborea* sawdust) when using three drying techniques: air, solar, and hot air drying. The optimum moisture content, which represents the highest energy balance reached, was determined for each drying technique and residue.

MATERIAL AND METHODS

Materials

Three different types of lignocellulosic residues from agricultural and forest industries were investigated: pineapple leaves (PL) from a cropped plantation, fibers from the empty fruit bunch of oil palm (EFB), and sawdust of *Gmelina arborea* (GAD). EFB and GAD did not receive any pre-treatment because they had adequate size, but PL was processed using several pre-treatment methods to promote faster drying. These pre-treatments consisted of:

- Processing to three different particle sizes: PL were cut into strands of 2 cm, 6 cm, and 10 cm in length. The epidermis and cuticle layer were maintained for all particle sizes, which were named as follows: 2 cm as 2-strand without grooves, 6 cm as 6-strand without grooves, and 10 cm as 10-strand without grooves. Also, PL with grooves was tested again: PL were cut to particle size of 2 cm and grooves were opened in the underside to break the cuticle (2-strand with grooves). The grooves were drawn 5 mm apart with nails. The grooves were applied to allow water flow.

- Shredded PL: The pineapple plants were pulled up, their roots were removed, and the material crushed in a shredder commonly used for the extraction of sugar cane juice.

Sawdust was directly extracted from a sawdust evacuation system for a circular sawing at a sawmill. Empty fruit bunch (EFB) material was taken from the oil extraction process, in which the oil is extracted from the bunch through a hot water and threshing process in a mill. This type of residue comes in a fibrous shape. More information about the preparation these materials can be found in Tenorio and Moya (2012).

Drying Techniques, Residue Stacking, and Moisture Content Control

Three drying systems were tested: air (AD), solar (SD), and hot air drying (HAD). Average temperatures are detailed in Table 2. When stacking the residues for drying, containers were used that allowed air circulation under and over the materials. Trays were separated by a space of 25.4 mm to allow airflow. Four dry samples were used to determine the moisture content (MC) variation in each residue type and drying system. A textile bag was used to contain the material, avoid material loss, and allow air circulation both over and under the material. The bags were placed on trays at different heights (top and lower part in each side of pile) in the drying systems so that the MC in different parts of the chamber (3 bags in each side of the devices at lower, upper, and middle heights) could be measured. The samples were weighed at the beginning of each drying process and twice throughout the day for AD and SD until it reached constant weight. For HAD, the MC control samples were weighed every 2 h, since the weight loss for the material studied is faster than other methods evaluated. Tenorio and Moya (2012) describe in detail the drying systems, stacking methods, and moisture content control used in this work.

Energy Input for Transformation, Transportation, and Drying

The energy used for transformation, transportation, and drying of materials was measured in kilowatts per hour (kWh) and will henceforth be termed energy input. PL residue was the only material requiring pre-treatment, since GAD and EFB are residues from industrial processes. Two different pre-treatments were tested and evaluated for PL, which consisted of chipping and shredding the material with a grinder. The amount of diesel fuel used during the process of chipping pineapple plants was measured over an 8-h period. For both pre-treatments, the energy input was determined by relating the energy consumption in the processing to the weight of the processed material (Equation 1). For the process using diesel, a density factor of 0.85876 kg per each liter of fuel and combustion heat of 42900 kJ per kg was used (Recope 2012). The energy used by the grinder was measured by placing an electricity consumption gauge, measurements in kWh, at the main inlet of the control panel during its operation.

Energy input for transportation was then calculated for each of the residues. The apparent density of the materials and fuel consumption used in transportation was measured for each kilometer transported. The apparent density of the materials was determined by weighing 5 samples of known volume (Table 2). With this information, density parameter (mass/volume) was calculated. The distances the material was transported was measured to be 150 km for all residues. Fuel consumption was measured according to the amount of liters used by a truck to carry 33 m^3 across the previously established distances. Then, the energy spent in transportation was calculated using the density factor of 0.85876 kg per liter of fuel and combustion heat of 42900 kJ per kg (Recope 2012). Finally, the energy input for transportation was calculated using Eq. 2.

