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Drying kinetics and mathematical modelling of *Arundo donax* L. canes, a potential renewable fuel

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Abstract: *Arundo donax* L. is an energy crop with the potential use as a renewable fuel. This study focused on the drying process of the canes in field and laboratory conditions to determine the effect of the harvest conditioning on the kinetics parameters of whole and slashed canes. The lab drying test was conducted in a thin layer dryer at temperatures between 30 and 80 °C and a 0.5 m·s^{-1} air velocity. The whole and slashed canes showed faster water evaporation rates as the temperature increased, but the slashed canes achieved a lower final moisture content in a shorter time. The effective diffusion coefficient varied between 3.67×10^{-12} and 1.28×10^{-11} m^2·s^{-1} and showed a significant effect of the temperature, but not between samples; its temperature dependence was determined by the Arrhenius equation giving activation energies of 24.4 and 20.2 kJ·mol^{-1} for the whole and slashed canes respectively, not significantly different. The modelling of the experimental drying data to six thin layer drying models achieved good performance (R^2 > 95.9%), although the Logarithmic model showed the best fit for both samples (R^2 > 99.4%). In addition, a temperature dependent equation for the drying constant was included in the Logarithmic model for the whole and slashed canes which predicted with good performance (R^2 > 97%) the moisture loss. The developed tools constitute an adequate model for the simulation of the drying process of *Arundo donax* L. that could be useful for the design of various equipment and systems.

Keywords: diffusivity; Fick's diffusion model; giant reed; thin-layer drying

The decrease in fossil fuel reserves and their impact on the generation of greenhouse gases (GHGs) intensified the study of new renewable energy sources. Energy crops are promising sources for bioenergy production, whose development demands cost-competitive market. *Arundo donax* L. (AD), or the giant reed, is a perennial herbaceous plant whose exploitation differs worldwide. The US Department of Agriculture declared AD as a transformer species that alters habitats and ecological processes, particularly in California, where it is considered a highly aggressive, non-native plant (Christou et al. 2018). However, other authors described AD as a candidate for developing biofuels in North America based on its fast biomass production rate and use for co-combustion in power plants after the torrefaction process (Garcia-Perez et al. 2011). The European Commission identified the giant reed as one of the most cost-effective and environmentally friendly crops (Christou et al. 2018) based on vast scientific literature on yield assessments from different regions in the Mediterranean area.

A work reported by Mantineo et al. (2009) revealed that the net energy provided by AD was low

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or negative in the year of planting, but increased significantly for the second year, describing values between 487 and 611 J·ha^{-1} with a positive influence of irrigation and nitrogen fertilisation. Most recently, Jambor and Torok (2019), based on sixty-eight relevant works performed in Italy and the European Mediterranean region, highlighted that AD showed a high economic potential for biomass production in marginal or unattractive lands, giving a high energy balance with high investment, but low maintenance costs. Abreu et al. (2020) observed that this species has the potential to become the benchmark in the world of biofuels due to its ecological characteristics, with a biomass yield rounded to 20–27 t·ha^{-1} for the first year of planting and 35–42 t·ha^{-1} from the second year onwards.

In Argentina, the first research conducted on AD was related to the development of base materials for the production of activated carbon and the conversion to solid fuel via pyrolysis based on a laboratory scale (Basso and Cukierman 2005). After the first study that identified the most likely areas for AD cultivation in the country (Falasca et al. 2011), recent advances point out the potential biomass yield increase of this perennial herbaceous plant under irrigation and fertilisation conditions (Barrado et al. 2019; Rodríguez et al. 2021). Based on these results, the latest studies evaluated the performance of AD as a renewable partial substitute biofuel in the cement industry (Córdoba et al. 2021; Pereyra Müller et al. 2021) and revealed the acceptable behaviour of this biomass in terms of the calorific value and the gaseous emissions. Although there is a lack of information about the post-harvest management of the crop, which will allow for the disposition of knowledge regarding the best conditions that assure adequate conditions before further technological applications can be applied. No reference was found until now regarding the suitable conditions of the drying process that facilitate the loss of moisture of the canes before any technological application is applied.

The biomass industry requires low-cost and moisture tolerant storage solutions to preserve feedstocks before use; moreover, energy crops require a positive energy balance. Therefore, the challenge is to optimise the mechanisation and post-harvest processes. Drying is one of the widely used methods for the post-harvest preservation of agricultural products, applied to reduce the moisture content and microbiological activity in order to assure product stability under ambient temperatures. The process should ensure fast moisture loss to reduce the energy costs of further processing, such as crushing or grinding for pelletising without affecting the thermal properties of the material. Pari et al. (2015) investigated different storage systems for AD finding out that climatic factors mainly influence the moisture content trend, and the dry matter losses of the biomass could affect the bio-energy potential of the end products such as bioethanol and biogas. According to Villalba Vidales and Arzola De La Peña (2015), the drying of biomass before combustion is crucial to improving the efficiency of these processes; as the lower the moisture content, the higher the obtained energy (Bhaskar et al. 2011). In this sense, Williams and Biswas (2010) remarked that a moisture content below 10% is required for the chemical conversion of a biomass.

Moreover, the drying of biomass is a complex phenomenon of heat and mass transfer. The time and temperature dependence in the drying process can be explained through several kinetic models that contribute to predicting the optimal operational conditions and improving the design of the related equipment. The drying kinetics of several materials have been widely described in the literature. Still, no reference was found for AD until now, except one study related to the effect of the drying conditions of AD on the intensity of the collapse of the canes when they are used in the manufacture of woodwind instruments (Obataya et al. 2005). Villalba Vidales and Arzola De La Peña (2015) described a wide variety of mathematical models to predict the drying kinetics of several materials and highlighted that the challenge would be the development of new models fed with specific information on each biomass and condition.

Based on the increasing demand for new renewable energy resources, the interesting potential of the biomass yield that AD demonstrated in previous studies, and the lack of information about the post-harvest management of this perennial herbaceous plant, this work investigated the drying kinetics of this biomass in field conditions and on a laboratory-scale under controlled conditions on conventional and conditioned AD samples. The parameters of the kinetics, diffusivity, and activation energy were calculated. The experimental data were used to verify the accuracy of mathematical models commonly used in the literature in order to find the best fit that contributes to the design and optimisation of the post-harvest operations of AD.

