DENDROMETRIC CHARACTERIZATION OF CORN CANE RESIDUES AND DRYING MODELS IN NATURAL CONDITIONS IN BOLIVAR PROVINCE (ECUADOR)

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Abstract

The use of biomass raw material from agricultural areas is a challenge for Ecuatorian government. However there is lack information about surveying systems and processing in its height and weather conditions. The objective of this work was to develop methods to quantify straw residues, easily applicable in corn areas of Guaranda (Ecuador), and model the drying process at different air conditions. Two dendrometric equations were obtained for predicting dry available biomass by stem and cultivated area respectively, from corn mean height and radius of the stem. High coefficients of determination were obtained (0.94 and 0.97 respectively). Straw chips with initial moisture content ranging from 70-80% with an average moisture content of 76.7% wet basis were dried until they reached constant moisture content. Traditional models used to describe the drying process of agricultural products were employed to fit the observed data of the drying process of straw corn chips. Among the tested models, the Midili, Page, and sigmoid model were those that best fit the observed data representing the drying process. The effective diffusion (D_{ef}) was determined by means of an analytical solution of Fick's second law. Effective moisture diffusivity values obtained at natural outdoor drying conditions were 2.443E-11 and 2.035E-10 m^2/s, for the first and second falling periods, respectively.

Keywords: biomass, biomass surveying, drying kinetics, effective diffusivity

INTRODUCTION

Corn is one of the most important cultivated and consumed cereals in Ecuador and in the world due to its potential productivity, chemical composition and nutritional value. Corn ears, still fresh, are often used in Ecuador as raw materials for some traditional recipes, such as porridge, pamonha and cakes, besides being consumed in cooked or baked form. Recently the Ecuadorian government has launched a reform of the country's productive matrix, which aims to exploit efficiently all available resources to achieve the better life levels in the current social context involved in the globalized economy of the world. A lot of residual biomass for energy use can be used from the management of the Ecuadorian agriculture, especially in pruning operations, renewing plantations or crop residues. The management of this waste biomass could bring additional income to farmers, who, on the one hand, can commercialize food products, and the other hand, market these residues for energy, raw materials or processed byproducts. This will contribute to achieving the millennium goals such as poverty eradication, the upkeep of the environment or promote partnership for development. This source of biomass has not been used so far, because it presents various technical difficulties, lack of sufficient information about the amount and processing of these wastes [1-2] . A dendrometric characterization and natural different drying models for the maize cane residues in the province of Bolivar (Ecuador) is developed in this paper. Dendrometric studies have been successfully used to quantify available biomass in herbaceous plants [3]. These studies are necessary to relate this biomass with Lidar data [4-5] or vegetation index from multiespectral images [6-7]. They open a new tool to plant management. These studies will allow carry out measures for inventory and assessment of this resource to define the requirements and planning its use by farming communities in the Andean region [8-9]. The drying models of Table 2 were analyzed. They allow knowing drying kinetics, and minimum moisture content achievable in determined conditions. A model of special interest is the Fick's model, which is based on the proportionality between the speed drying and the moisture gradient between the material and environment [10]. The coefficient of proportionality is the effective diffusivity, which was calculated.

MATERIALS AND METHODS

Study Area

The study was conducted in the province Bolivar (Ecuador) (Figure 1); Bolivar is a province in the center of Ecuador in western Andes side. Its capital is the city of Guaranda. It is characterized by deep valleys in the high Andes, serving a vast hinterland of agricultural settlements. Its climate is subtropical, with a long (May - October) dry season. In this area corn is harvested between May and July. Afterwards, corn stems are a residue, which have not been used up to now, but could be used as energy biomass or raw material for byproducts. The corn variety most cultivated in Guaranda is INIAP-111 (Guagual improved). Samples were collected in three Andean locations: a) San Simón, which is located at 7.8 km from Guaranda, at 2673 AMSL height; b) Julio Moreno, which is at 6.6 km from Guaranda, with 2900 AMSL height; and c) Llacán at 8 km from Guaranda, at 2550 AMSL height. These locations were chosen because they are representative of many places in the Andes regions where a lot of small plots exist; corn is usually cultivated with not mechanized methods, and better incomes are searched.