The energy input for solar and conventional drying processes was determined by measuring the electricity average consumption, kWh, used for drying of each residue. A Schneider Electric model PM200 digital gauge was used to record electricity consumption, and it was measured every time the samples were weighed. The electricity input was determined as (i) the total electrical energy used for drying and (ii) electricity consumed at each of the different MCs measured. The energy used per drying process was expressed per kilogram of material. The accumulated consumption was estimated by relating the consumption in kWh of each of the measurements and material weight (kg) at the moisture content at the time measures were taken. Besides studying the variation of energy consumption in relation to MC, the total energy consumption for drying was also presented.

$$\text{Energy input for pre-treatment (kJ/kg)} = \frac{\text{Diesel consumption (L)} * 36840.4\ \text{(kJ/L)}}{\text{Processed material mass (kg)}} \tag{1}$$

$$\text{Energy input for transportation (kJ/kg)} = \frac{\text{Diesel consumption (L)} * 36840.4\ \text{(kJ/L)}}{\text{Material apparent density (kg/m}^3\text{)} * \text{Transportation capacity (m}^3\text{)}} \tag{2}$$

Energy Gain

The energy gained by reducing the moisture content for each material was determined by measuring the heating value at varying moisture contents. Each residue was ground green to obtain approximately 100 g of material of less than 600 µm in size. The samples were then passed simultaneously through 420 µm (#40 mesh) and 600 µm (#60 mesh) screens, where the particle size used was the one that remained between the meshes. The samples were then spread out and dried at room temperature for 15 h. During drying, approximately 8 g of material was extracted every 30 min with a small spoon, and the heating value was measured to determine the variation in heating value at varying MC. The samples were then divided into two parts: 2 g for the determination of MC and three samples of 2 g each for determining the heating value. Heating value was determined based on the amount of total energy that an organic material emits and was determined using Parr's calorimetric test, ASTM D-5865 (ASTM 2003).

Energy Balance

The total energy input for different MC was determined for each weight unit of dried material (Eq. 3). First, the energy consumption per weight unit (kWh/kg) and MC was modeled. A polynomial model was used (energy input = $\beta_1 MC^3 + \beta_2 MC^2 + \beta_3 MC + \beta_4$) for GAD and EFB in the solar and hot air drying processes, as well as PL in hot air drying. A logarithmic model was used (energy input = $\beta_1 \ln(MC) + \beta_2$) for PL that was solar dried. These models were obtained by STATISTICA (Stat soft Inc). To calculate the total energy consumption for each MC, the transformation and transportation expenditures were then added (Eq. 3). These models were selected according to the determination coefficient (r^2). Different models were tested, and those selected had the highest values of r^2. In the residue energy generation calculation, the heating values from Parr's calorimetric test were used at different MC (ASTM 2003). This generated a *Gain Energy* = *ax* + *d* model. Later on, the heat generation at the same MC established by the energy input was calculated. Finally, the energy balance was calculated for the different moisture contents through the difference between energy gain and input (Eq. 4),

$$\text{Energy balance} \left(\frac{\text{kJ}}{\text{kg}}\right) = \text{Energy input} \left(\frac{\text{kJ}}{\text{kg}}\right) - \text{Enery output total} \left(\frac{\text{kJ}}{\text{kg}}\right) \tag{3}$$

$$\text{EC total} \left(\frac{\text{kJ}}{\text{kg}}\right) = \text{EC transformation} \left(\frac{\text{kJ}}{\text{kg}}\right) + \text{EC transportation} \left(\frac{\text{kJ}}{\text{kg}}\right) + \text{EC drying} \left(\frac{\text{kJ}}{\text{kg}}\right) \tag{4}$$

where *EC* is energy consumption and MC is moisture content.

Statistical Analysis

A descriptive analysis was performed (average, standard deviation, maximum, and minimum values) for all response variables. Normality was verified for each variable in addition to testing for the presence of outliers. Subsequently, an analysis of variance (ANOVA) was applied to test differences in initial moisture content (MCi), final moisture content (MCf), and drying time between the different types of drying techniques for each residue. A mixed linear model was used in the analysis of variance of wood properties. The model included the following sources of variation: type of drying (d) in three levels (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 type of residue. Four dry samples were used for testing per residue and per type of drying (3 types of residue, 3 types of drying, and 4 dry samples = 36 samples total). The general linear model (GLM) procedure from SAS (SAS Institute 1997) estimated the significance of sources of variation. The existence of significant differences between the averages from MCi, MCf, or drying time was verified through Tukey's test ($P < 0.01$).

In order to establish the moisture content where an inflection of energy consumption occurs, a linear regression ($y = ax + b$) was applied in two segments. The first segment corresponds to the range of the highest MC, up to a MC where the slope of the line does not show any change. The second segment corresponds to the MC where the first segment ended to approximately 4%-6% MC. The point where the two segments intercept is called the critical point of drying. The total energy input at a determined MC was established for each weight unit of dried material (Eq. 3).