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MATERIAL AND METHODS

Sample preparation. AD canes were collected from a farm located close to Olavarría, Argentina (37°01'23.2"S, 60°18'57.3"W) during autumn in 2020. The harvest was carried out with a conventional mower providing whole cut canes (Figure 1A) and a conditioner producing a lengthwise cut providing slashed canes (Figure 1B). The loss of water in the field conditions was evaluated by collecting samples of 500 g of each cut twice per week and determining the moisture content immediately after collection. The climate conditions (temperature and relative humidity) were continuously measured through two data loggers (HITRO, Argentina) placed inside the piles of whole and slashed canes at the field.

For the laboratory drying tests, fresh AD samples were collected after harvest and packaged in double-layer low-density polyethylene bags, sealed, and stored at a low temperature (5 °C) to preserve the original conditions. A portion of the original sample was cut into pieces of fixed length, named "whole cane" (WC, Figure 1C) and another portion, named "slashed cane" (SC, Figure 1D), was cut lengthwise to simulate the conditioned cane obtained after harvest. The dimensions of the samples were manually determined by sampling a set of ten units of each type of cut using a micrometer; the diameter, thickness, and length are shown in Figure 1E.

The moisture content of the samples from the field and laboratory experiments was determined in triplicate according to the American Society of Agricultural Engineers Standard S358.2 (ASAE 2012) using a forced oven drier at 65 °C for 72 h until reaching constant weight.

Laboratory test experimental set-up. The thin-layer drying process was simulated at controlled conditions using an UOP 8 pilot dryer (Armfield, UK, Figure 2) with temperature and air velocity controls. Four trays, separated by 0.052 m, were used to carry out the experiments at each desired temperature. The convective airflow passed through the samples (placed on rectangular steel mesh trays, 0.14 m^2 × 0.23 m^2, with a 0.002 m opening size) in a parallel direction, allowing the drying of both sides. The drying runs were carried out at three air temperatures (30, 60, 80 °C) controlled by an automatic controller (± 4 °C) and a constant air velocity of 0.5 m per second. The air velocity was measured through a LCA 6000 anemometer (Airflow, USA) and the relative humidity with an aspirated psychrometer (dry and wet bulb temperatures) at the up and down air streams.

Each thin-layer drying test was conducted in duplicate, and the weight loss was measured every 15 minutes. The test was finished when the difference between two consecutive weighings was lower than 1%.

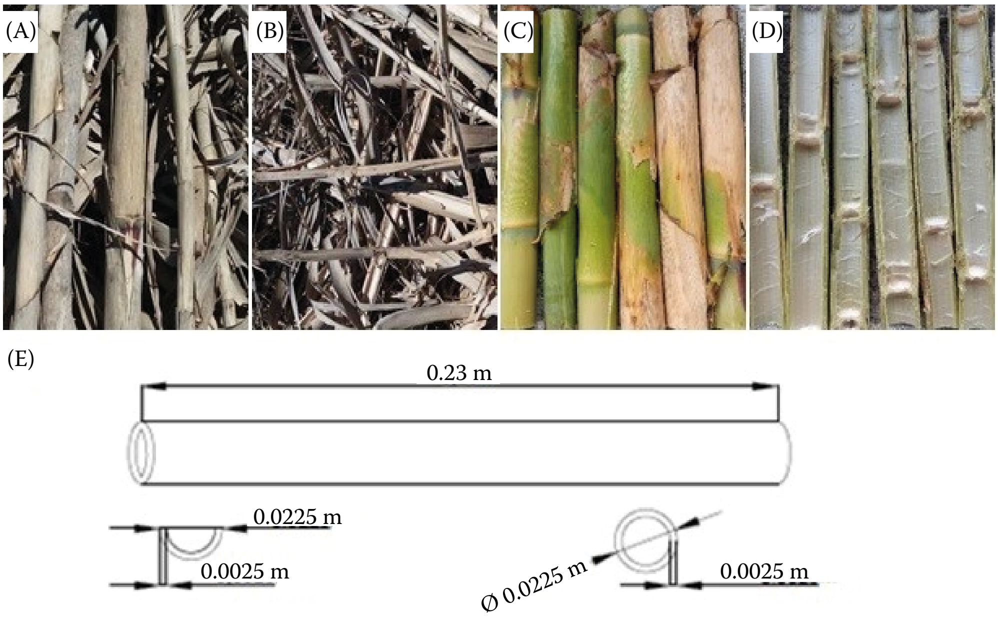

Figure 1. Samples of the whole (A, C) and slashed (B, D) *Arundo donax* L. (AD) canes, (A, B) dried in the field conditions and (C, D) prepared for the pilot drying test; length, diameter and (E) thickness of the AD canes used in the drying tests The maximum standard deviations obtained for the thicknesses were lower than 1.5 × 10^{-4} m

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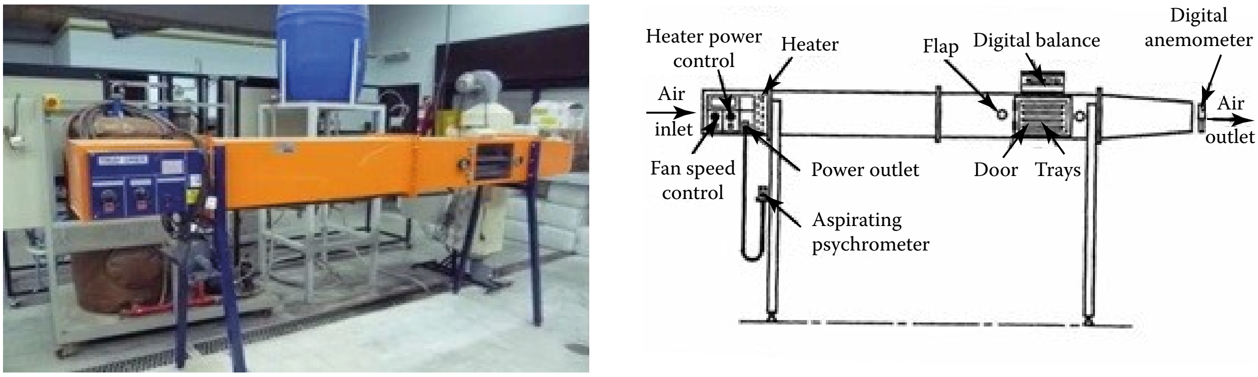