Figure 1. Location of Bolivar Province.

Dendrometric Analysis

Five plots were selected from each location. Each plot was divided in 6 stands where 1 m^2 was clear cut. Plant rows in the stands were separated between 80 and 100 cm. In the row plants were separated between 40 and 60 cm. This frame represents 8.89 stems/m^2 average considering two stems by plant. Every corn straw stem was measured in this area, obtaining weight, length, diameter at base and upper points. Sample was formed by more than 900 stems. The volume of each stem was calculated by equation 1 where R_{max} is the base radius of cane. R_{min} is the minimum radius of cane, and L in the cane length.

$$V_c = \frac{1}{3} \cdot \pi \cdot L \cdot \left(R_{\max}^2 + R_{\min}^2 + R_{\max} \cdot R_{\min} \right) \quad (1)$$

Moisture content in wet basis (ω) of samples in each stand was measured, so dry weight ($m_{\text{dry matter}}$) and dry densities ($D_{\text{dry matter}}$) were obtained by equations 2 and 3.

$$m_{\text{dry matter}} = m_{\text{wet matter}} \cdot \left(1 - \frac{\omega}{100} \right) \quad (2)$$

$$D_{\text{dry matter}} = \frac{m_{\text{dry matter}}}{V_c} \quad (3)$$

With the aim of obtaining a predictive model of available residual biomass from corn cultivation two regression models were proposed, one for determination of biomass in a single cane and one for available biomass in a defined area, depending both from its length and the mean radius (R_m) (Table 1).

Determination and modeling of drying curves

Samples of residual stem were collected after corn harvesting, between the July 15th and July 20th , and then, they were chipped and piled on the ground. The influence of sizes of chips, extended over three kinds of surface was studied in natural outdoor drying. Three lengths of corn straw pieces of variety INIAP-111 (improved Guagual) were utilized: 10, 20 and 30 cm. They were dried in three ground surfaces: cement, grass and dirt. During the drying period, the maximum and minimum temperatures observed were 22.5 ^{o} C and 6.8 ^{o} C respectively, the mean relative humidity in the air was 53%, and the average monthly rainfall was 14.3 mm.

Ranging from 70-80% with an average moisture content of 76.7% wet basis, to model drying. piles of the different piece sizes were dried in open natural conditions until constant moisture content was reached. To measure the evolution moisture content, a piece was randomly chosen and dried in an oven at 105 ± 1°C during 24 hours. The experimental data of the drying process were fit to mathematical models expressed by equations indicated in the Table 2. These models are frequently used to describe the drying phenomenon in agricultural products [11]. Moisture ratio (MR) was estimated by the equation (4), where: *MR* is the dimensionless moisture ratio; ω_t, ω_e and ω_o are the moisture content at any time, initial moisture content and equilibrium moisture content, respectively.

$$MR = \frac{\omega_t - \omega_e}{\omega_o - \omega_e} \qquad (4)$$

Determination of the Effective Diffusion Coefficient

A decrease in the material moisture content reduces its biological activity as well the chemical and physical changes that occur during storage. The moisture content reduction involves simultaneously heat and mass transfer processes [12]. Kinetics and cost depends on the method used and on the drying conditions. When gradients of concentration exist in a substance, such as moisture content or temperature, a flow of particles or heat tends to homogenize the solution and uniformize the concentration [13]. Homogenized flow is a statistical result of the movement of the particles which gives rise to the second law of thermodynamics, also known as random thermal motion of the particles. So the physical processes of diffusion can be seen as physical or irreversible thermodynamic processes. In the event of any differences in concentration of any kind particles (water concentration, humidity), the random passage of molecules will be held from regions with higher concentration to regions of lower concentration. Fick's second law of diffusion equation, symbolized as a mass-diffusion equation for drying of agricultural products drying in a falling rate period, and if considering a long circular cylinder in which diffusion is everywhere radial, then concentration is a function of radius *r* and time *t* only, and the diffusion equation becomes [14]:

$$\frac{dC}{dt} = \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot D_{ef} \frac{\partial C}{\partial r} \right) \qquad (5)$$