RESULTS

Energy Consumption, its Variation and Drying Critical Point

EFB had the highest transportation energy, with 0.0947 kWh/kg, followed by shredded and chipped PL, both with 0.0898 kWh/kg, and finally, GAD with 0.0506 kWh/kg (Table 1). The transformation energy for PL varied from 0.0406 kWh/kg to 0.0898 kWh/kg with the lowest value for shredded PL and the highest for chipped PL of 2-strand.

Table 1. Energy Consumption for Transportation and Transformation of Each Type of Residue

Lignocellulosic Residue	Transformation Energy Consumption (kWh/kg)	Transportation Energy Consumption (kWh/kg)
Sawdust	-	0.0506
Empty fruit bunch	-	0.0947
PL 2-strand with grooves	0.0898	0.0898
PL 2-strand without grooves	0.0898	0.0898
PL 6-strand without grooves	0.0898	0.0891
PL 10-strand without grooves	0.0898	0.0856
PL shredded pineapple leaves	0.0406	0.0898

The values for total energy used for solar and hot air drying are shown in Table 2. It is notable that the highest energy used for consumption for drying was for 2-strand PL with grooves in SD (1.87 kWh/kg) and for 10-strand PL without grooves in HAD (1.90 kWh/kg). In addition, other values for high energy consumption in SD were given for GAD and EFB, 2-strand PL without grooves with values of 0.22 kWh/kg, 0.36 kWh/kg, and 1.46 kWh/kg, respectively. With HAD, high energy inputs of 1.68 kWh/kg and 0.89 kWh/kg were measured from 6-strand PL without grooves and shredded PL, respectively (Table 2).

Regarding energy consumption in relation to MC, as would be expected, more energy was consumed for all drying methods and residues in the course of achieving lower moisture contents (Fig. 1).

Table 2. Total Energy Consumption for Lignocellulosic Residues Treated by Different Drying Techniques

Lignocellulosic Residue		Apparent Density (kg/m^3)	Drying Technique and Average Temperature (°C)		
			Air 20.5	Solar (SD) 31.0	Hot Air (HAD) 80.0
			Total Energy Consumption (kWh/kg)		
Gmelina arborea sawdust (GAD)		157.9	-	0.22	0.20
Empty Fruit bunch (EFB)		70.0	-	0.36	0.28
Pineapple leaves (PL)	2 –strand with grooves	98.5	-	1.87	1.10
	2 –strand without grooves	98.5	-	1.46	1.37
	6–strand without grooves	92.5	-	1.57	1.68
	10 –strand without grooves	89.9	-	1.76	1.90
	Shredded	87.7	-	0.78	0.89

GAD and EFB energy use values were lower than 0.65 kWh/kg (Fig. 1a). Another result was that the energy input of SD in GAD was similar to that found for HAD. For EFB, SD had a slight increase in energy use in relation to HAD in an oven (Fig. 1a). For PL, 10-strand without grooves had the highest energy input values in HAD, followed by 6-strand without grooves and 2-strand without grooves. Shredded PL had the lowest values for energy input (Fig. 1b). The energy requirement for pineapple leaves in SD was close to 4 kWh/kg (Fig. 1c) For SD, 2-strand PL with and without grooves had the highest drying input values, followed by 10-strand PL without grooves, 6-strand PL without grooves, and finally shredded PL (Fig. 1c).

In the model for the energy input with varying MC for the different residues, two types of relationships were found: one polynomial (energy input = β_1MC^3 + β_2MC^2 + β_3MC + β_4) for GAD and EFB in SD and HAD, and PL in HAD, and the other logarithmic (energy input = $\beta_1$ln(MC) + β_2) for PL in SD. Table 3 shows the different model coefficients, the determination coefficients (r^2), and the percent error in the different lignocellulosic residues and in the two types of models.

The residues presented high r^2 values (higher than 0.92) for both models, with the exception of 2-strand PL both without grooves (r^2= 0.84) and with grooves (r^2= 0.82). The error percentage was lower in the polynomial models (GAD and EFB in SD, HAD drying, and PL in HAD) compared to the logarithmic one (PL in SD). In the polynomial models, the error varied from 1.13% to 14.27% and in the logarithmic model from 10.78% to 58.54%. The highest values were those in 2-strand PL with and without grooves with an error of 14.27% and 9.71%, respectively, for the polynomial model, and 58.54% and 52.48% for the logarithmic model. However, the lowest error percentages were from GAD and EFB in HAD, which presented 1.13% and 3.27% for the polynomial model. The lowest value in the logarithmic model was 10.78%, introduced by the shredded PL.

When MC decreased, the energy input increased in all drying methods and all residues.