Figure 2. Experimental dryer (Armfield Tray Dryer Type UOP8-A, Armfield Ltd Ringwood, Hamsphire, UK) and scheme from original Armfield catalogue (1997)

Mathematical modelling. The drying rate N_A (kg water per m^2 per h), defined as the rate of moisture diffusion from the interior of the material being dried into the external environment, was calculated as in Equation (1) (Burova et al. 2017):

$$N_A = \frac{-S_s}{A}\frac{dX}{dt} \tag{1}$$

where: S_s – the mass of the dry solid after each run (kg dry solids); A – the humid surface where the gas flows and the evaporation takes place and is assumed as the area of the mesh tray (m^2); dX/dt – the moisture gradient (kg water per kg dry solids per hour).

The moisture ratio X^* (dimensionless) was calculated through Equation (2):

$$X^* = \frac{X_t - X_e}{X_0 - X_e} \tag{2}$$

where: X_t – the moisture content at a given time (kg water per kg dry solids); X_0 – the initial moisture content; X_e – the equilibrium moisture content (all on a dry basis).

The equilibrium moisture content (X_e, kg water per kg dry solids) for each temperature was obtained from the modified Oswin model, described in Equation (3). According to Chen and Danao (2015), this model best fits the isotherm data for individual energy crops (energy cane, *Miscanthus sinensis*, miscane, and energy sorghum) and also compiled for the pooled data in a global isotherm model:

$$X_e = \left(A + B \times T\right)\left(\frac{ERH}{1 - ERH}\right)^{1/c} \tag{3}$$

where: ERH – corresponds to the equilibrium relative humidity in the inner part of the drying chamber (–); A, B and C – temperature-dependent constants for the whole energy cane (A = 15.8, B = –0.22 and C = 2.12) obtained from (Chen and Danao 2015).

Table 1 describes the X_e values obtained from Equation (3) and the laboratory conditions. The air temperature was periodically measured along each run with a thermo-hygrometer (model 20250-21, Digi-Sense, USA), and ERH was obtained through the psychrometric chart based on the dry and wet bulb temperature measurements inside the drying chamber.

The drying characteristics of the AD canes were determined by fitting the experimental drying data to the empirical and semi-empirical models detailed in Table 2. These models have been widely described and applied to study the drying kinetics of sugar cane, as Agote Goyalde et al. (2009) detailed.

The correlation coefficient (R^2), the reduced chi-square (χ^2), the sum of squared estimate of errors (SSE), and the root mean square error (RMSE) were calculated to evaluate the goodness of fit of the math-

Table 1. Equilibrium moisture content of the AD canes based on the modified Oswin model at the experimental pilot plant test conditions

T (°C)	ERH	X_e (d.b.)
30 ± 4	0.286 ± 0.016^c	0.0597 ± 0.0022^c
60 ± 4	0.095 ± 0.007^b	0.0090 ± 0.0003^b
80 ± 4	0.056 ± 0.003^a	0.000 ± 0.0004^a

Values with different letter in the same column show statistically significant differences at the 95.0% confidence level according to LSD's test; T – air temperature; ERH – corresponds to the equilibrium relative humidity in the inner part of the drying chamber (–); X_e – equilibrium moisture content (dry basis – d.b.)

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Table 2. Mathematical models used to describe the drying kinetics of the *Arundo donax* L. canes

Model name	Model equation	Reference
Newton	$X^* = exp(-kt)$	Lewis (1921)
Page	$X^* = exp(-kt^n)$	Page (1949)
Logarithmic	$X^* = a \times exp(-kt) + b$	Chandra and Singh (1995)
Henderson and Pabis	$X^* = a \times exp(-kt)$	Henderson (1961)
Two-term	$X^* = a \times exp(-k_1t) + b \times exp(-k_2t)$	Henderson (1974)
Midilli	$X^* = a \times exp(-kt^n) + bt$	Midilli et al. (2002)

X^* – moisture ratio (–); k, k_1, k_2 – drying constants (h^{-1}); t – drying time (h); a, b, n – empirical constants in the drying model

ematical models to the experimental data. The best model describing the thin layer drying characteristics of the AD is that with the lowest reduced chi-square (χ^2), *SSE* and *RMSE* and the highest R^2. The *SSE*, *RMSE* and reduced chi-square (χ^2) can be calculated as in following Equations (4–6):

$$SSE = \sum_i^N \left(X^*_{pred,i} - X^*_{exp,i}\right)^2 \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_i^N \left(X^*_{pred,i} - X^*_{exp,i}\right)^2} \quad (5)$$

$$\chi^2 = \frac{\sum_i^N \left(X^*_{pred,i} - X^*_{exp,i}\right)^2}{N - z} \quad (6)$$

where: $X^*_{exp,i}$ and $X^*_{pred,i}$ – the experimental and predicted moisture ratios, respectively; N – the number of observations; z – the number of model constants.

The models were fitted by a non-linear regression analysis using Marquardt methods and Statgraphics Centurion XVI to perform the fitting.

Effective diffusion coefficient and activation energy calculation. The effective diffusion coefficient shows the trend of the drying rate when the diffusion is the controlling stage. This coefficient is estimated by considering that the solid moisture content is uniform, and the internal movement constitutes the main resistance to the transfer (Santalla and Mascheroni 2010). The Equation (7) used to obtain the diffusion coefficient was derived from Fick's second law of diffusion:

$$\frac{\partial X}{\partial t} = D_{eff}\, \nabla^2 X \quad (7)$$

where: X – the local moisture content (dry basis, kg water per kg dry matter); t – the drying time (h); D_{eff} – the effective diffusivity ($m^2 \cdot s^{-1}$); ∇ – the gradient operator.