The analytical solutions of Fick's second law Eq. (5) for an infinite cylinder can be given as Eq. (6) with the assumption of constant diffusion coefficients, and uniform distribution of temperature and initial moisture [15].

$$MR = \frac{\omega_t - \omega_e}{\omega_o - \omega_e} = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left[\frac{-\lambda_n^2 \cdot D_{ef} \cdot t}{r^2}\right] \quad (6)$$

Where:

MR = moisture ratio, dimensionless; λ_n = characteristic root of first kind and zero order of Bessel function (λ_1=2.4048); D_{ef} = effective diffusion coefficient (m^2/s); t= drying time (s); r = cylinder radius (m).

The analytical solution of this equation is presented in the form of an infinite series, and therefore, finite terms numbers (n) in truncation are able to determinate the results with satisfactory precision. For long drying periods Eqn (6) can be further simplified to only the first term of the series (n=1). Eq. (6) is written in a logarithmic form as follows:

$$\ln MR = \ln \frac{4}{\lambda_n^2} - \frac{-\lambda_n^2 \cdot D_{ef} \cdot t}{r^2} \quad (7)$$

The effective moisture diffusivity was calculated from a slope of a straight line at the different falling rate drying steps, by plotting data in terms of ln(MR) versus drying time, which gives a straight line with a slope of (k), in which:

$$D_{ef} \cdot = \frac{k \cdot r^2}{\lambda_1^2} \quad (8)$$

Biomass characterization

To characterize the material as energy biomass UNE-CEN/TS 14780: 2008 EX [16] was followed. Elemental components (C, H, N) were obtained using a elemental analyzer LECO Truspec CHN according to UNE-CEN/TS 15104: 2008 EX [17]. For the determination of S ASTM E775-87 (2008)e1 [18] was followed. HHV (MJ kg^{-1})

was obtained using a LECO AC-500 calorimeter by UNE 164001: 2005 EX [19] and UNE 164001:2005 EX ERRATUM: 2008 [20].

RESULTS AND DISCUSSION

Dendrometric analysis

In Table 1 the regression models obtained to predict dry biomass in the plots is shown. This can be calculated by measuring length and mean radius in a plant or in an area, by measuring the mean height and mean radius of the inside plants. It can be seen that a high coefficient of determination R^2 (0.9706 and 0.9707 respectively) and a low mean absolute error MAE (0.083 kg/m^2 and 0.092 kg/stem respectively). Density of wet material is an average of 0.849 g/cm^3 with 0.052 g/cm^3 standard deviation. These type of models has been used in other crops, and they have been related on residual materials. The statistics obtained in these work are quite better than some of them

Biomass models could be used to analyze water, fertilizers or other inputs; yield too. [21-22]

Table 1. Statistical results obtained for the dry biomass predicting models (N=894).

Equation	R^2	MAE	RMS
$B_{dry\ area} = -2.78446 + 0.00718.L + 2.5488.RM$	0.9706	0.083	0.105
$B_{dry\ stem} = -0.3132 + 0.000808.L + 0.286.RM$	0.9707	0.092	0.118

$B_{dry\ stem}$ is the dry biomass in stem in kg; $B_{dry\ area}$ is the biomass available kg/m^2, L is length of stem in cm; RM mean radius of stem in cm

Determination and modeling of drying curves

The variation of moisture content was studied for different chip length, drying surface and location. The results didn't point to any of these factors as significant in the curve (Figure 2). All of them showed a similar trend. This was checked by paired sample test, which is based on t-student distribution. Figure 3 shows the variation of average moisture content (ω) versus time. As it can be seen, the mean initial moisture content was about 76% and reached constant value at 15 days.

Small oscillations are as a consequence of different relative humidity in the air on different days. The minimum moisture content was about 10%. This value allows combusting this material in boilers or being processed for pellet.