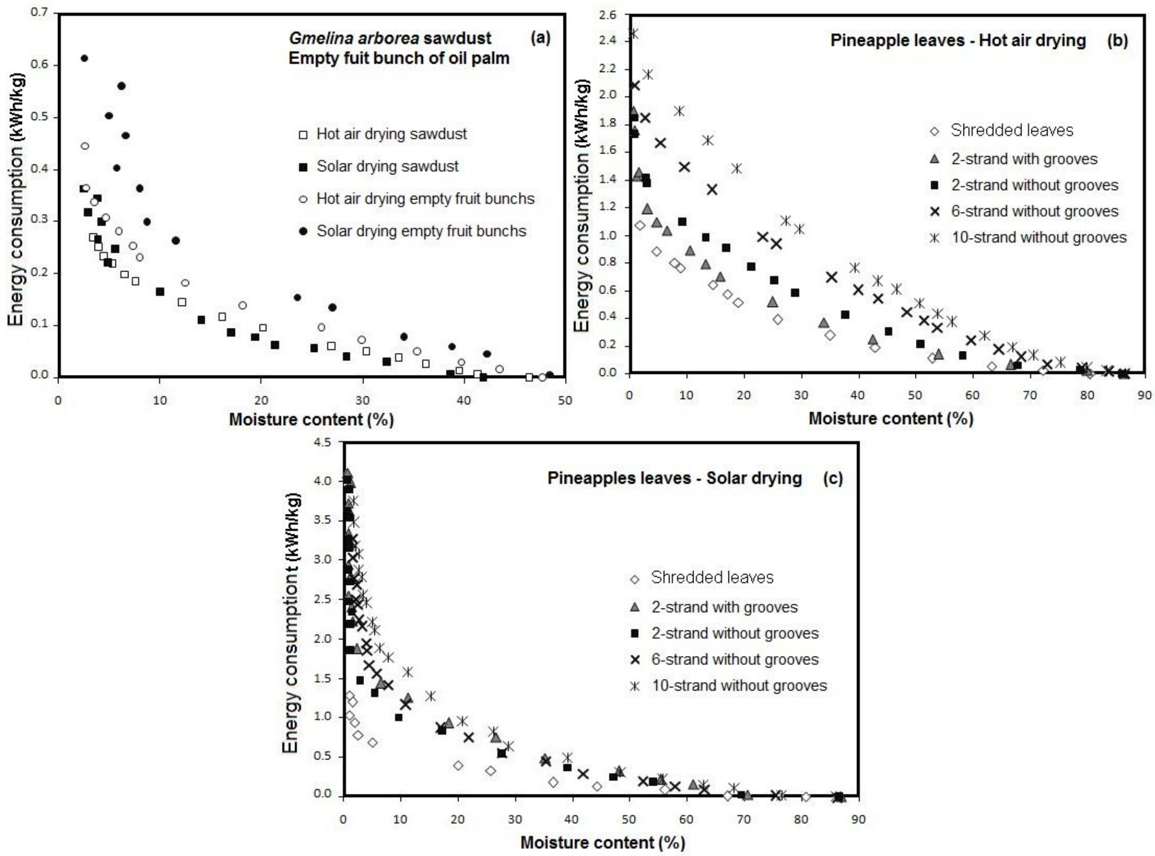

Fig. 1. Energy consumption (kWh/kg) for each residue per drying technique. Hot air drying (HAD) and solar drying (SD) of GAD and EFB (a), Hot air drying of pineapple leave (PL) (b), and solar drying (SD) of pineapple leaves (c).

The critical point for energy input was established (Fig. 2), and MC, the factor where the energy input increases, varied according to residues:

1. For sawdust, the critical point for SD and HAD was at MC approximately 10% (Fig. 2a).
2. The critical point for EFB was close to MC of 11% for HAD and approximately 13% for SD (Fig. 2b).
3. The critical point for 2-strand PL without grooves was at MC of 5% for HAD and 3% for SD (Fig. 2c).
4. The critical point for 2-strand PL with grooves was at MC of 8% for HAD and 4% for SD (Fig. 2d).
5. For 6-strand PL and 10-strand PL, both without grooves, and shredded PL there was no critical point for HAD. The critical point for SD occurred at MC of 9%, 9%, and 8%, respectively (Fig. 2e, f, and g).