For the case of the thin-layer and assuming one-dimensional moisture movement without volume change, constant diffusivity, uniform initial moisture distribution, and negligible external resistances (Crank 1979), the analytical solution of Equation (7) results in Equation (8):

$$X^* = \frac{8}{\pi^2}\sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{-(2n+1)^2 \frac{\pi^2 D_{eff} t}{4L^2}} \quad (8)$$

where: L – the thickness of the layer (m); t – the time (h); D_{eff} – the effective diffusion coefficient ($m^2 \cdot s^{-1}$); e – the base of a natural logarithm; n – mathematical constant (adimensional).

For long drying times, Equation (8) can be expressed as Equation (9) (Crank 1979):

$$X^* = \frac{8}{\pi^2}\, e^{-D_{eff} t \frac{\pi^2}{4L^2}} \quad (9)$$

Experimental values of the moisture ratio X^* were used to fit Equation (9) to obtain the diffusion coefficient at each temperature. The temperature dependence of the effective diffusion coefficient may be described by the Arrhenius Equation (10) as follows:

$$D_{eff} = D_0 e^{-\frac{E_a}{RT}} \quad (10)$$

where: D_0 – the Arrhenius factor ($m^2 \cdot s^{-1}$); E_a – the activation energy for the moisture diffusion ($kJ \cdot mol^{-1}$) and represents the minimum energy required to diffuse and evaporate the water molecules during the drying process (Scheufele et al. 2015); R – the universal gas constant (8.314 $kJ \cdot kmol^{-1} \cdot K^{-1}$); T – the absolute temperature (K).

The activation energy (E_a) could be determined by plotting ln (D_{eff}) versus ($1/T$).

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RESULTS AND DISCUSSION

Field drying experiment. According to the agronomic management of AD, the planted culture is harvested when a higher aerial biomass is achieved, usually after the first frosts. As the winter was delayed, the harvest was conducted at the beginning of August 2020 using conventional and conditioning mowers forming separate piles of whole and slashed canes on the ground. The loss of moisture of each reed shape (Figure 1A–B) was studied by continuous measurements of the environmental conditions (temperature and relative humidity). Twice a week, the piles were sampled to determine the moisture content of the canes. The mean temperature remained at 10.74 ± 4.38 and 11.43 ± 4.06 °C for the WC and SC, respectively, and the relative humidity remained between 50.20 ± 13.4 and 49.05 ± 14.3% for the WC and SC, respectively, without any significant differences between them. Figure 3 shows the behaviour of both samples over one month. The final moisture content resulted in 69.6 ± 3.2% d.b. for the WC and 10.07 ± 0.37% d.b. for the SC revealing a strong effect of the harvest conditions on the moisture loss. The weather during the test was arid since no significant rainfalls were registered. Short periods of an ambient relative humidity around 70% were observed at the starting and between 500 and 650 h of the test, which did not affect the moisture loss in the SC, but influenced the WC moisture content, showing a slight increase in this parameter at 400 hours. The lengthwise cut of the cane significantly decreased the drying time since, after ten days of field drying, the SC decreased its moisture content by 89% and remained around the final value close to 10%, indicating that is safe for further use. On the other hand, the WC only reduced its moisture content by 23% during the first days and remained at 72.1 ± 6.0% humidity.

Drying kinetics on the laboratory scale. The initial moisture content of the cane samples prepared for the laboratory test, harvested during autumn 2020, was 150 ± 7% dry basis. The thin-layer tests were conducted on the whole and slashed samples at 30, 60 and 80 °C air temperature and a 0.5 $m \cdot s^{-1}$ air velocity. The temperature inside the dryer was measured regularly throughout the drying period. As expected, the drying temperature had a significant effect on the drying rate of the AD canes; however, the impact of the conditioning (slashed samples) on the moisture content was even more significant. Both samples showed faster water evaporation rates as the temperature increased, but the slashed canes achieved a lower final moisture content in a shorter time (Figure 4A).

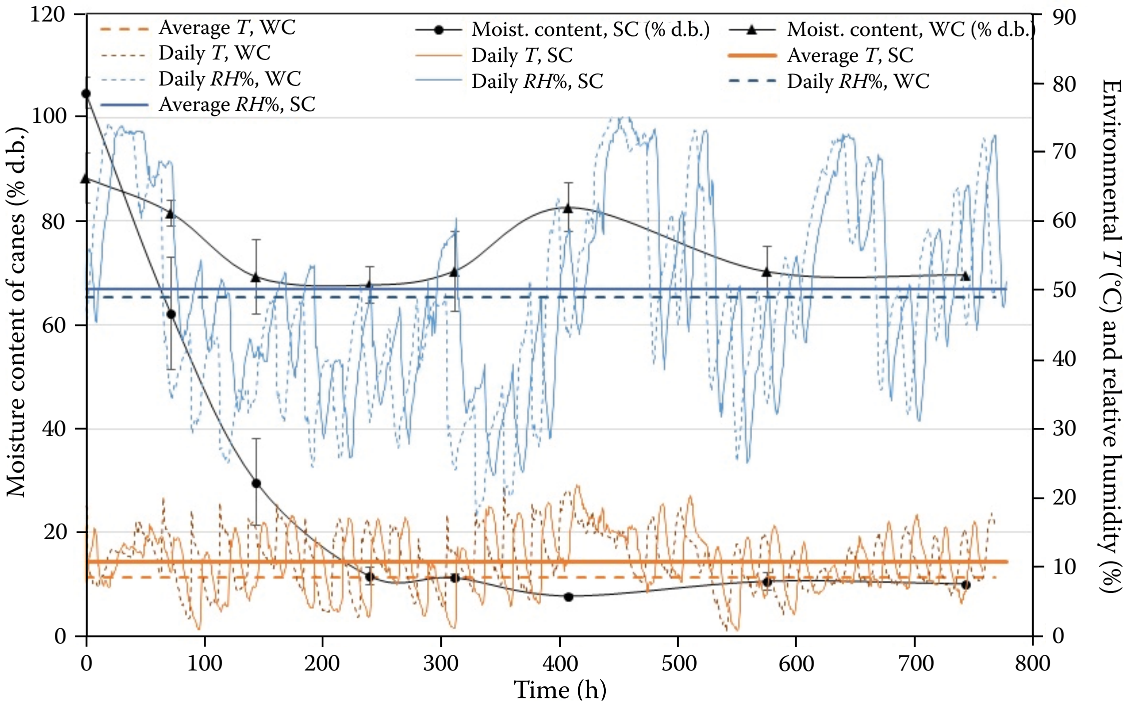

Figure 3. Drying of the whole and slashed canes in the field drying conditions from August 7th, 2020 to Sep 9th, 2020 at Olavarría, Argentina (37°01'23.2"S, 60°18'57.3"W)