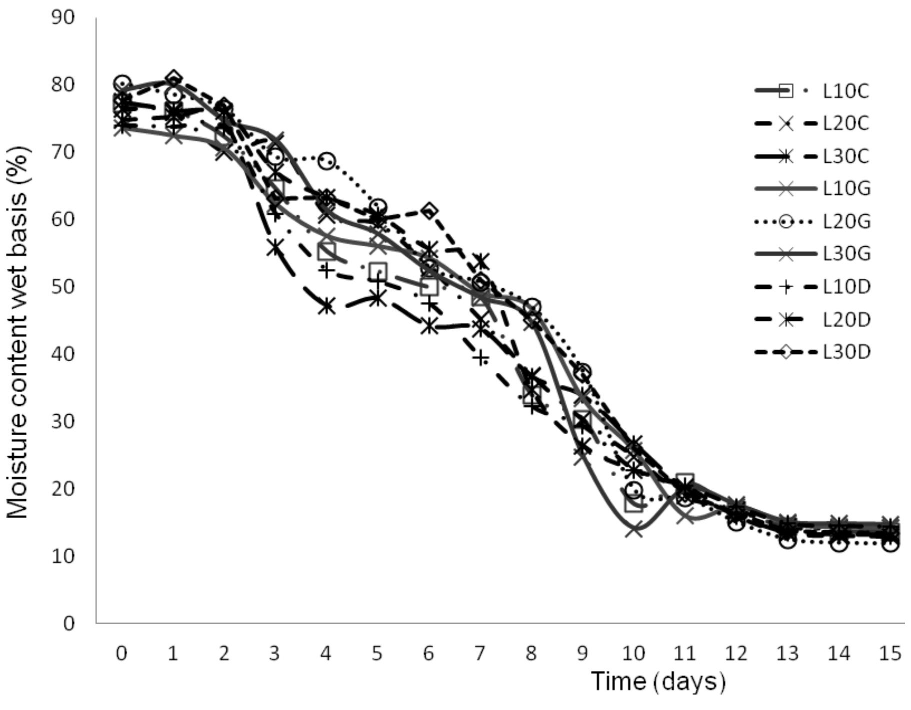

Figure 2. Comparison of drying curves for three chip sizes (L10= 10 cm length, L20= 20 cm length, L30= 30 cm length) on three drying surface (C= on cement, G= on grass, D= on dirt) in natural outdoor drying.

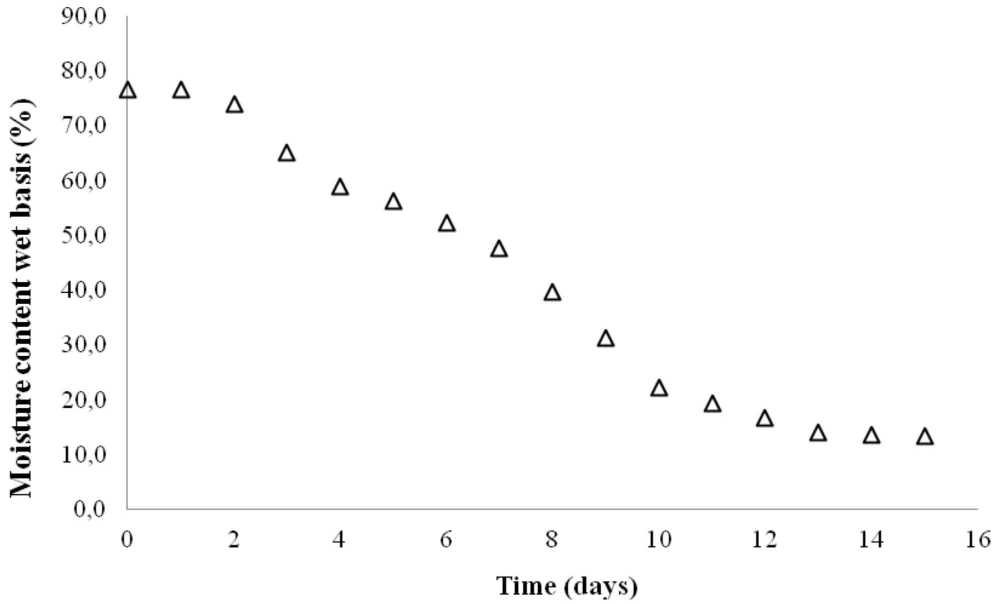

Figure 3. Variation of average moisture content with the drying days.