Table 3. Model Coefficients, Determination Coefficients, and Percentage Error of the Energy Input Variation and Moisture Content for Lignocellulosic Residues

Model	Lignocellulosic Residue	Type of Drying	Coefficient of Model				Determination Coefficient	Error (%)
			β_1	β_2	β_3	β_4		
Polynomial $\beta_1MC^3+\beta_2MC^2+\beta_3MC+\beta_4$	GAD	SD	-0.00**	0.00**	-0.03**	0.42**	0.96	2.50
		HAD	-0.00**	0.00*	-0.02**	0.31**	0.99	1.13
	EFB	SD	-0.00**	0.00**	-0.05**	0.64**	0.92	6.50
		HAD	-0.00**	0.00**	-0.03**	0.44**	0.94	3.27
	2-strand PL with grooves	HAD	-0.00**	0.00**	-0.08**	1.61**	0.95	14.27
	2-strand PL without grooves		-0.00**	0.00**	-0.06**	1.68**	0.97	9.71
	6-strand PL without grooves		-0.00**	0.00**	-0.05**	2.01**	0.99	5.93
	10-strand PL without grooves		-0.00**	0.00**	-0.06**	2.41**	0.99	5.85
	Shredded PL		-0.00^{NS}	0.00^{NS}	-0.02**	0.97**	0.94	9.23
Logarithmic $\beta_1\ln(MC)+\beta_2$	2-strand PL with grooves	SD	-0.68**	0.03**	-	-	0.82	58.54
	2-strand PL without grooves		-0.71**	2.93**	-	-	0.84	52.48
	6-strand PL without grooves		-0.74**	3.08**	-	-	0.97	19.63
	10-strand PL without grooves		-0.89**	0.02**	-	-	0.97	19.90
	Shredded PL		-0.26**	1.15**	-	-	0.95	10.78

Note: **statistically significant at 99%, *statistically significant at 95%, and NS = non significant. GAD = *Gmelina arborea* sawdust, EFB = empty fruit bunches, PL = pineapple leaves, SD = solar drying, HAD = hot air drying

Energy Balance

The variation in energy balance for different residues is shown in Fig. 3. The behavior of the energy balance was different for each drying and residue type. In the case of HAD of PL, from the green condition (60 to 70%) up to a MC equivalent to 20%, the energy input for the drying process slightly increased. When attempting to reach values of MC lower than 20%, the energy balance decreased to values between 2 kWh/kg and 3 kWh/kg; however, this decrease was minor for shredded pineapple (Fig. 3). In the case of GAD and EFB, the behavior was different; the energy balance increased when reducing the MC (Fig. 3a). Concerning the different treatments of PL, shredded PL presented the highest energy balance at MC of 25% (3.35 kWh/kg); 2-strand PL without grooves at MC of 35% (3.21 kWh/kg); 2-strand with grooves at MC of 20% (3.39 kWh/kg), and 6-strand PL without grooves at MC of 50% (3.10 kWh/kg). In the case of GAD, the highest energy balance value was observed at MC of 3% (4.38 kWh/kg), and for EFB at MC of 5% (4.15 kWh/kg, Fig. 3).

In SD (Fig. 3b), PL presents the highest energy balance between 25 to 35% MC. Shredded and 2-strand PL without grooves present their highest balance at 25% with 3.47 kWh/kg and 3.64 kWh/kg, respectively. 2-strand PL with grooves and 6-strand without grooves PL at 30% MC show the highest energy balance, with 3.37 kWh/kg and 3.42 kWh/kg, respectively. Finally, for 10-strand without grooves, the highest energy balance is 3.46 kWh/kg at 35% MC (Fig. 3a). Just like with the previous drying (HAD), GAD and EFB reached their highest balance at 0% and 5% with values of 4.24 kWh/kg and 3.97 kWh/kg, respectively.