T – temperature; *RH* – relative humidity; WC – whole canes; SC – slashed canes; d.b. – dry basis

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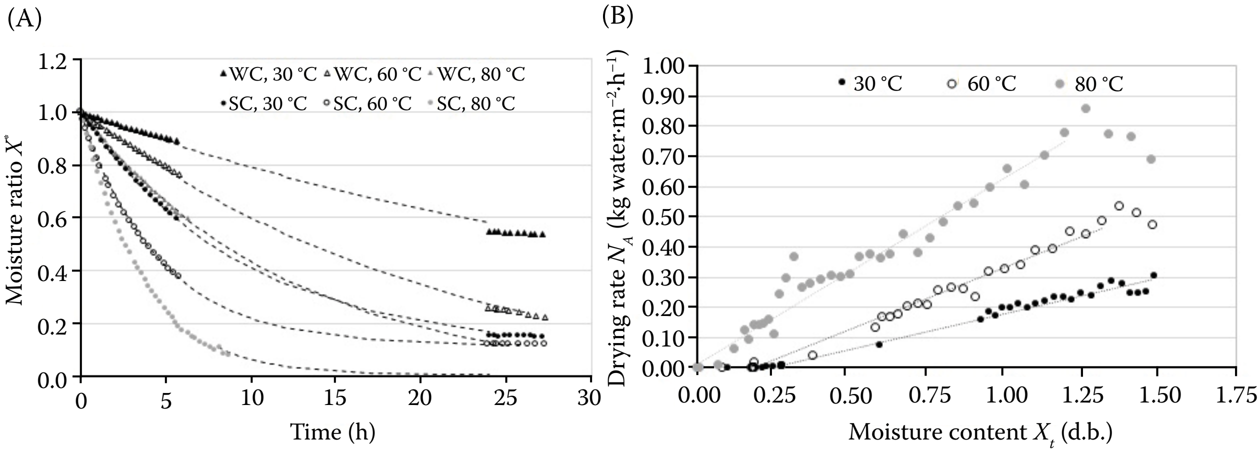

Figure 4. Drying rate of the whole and slashed canes at 30, 60 and 80 °C (A); and effect of the air temperature on the drying rate of the AD slashed canes (B)

WC – whole canes; SC – slashed canes; AD – *Arundo donax* L.; d.b. – dry basis

The drying rate (N_A) calculation is shown in Equation (1) (kg H_2O per m per h) was plotted against the mean moisture content (X_t) as shown in Figure 4B. The falling rate period was observed for both samples and all the temperatures, revealing that the internal flow of liquid to the surface controlled the overall drying process. Similar behaviour was observed for slashed sugar cane by Agote Goyalde et al. (2009) and by Scheufele et al. (2015) for sugar cane bagasse, which indicated that the falling rate period is commonly observed in non-porous solids (e.g. wood, paper, starch, and textile fibres). After the moisture adjustment period, the rate of evaporated water decreased from 0.18 (80 °C) to 0.09 (30 °C) kg water kg per dry cane per h in the SC and from 0.09 (80 °C) kg to 0.03 (30 °C) kg water kg per dry cane per h for the WC revealing significant effects of the temperature and conditioning during harvest on the length of the drying time.

The safe moisture content (SMC) is an essential parameter in post-harvest operations of most agricultural products since it assures the preservation of the materials until further use. No references to this value for AD were found in the literature. Regarding lignocellulosic biomasses, Li and Liu (2000) studied the effects of conditioning over palletisation. They concluded that a moisture content between 5 and 12% produced good quality wood-based pellets from wood residue; Gilbert et al. (2009) found out that 10% is the ideal value to obtain pellets with higher tensile strength. Yancey et al. (2009) studied the effect of moisture content for the grinding tests of lignocellulosic biomass for feedstocks and did not find any induced effect on the particle size when the moisture content was in the range between 10 and 25%. Assuming that 20% is an acceptable moisture content when AD is used as fuel for thermal energy, the required time to achieve this value resulted in times more than 124, 38, and 24 h for the WC and 37, 22, and 7.5 for the SC at 30, 60, and 80 °C, respectively. These results, obtained in laboratory conditions, were significantly lower than those obtained in the field drying since the SC achieved an SMC of 20% after 185 h at a mean environmental temperature of approximately 11 °C, while the WC could not achieve that value.

Effective diffusion coefficient. The experimental data of the moisture ratio during the drying time of the falling rate period were fitted to Equation (9) to obtain the effective diffusion coefficient (D_{eff}) at each temperature. The L factor from Equation (9) corresponds to the thickness of the canes. For WC was used the value 0.0225 m, and for SC 0.0125. No differences were observed in the measured thickness from canes of differents initial moisture contents. The obtained results are shown in Table 3 with the corresponding standard errors and the coefficients of determination.

The multifactor analysis of variance (ANOVA) showed that the effective diffusion coefficients significantly increased with the temperature (46% to 117%, P-value = 0.0000). Still, no significant differences were observed for D_{eff} between the whole and slashed canes at each temperature (maximum difference 13%, P-value = 0.0723). The Arrhenius type-relationship [Equation (10)] was applied to fit the experimental values of the moisture diffusivity with the temperature obtaining a good adjustment (R^2 > 98%) as shown in Figure 5A. The obtained activation energy resulted in 24.4 ± 2.17 and 20.2 ± 2.41 kJ·mol^{-1} for the WC and SC, respectively, not significantly different.