Table 2 shows that the average data fit with different drying models. They will possible to determine the ratio of moisture in every moment from drying out. Page, Midili and Sigmoid models are shown with the best fit.

Effective Diffusion Coefficient

Figure 4 shows the variations of the ln(MR) *versus* drying time (days) with natural outdoor drying conditions. These drying curves show that drying of corn straw occurred in two falling-rate period. In other words, drying force, controlled by the liquid diffusion, follows a first and second falling-rate drying process. They can be fit to drying straight lines as the first and second falling-rate periods [23].

Table 2. Drying models tested for determine drying kinetics.

Model name	**Model equation**	**Parameters model**	**Statistics**
Newton (Lewis)	$MR = e^{-k \cdot t}$	k = 0.129478	R^2 = 0.882 RMS = 0.034
Page	$MR = e^{-k \cdot t^n}$	k = 0.010382 n = 2.209299	R^2 =0.986 RMS = 0.011
Henderson and Pabis	$MR = a \cdot e^{-k \cdot t}$	k = 0.152598 a= 1.1836603	R^2 = 0.899 RMS = 0.029
Logaritmic	$MR = a \cdot e^{-k \cdot t^n} + b$	k = 0.0269577 a = 3.5517524 b = -2.4669486	R^2 = 0.969 RMS = 0.017
Midili	$MR = a \cdot e^{-k \cdot t^n} + b \cdot t$	k = 0.0109037 n = 2.1081264 a = 0.9869401 b = -0.0048453	R^2 = 0.989 RMS = 0.009
Diffusional Model	$MR = a \cdot e^{-k_1 \cdot t} + (1-a) \cdot e^{-k_2 \cdot t}$	k_1 = 0.000290 k_2 = -0.000350 a = 116.06207	R^2 = 0.980 RMS = 0.014
Two Exponencial terms	$MR = a \cdot e^{-k_1 \cdot t} + b \cdot e^{-k_2 \cdot t}$	k_1 = 0.002449 k_2= 0.0018537 a = 3.8567575 b = -2.7708039	R^2 = 0.975 RMS = 0.014
Sigmoid	$MR = \frac{a}{1+e^{-\frac{x-b}{c}}}$	a = 1.0247077 b = 6.7145297 c = -2.1435234	R^2 = 0.987 RMS=0.010
Data:	Time (days)	Moisture content (%)	Moisture ratio MR
	0	76.74	1.00000
	1	76.60	0.99781
	2	73.87	0.95471
	3	65.12	0.81638
	4	58.87	0.71762
	5	56.33	0.67752
	6	52.33	0.61421
	7	47.77	0.54220
	8	39.74	0.41539
	9	31.39	0.28342
	10	22.26	0.13917
	11	19.40	0.09401
	12	16.61	0.04985
	13	14.06	0.00955
	14	13.56	0.00169
	15	13.45	0.00000