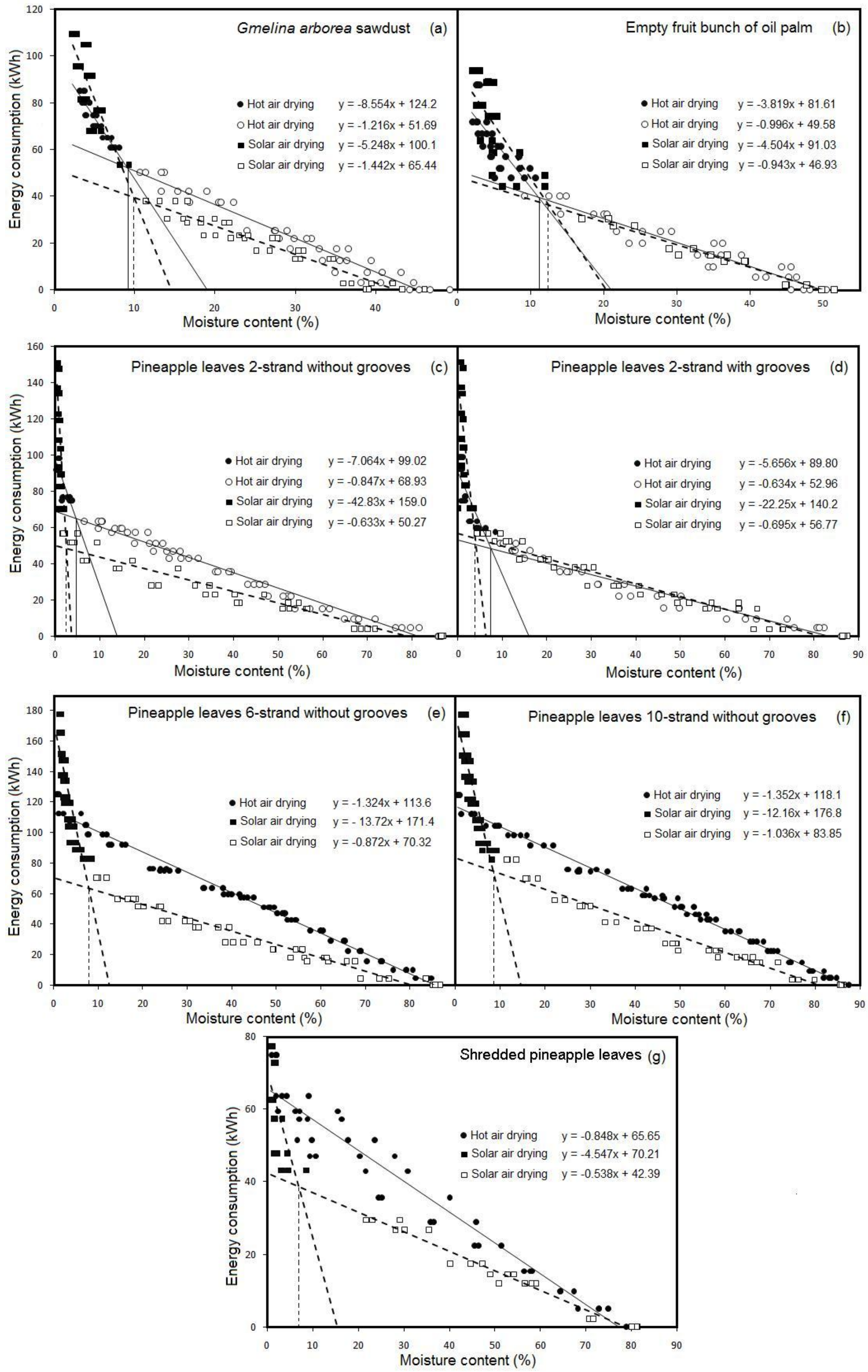

Fig. 2. Critical point in energy consumption (kWh) for hot air and solar drying of *G. arborea* sawdust (a), empty fruit bunch of oil palm (b), pineapple leaves 2-strand without grooves (c), pineapple leaves 2-strand with grooves (d), pineapple leaves 6-strand without grooves (e), pineapple leaves 10-strand without grooves (f), and shredded pineapple leaves (g)

Regarding air drying (Fig. 3c), all the residues (PL, GAD, and EFB) obtained their highest energy balance at 3% MC, where the 2-strand with and without grooves, the 6-strand, and 10-strand without grooves have the same energy balance value of 4.18 kWh/kg; shredded PL of 4.15 kWh/kg, GAD of 4.71 kWh/kg, and EFB of 4.59 kWh/kg.

DISCUSSION

Energy Consumption, Variation, and Critical Point in Drying

The use of PL can be a high-energy input activity, as the operations of harvesting and transportation not only demand energy, but can also cause possible pollution problems (McKendry 2002). Stranded PL consumed twice the energy of shredded PL (Table 1). This increase can be attributed to the fact that the second process used a stationary shredder adapted to the processing of sugar cane, and consumes more or less energy. However, shredded PL presented shorter total drying time and lower energy input to reach different MC when compared to stranded PL (Table 2 and Fig. 1).

As expected, the energy input for transportation was related to apparent density and the transportation distance (Hamelinck *et al*. 2005). The lowest energy input was observed for the biomass with the highest apparent density, whilst the highest energy input was for EFB, which presented the lowest apparent density (Table 2).