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Table 3. Average values of the moisture diffusivity in the whole ($D_{eff,\,WC}$) and slashed ($D_{eff,\,SC}$) AD canes at each temperature obtained through the adjustment of the experimental data to Equation (9)

Temperature (°C)	$D_{eff,\,WC}$ ($m^2·s^{-1}$)			$D_{eff,\,SC}$ ($m^2·s^{-1}$)		
	value	std. error	R^2	value	std error	R^2
30	3.67×10^{-12}	2.36×10^{-14}	99.917	4.03×10^{-12}	7.96×10^{-15}	99.992
60	7.98×10^{-12}	2.82×10^{-14}	99.974	7.47×10^{-12}	7.72×10^{-14}	99.776
80	1.47×10^{-11}	6.68×10^{-14}	99.924	1.28×10^{-11}	1.08×10^{-13}	99.740

A multifactor ANOVA shows that temperature has a statistically significant effect on D_{eff} at the 95.0% confidence level (P-value = 0.0000), but not significant differences were observed between whole and slashed canes (P-value = 0.0723)

Modelling of the experimental drying data. Several models have been suggested to describe the behaviour of thin-layer drying kinetics. In this study, six different models (Table 2) were fitted to the experimental drying data. The statistical analysis results and the estimated values of the parameters are listed in Table S1 in electronic supplementary material (ESM). Most of the models showed a good fit (R^2 higher than 98%), except the Newton model (30 and 60 °C) and the Henderson and Pabis model (60 °C) for the SC, whose R^2 were between 95 and 97%. Regarding the rest of the statistical parameters, the Logarithmic and the Two-term and Midilli models showed the best fit with the highest R^2 and the lowest *SSE*, *RMSE*, and χ^2. Between them, the Logarithmic model resulted in the simplest one to describe the experimental data and will be selected for further analysis. Several researchers who analysed the drying kinetics of canes, reported different results. Agote Goyalde et al. (2009) indicated that the

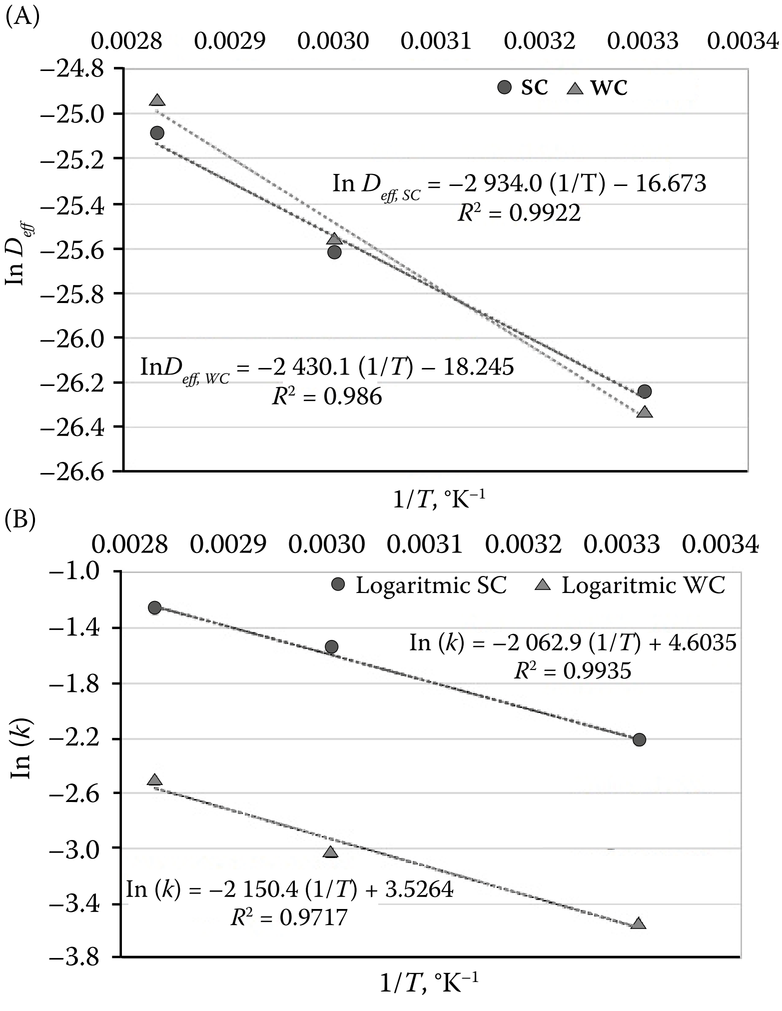

Figure 5. Relationship (A) between the reciprocal absolute temperature and the effective diffusion coefficient of the whole and slashed AD canes and the relationship (B) between the k parameter of the Logarithmic model and the reciprocal of the absolute temperature (1/T) for the AD canes