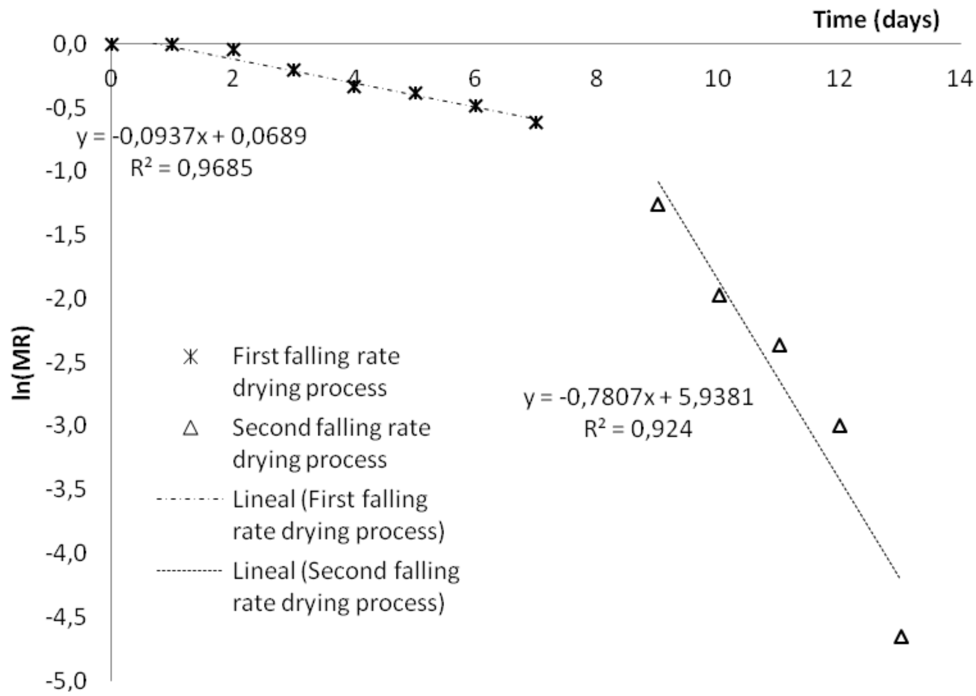

Figure 4. From Eq. (7) Ln(MR) *versus* time (days) for cylindrical chip corn drying of high moisture.

The procedure for estimating the effective diffusivity D_{ef} was based on derived from the slope determined by the Eq. 7 and 8. These values are shown in Table 3. MR was obtained from Eq. 4 from values depicted in Figure 3.

Table 3. Effective diffusivity and correlation coefficient at natural outdoor drying conditions. FFP and SFP are first and second falling periods, respectively (models Fig. 4).

FFP (cm^2/s)	R^2	SFP (cm^2/s)	R^2
2.443E-11	0.9685	2.035E-10	0.924

The effective diffusivities obtained by Eq. (8) with natural outdoor drying conditions were 2.443E-11 and 2.035E-10 m^2/s. for the first and second falling periods, respectively. These values of effective moisture diffusivity differ with 9-11 m^2/s obtained for food materials [24].

Biomass characterization

The average and standard deviation of high heat value (HHV) were 14.87 and 1.51 MJ/kg respectively. Average carbon content was 41.31%, hydrogen content 5.75%; Nitrogen content 0.89%, sulphur 0.083% on wet basis. Average ash content was 2.43%.

I can be noted that ash content is lower than 3%, which is lower than the limit fixed by UNE-EN 14961 [25]. Restrictions of 1% N maximum and S maximum according to this norm are also complied. Carbon ratio could be used to predict the CO_2 captured from photosynthesis by multiply of biomass. Moles of C are calculated by dividing carbon mass by its atomic mass (12 u). C moles are equivalent to moles of CO_2 [3][21-22]

CONCLUSIONS

Methods have been developed to predict residual biomass contained in an area of maize crop from average length and mean radius of the stems. The good fit of the obtained models allows be applied in surveys process.

Based on the obtained values, the Page, Midili and Sigmoid models were adequate in describing outdoor drying phenomena of corn straw chips in Guaranda conditions. These models allow the moisture content to be predicted from the number of drying days. The minimum moisture content reachable is 10%. This moisture content allows using the material as biomass in a domestic boiler.

The effective diffusivities obtained by Eq. (8) with natural outdoor drying conditions were 2.443E-11 and 2.035E-10 m^2/s. for the first and second falling periods. respectively.

Residue materials have been characterized. The high heat values are being about 12.45 and 15.53 MJ/kg. Average carbon content was 41.31%, hydrogen content 5.75%; Nitrogen content 1.09%, sulphur 0.123% on wet basis. Average ash content was 2.43%. These values are into limits established by the norm UNE-EN 14961 (part 4)

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