The drying times were longer for biomass with high MCi (Table 2), which makes it necessary to rely on increased energy to properly dry it. For example, GAD with the lowest MCi had the lowest total energy input (Table 2), and the energy input was the lowest compared to all the residues and drying techniques studied (Fig. 1). The highest energy input (Table 2 and Fig. 1) occurred for PL, which can be explained by the specialized tissues (cuticle) that prevent moisture loss (Bartholomew *et al*. 2003). However, the energy input can be reduced when PL is treated using a method to break the cuticle on the leaf's surface. For example, in this research, when the PL was cut to smaller pieces and ripped through grooves, the energy input for drying decreased (Table 2, Fig. 1). There was a relevant reduction of 50% in energy input during HAD when PL is shredded in a mill in comparison with leaves that were not shredded.

Moreover, it was found that the drying time decreased with increasing temperature, and this decrease was associated with an increased energy input (Table 2). However, our results disagreed; the reduction of drying time does not occur with the energy input. SD, with lower temperature than HAD, showed higher energy input (Table 2). This is likely due to the high-energy consumption in ventilation fans. Another aspect that may affect the high-energy input in SD is the irregular temperature inside the chamber and the lack of high temperatures available in the process. The highest temperatures, which were close to 50 ºC, were only produced for short periods of time, resulting in adequate moisture flow in biomass. The higher energy input required for SD should be considered when selecting a drying technique, as one of the objectives of SD is reducing energy input through alternate energy sources such as solar radiation (Sharma *et al*. 2009).

The results showed that the polynomial model proposed for Energy input ($Y = \beta_1 MC^3 + \beta_2 MC^2 + \beta_3 MC + \beta_4$) provides the best fitting curve for the GAD, EFB, and PL in HAD, similar to what was found for the MC variation with the time in the same residue (Tenorio and Moya 2012). As expected, this model shows that the incremental amount of energy consumption per unit of evaporation increases with the reduction of MC for all three kinds of lignocellulosic residues. This behavior may be reflective of the fact that more energy is required for evaporating water from within the lignocellulosic material.

According to the model for energy input variation with MC, it is possible that the energy input has a turning point where energy input starts to increase in higher proportion than what had been presented before the turning point (Fig. 3). The water in woody cells is found in three locations: (i) occupying free cell spaces and lumens, (ii) in the cell wall, and (iii) as part of the fiber cell wall (Berry and Roderick 2005). The turning point found can be explained by the fact that as MC diminished, the water came out of the cell wall, thus requiring higher energy input (Berry and Roderick 2005). However, the turning point differs for the different biomass studied. GAD and EFB showed similar critical MC for the different drying technique. However, it was different for PL.

Another important result related to the input tendency was that the change in energy input for PL was of higher intensity (higher slope) compared to the other biomasses. This behavior can again be explained by the fact that PL has a water resistant cuticle that prevents adequate diffusion of water (Bartholomew *et al*. 2003).

Knowledge of the critical point allows for the establishment of a higher energy efficiency point. For example, if it is necessary to dry this biomass to a MC lower than the critical point, it should be considered that the energy input is very high. Also, if the MC must be under the value, the change of 1% in moisture will lead to a high-energy input.

Energy Balance

The energy balance was different for each kind of residue. GAD and EFB presented a similar behavior regarding the different drying techniques, as those materials showed similar MC (Table 2). Also, the water elimination process for both kinds of residues involves similar behavior, contrary to PL, which presents a natural barrier (cuticle) for the elimination of water from the inner part of the leaf. On the other hand, the energy balance (Fig. 3) does not reflect the critical point found when measuring the energy input (Fig. 1). In the case of energy input, the input values increased greatly when MC changed from 4 to 13%, called the critical point, while the energy balance tendencies showed that between 20% and 30% of MC for PL there was an inflection of the tendency (accelerated decrease) in HAD and SD (Fig. 3a, b). This is contrary to the other residues and AD, which did not show these inflexions. The energy balance was linear with MC reduction (Fig. 3).

Knowledge of the energy balance in the drying of different residues has practical implications, such as accurately establishing the proper MC to dry a specific residue that will then be used as a heat source. For example, even if there is an energy balance with PL at all times, the MC to obtain the highest energy balance is when the residue is at 25% and 60%, the lowest value being for shredded PL and the highest for 10-strand PL without grooves in HAD, respectively (Fig. 4a). On the other hand, for GAD and EFB, the highest energy balance value was at 0 and 5%, respectively, in HAD.

Even if there were maximum energy balance points in all the types of drying, the values were higher for a pre-treatment or a drying process. For instance, for all the residues, there was a maximum energy balance when air-drying at MC close to 0%, a result to be expected, as this drying does not demand much energy. While for the other drying techniques (HAD and SD) for PL, that energy balance was the highest for shredded PL in SD (Fig. 3b). This means that there is a limit to the minimum moisture content, where the energy recovery from biomass sources can be effectively performed though thermal conversion (Abbasi and Abbasi 2010).