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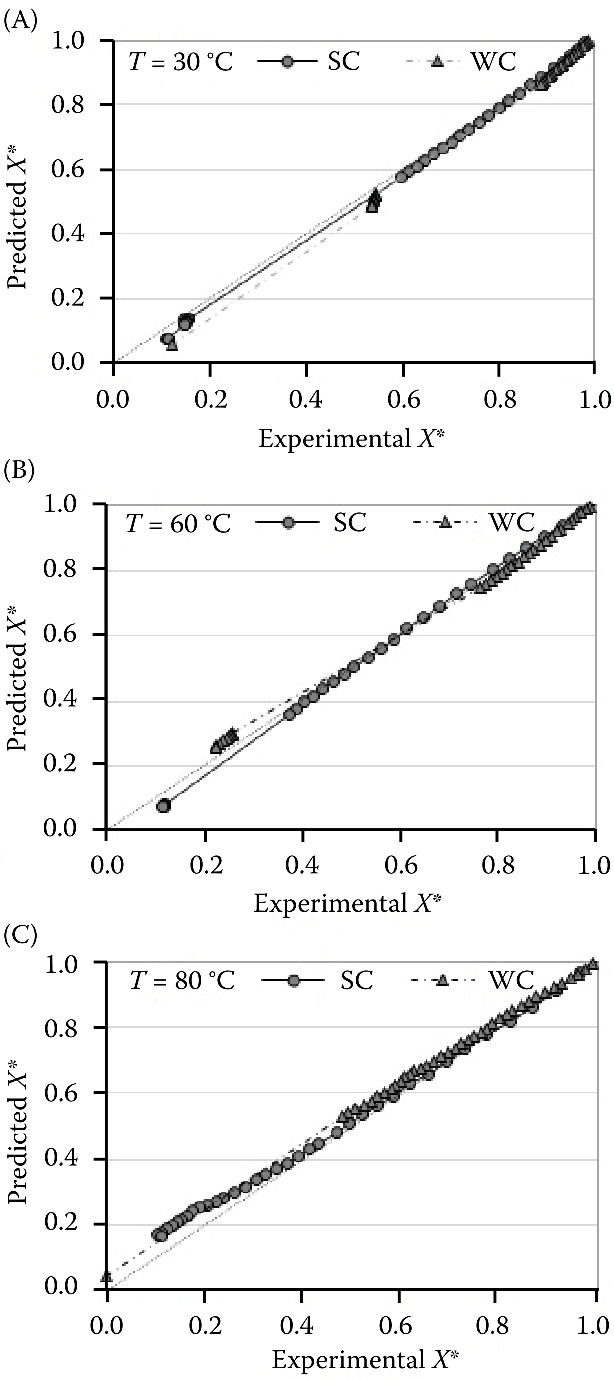

Figure 6. Experimental *vs.* predicted moisture ratio from the Logarithmic model at 30 (A), 60 (B) and 80 °C (C) for the WC and SC

WC – whole canes; SC – slashed canes

Midilli model was the most suitable in representing the drying process of sugar canes, while Scheufele et al. (2015) highlighted that the Lewis, Page, Henderson and Pabis, Logarithmic, Midilli-Kucuk and Two-term exponential models achieved a good fit; however, due to the simplicity and the lowest number of parameters, the Lewis model resulted in the most suitable one in describing the drying kinetics of sugarcane bagasse.

Regarding the temperature dependence of the Logarithmic model parameters, *a* and *b* parameters did not reflect any dependence, therefore, they were averaged (0.978 ± 0.126 and 0.936 ± 0.074 for a and 0.0731 ± 0.0615 and 0.0283 ± 0.1223 for b, of the WC and SC respectively); while the drying constant *k* showed a strong relationship, verified through an adequate adjustment obtained with the Arrhenius equation for both samples ($R^2 > 97\%$) as shown in Figure 5B. The following equations described the relationships found between the moisture ratio X^* of the AD canes with the temperature (°K) and time (h) for each sample based on the Logarithmic model for the studied temperature range:

$$X^*_{WC} = 0.9786 e^{\left(-\left(e^{-2\,150.4\frac{1}{T}+3.5264}\right)t\right)} + 0.0283 \quad (11)$$

$$X^*_{SC} = 0.9363 e^{\left(-\left(e^{-2\,062.9\frac{1}{T}+4.6035}\right)t\right)} + 0.0731 \quad (12)$$

The goodness of the fit of the proposed model was checked by comparing the calculated dimensionless moisture (Predicted X^*) with the measured values (Experimental X^*) obtaining the highest error (as the differences between the measured and modelled data) of 0.038 (30 °C) as shown in Figure 6.

CONCLUSION

The experimental results of the AD drying kinetics demonstrated that conditioning the canes during harvest favoured the moisture loss in the field conditions, which was verified in the controlled laboratory conditions. An increase in the temperature decreased the moisture content, being more accentuated in slashed canes. The moisture transfer was described by Fick's diffusion model giving an effective diffusion coefficient between 3.67×10^{-12} and 1.28×10^{-11} $m^2 \cdot s^{-1}$ showing a significant effect of the temperature and the non-significant influence of the conditioning process, revealed in the close values of the activation energy obtained from the Arrhenius equation of 20.2 and 24.4 $kJ \cdot mol^{-1}$ for the slashed and whole canes, respectively.

The drying data were fitted to six empirical thin-layer models, where the Logarithmic model provid-

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ed the best prediction for all the drying air temperatures studied based on the analysis of the statistical indicators. Furthermore, the temperature dependence equations for the drying constant for the whole and slashed canes included in the Logarithmic model allowed one to predict the loss of moisture in the AD canes with good performance.

The results obtained in this study demonstrated the effect of the air temperature and conditioning of the AD canes on the drying kinetics. The proposed simulation model will contribute in predicting the drying behaviour of AD canes after harvest, thus being a useful tool in the design of new drying systems or to improve the existing ones.

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REFERENCES

Abreu M., Reis A., Moura P., Fernando A.L., Luis A., Quental L., Patinha P., Girio F. (2020): Evaluation of the potential of biomass to energy in Portugal – Conclusions from the CONVERTE project. Energies, 13: 937.

Agote Goyalde N., De Castro Melo E., Pereira Rocha R., Duarte Goneli A.L., Araújo F.L. (2009): Mathematical modeling of the drying kinetics of sugarcane slice. Revista Brasileira de Produtos Agroindustriais, 11: 117–121.

ASAE (2012): ASAE Standard S358.2 (DEC93) – Moisture measurement – Forages.

Barrado N., Elizalde F., Rodríguez D., Laddaga J., Hernández G., Bongiorno C., Vilatte C., D'Alfonso C., Aguas L., Confalone A. (2019): *Arundo donax*, una alternativa para producir energía en el centro de la provincia de Buenos Aires. IV Congreso Nacional de Ciencia y Tecnología Ambiental, 176 (in Spanish).

Basso M., Cukierman A. (2005): *Arundo donax* – Based activated carbons for aqueous-phase adsorption of volatile organic compounds. Industrial & Engineering Chemistry Research, 44: 2091–2100.