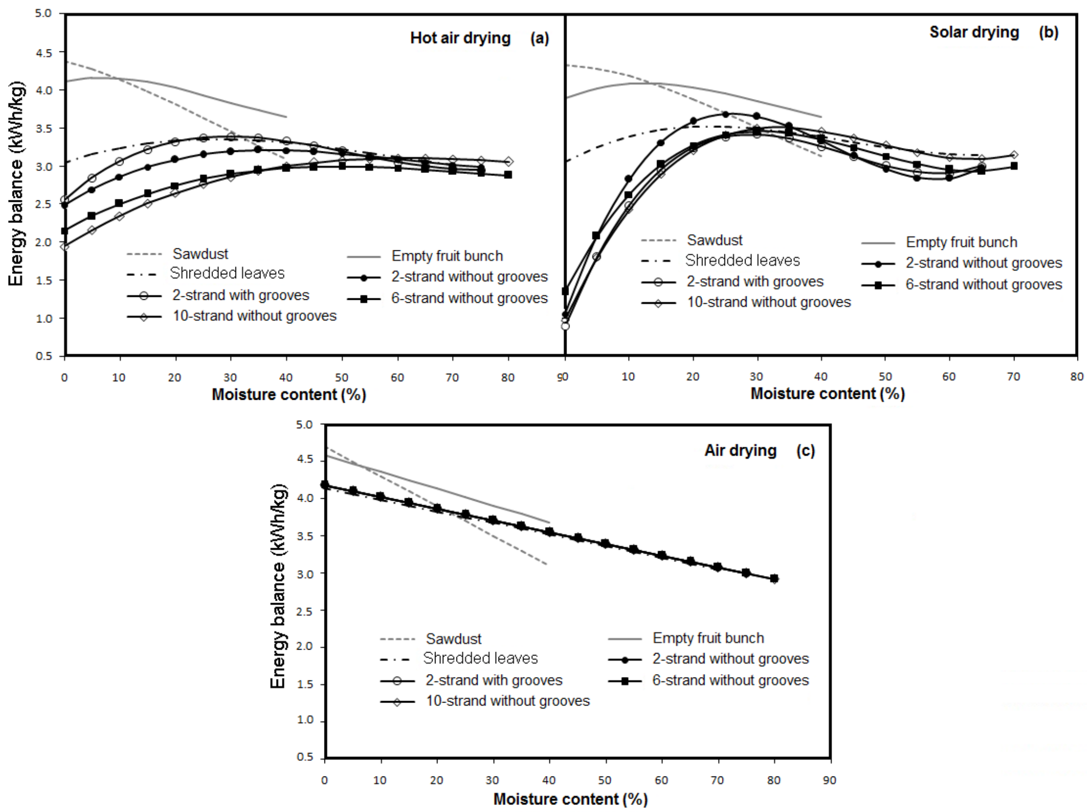

Fig. 3. Energy balance per residue for each drying technique, air drying (a), solar drying (b), and hot air drying (c)

CONCLUSIONS

1. The energy employed during the drying of different lignocellulosic residues (PL, GAD, and EFB) can be expressed by $\beta_1 MC^3+\beta_2 MC^2+\beta_3 MC+\beta_4$ (polynomial equation) or by $(\beta_1 \ln(MC)+\beta_2)$. An energy input inflexion occurred at specific moisture contents for all residues. The inflexion varied from 3 to 13% in MC for the different kinds of residues, the critical point being higher in GAD and EFB, and lower for PL. On the other hand, from 0% to the input inflexion MC, the change in energy input is of a higher magnitude that goes from green to inflexion point MC.

2. The energy balance also varied with the kind of residue and the type of drying. In PL HAD, the highest energy balance was at 25 to 60% MC with a balance of 2.99 kWh/kg to 4.38 kWh/kg. In GAD, the point of highest balance was at 0% MC with 4.38 kWh/kg, and EFB at 5% with 4.15 kWh/kg. In SD, PL presented the highest energy balance at MC between 25 and 35% and balances of 3.37 and 3.64 kWh/kg. Just as with the previous drying (HAD), the GAD and EFB reached their highest

balance at 0 and 5% with values of 4.24 kWh/kg and 3.97 kWh/kg, respectively. Regarding AD, all the residues obtained their highest energy balance at 0% MC with values of 4.18 and 4.59 kWh/kg. Treated PL, with grooves or crushed, allowed for a higher energy balance.

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