Bhaskar T., Bhavya B., Singh R., Naik D.V., Kumar A., Goyal H.B. (2011): Chapter 3 – Thermochemical conversion of biomass to biofuels. In: Pandey A., Larroche C., Ricke S.C., Dussap C.G., Gnansounou E. (eds): Biofuels. Cambridge, Academic Press: 51–77.

Burova N., Kislitsina N., Gryazina F., Pashkova G., Kuzminykh A. (2017): A review of techniques for drying food products in vacuum drying plants and methods for quality control of dried samples (technical note). Espacios, 38: 35–43.

Chandra P.K., Singh R.P. (1995): Applied Numerical Methods for Food and Agricultural Engineers. CRC Press.

Chen S., Danao M. (2015): Modeling the equilibrium moisture content (EMC) of *Miscanthus sinensis*, miscane, energy cane, and energy sorghum. Fuel, 147: 18–26.

Christou M., Alexopoulou E., Cosentino S.L., Copani V., Nogues S., Sanchez E., Monti A., Walter Zegada-Lizarazu L., Pari, A. (2018): Giant reed: From production to end use. In: Alexopoulou E. (ed.): Perennial Grasses for Bioenergy and Bioproducts: Production, Uses, Sustainability and Markets for Giant Reed, Miscanthus, Switchgrass, Reed Canary Grass and Bamboo. London, Academic Press: 64–75.

Córdoba V., Manzur A., Santalla E. (2021): Evaluación tecnológica del potencial energético y ambiental del *Arundo donax* L. In: III Jornadas Internacionales y V Nacionales de Ambiente 2021, May 12–14, 2021, online (in Spanish).

Crank J. (1979): The Mathematics of Diffusion. London and New York, Oxford University Press.

Falasca S., Flores Marco N., Galvani G. (2011): ¿Puede usarse una especie invasora como *Arundo donax* (caña común) con fines energéticos en Argentina? Available at https://inta.gob.ar/sites/default/files/script-tmp-inta_-_arundo_donax_con_fines_energeticos_en_argentin.pdf (in Spanish) (accessed Sept 27, 2021).

Garcia-Perez A., Englund K., Wang Z., Lewis T., Smith M., Zhou S., Das O., Pelaez-Samaniego M. (2011): *Arundo donax* sample preparation, torrefaction and analyses – Final report to the Portland General Electric Company. Available at https://assets.ctfassets.net/416ywc1laqmd/6bJmuBeWhCfmfpQRJAe9gq/c7ac5559392ab1fcbcdb6f5deecf4bf4/portland-ge-final-report.pdf (accessed Sept 27, 2021).

Gilbert P., Ryu C., Sharifi V., Swithenbank J. (2009): Effect of process parameters on pelletisation of herbaceous crops. Fuel, 88: 1491–1497.

Henderson S.M. (1974): Progress in Developing the Thin Layer Drying Equation. ASAE, 17: 1167–1169.

Henderson S.M., Pabis S. (1961): Grain drying theory: Temperature effect on drying coefficient. Journal of Agricultural Engineering Research, 6: 169–174.

Jambor A., Torok A. (2019): The economics of *Arundo donax* – A systematic literature review. Sustainability, 11: 1–22.

Lewis W. (1921): The rate of drying of solid materials. Industrial & Engineering Chemistry, 13: 427–432.

https://doi.org/10.17221/73/2021-RAE

Li Y., Liu H. (2000): High-pressure densification of wood residues to form an upgraded fuel. Biomass and Bioenergy, 19: 177–186.

Mantineo M., D'Agosta G., Copani V., Patanè C., Cosentino S. (2009): Biomass yield and energy balance of three perennial crops for energy use in the semi-arid Mediterranean environment. Field Crops Research, 114: 204–213.

Midilli A., Kucuk H., Yapar Z. (2002): A new model for single-layer drying. Drying Technology, 20: 1503–1513.

Obataya E., Gril J., Perré P. (2005): Shrinkage of cane (*Arundo donax*) II. Effect of drying condition on the intensity of cell collapse. Journal of Wood Science, 51: 130–135.

Page G. (1949): Factors Influencing the Maximum Rate of Air Drying Shelled Corn in Thin-Layers. Purdue University.

Pari L., Scarfone A., Santangelo E., Figorilli S., Crognale S., Petruccioli M., Suardi A., Gallucci F., Barontini M. (2015): Alternative storage systems of *Arundo donax* L. and characterization of the stored biomass. Industrial Crops and Products, 75: 59–65.

Pereyra Müller N., Manzur A., Santalla E., Córdoba V. (2021): Evaluación de *Arundo donax* como biocombustible para la producción de energía térmica. Energías Renovables y Medio Ambiente, 48: 11–17 (in Spanish).

Rodríguez D., Lázaro L., Ressia J., Laddaga J., Grosso J., Bongiorno C., Confalone A. (2021): Producción de biomasa de *Arundo donax* L., un cultivo bioenergético para el centro de la provincia de Buenos Aires. Revista Argentina de Meteorología RADA, 12: 15–20 (in Spanish).

Santalla E.M., Mascheroni R.H. (2010): Moisture diffusivity in high oleic sunflower seeds and kernels. International Journal of Food Properties, 13: 464–474.

Scheufele F., Ribeiro C., Módenes A., Espinoza-Quiñones F., Bergamasco R., Pereira N. (2015): Assessment of drying temperature of sugarcane bagasse on sorption of reactive blue 5G dye. Fibers and Polymers, 16: 1646–1656.

Villalba Vidales J., Arzola De La Peña N. (2015): Modelos matemáticos y experimentales sobre el secado de biomasa. Ingeniería y Desarrollo. Universidad del Norte, 33: 301–330 (in Spanish).

Yancey N., Wright C., Connor C. (2009): Preprocessing moist lignocellulosic biomass for biorefinery feedstocks. In: Proceedings of ASABE 2009 Annual International Meeting, June 21–24, 2009, Reno, USA: 1–17.

Williams C., Biswas T. (2010): Commercial Potential of Giant Reed for Pulp, Paper and Biofuel Production. Adelaide, Rural Industries Research and Development Corporation.

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