



Research Article

Drying Kinetics and Assessment of Relative Energy Cost for Drying of Woody Biomasses

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Abstract

The dynamic porosity concept was applied to the drying of 14 samples of sawdust at 50 °C, 60 % relative humidity and 87 kPa. Determination of the critical extent of drying, where the transition from constant-rate to decreasing-rate kinetic regimes occurs, indicates that *Lecythis ampla* sawdust is the material that allows water diffusion with the highest kinetic and energy efficiency, amongst the set of residual biomasses.

Keywords: Forest biomasses; drying kinetics; drying energy; water diffusivity.

Introduction

Forest and agro-industrial residues are materials of potential value as solid fuels. They must be easy to handle and have the least possible amount of moisture content.

Drying is an energy-demanding operation and therefore it is necessary to understand the supramolecular idiosyncrasies related to the migration of water in porous materials (*dynamic porosity*, that is the combined effect of porosity and of constrictivity and tortuosity of pores) [1].

Optimal combustion of biomasses also depends on their dynamic porosity [1]. Combustion occurs as the initial pyrolysis of the main bio-organic constituents. The resulting decomposition products react with each other and with oxygen in the air feed. Flames are due to combustion of the thermally produced gases and not by combustion of the solid fuel itself. Incomplete combustion gives rise to significant amounts of CO, hydrocarbons and tar that result in lower combustion heats and highly pollutant emissions. The entire combustion process, similar to other

kinds of biomass thermochemical conversions (*e.g.* gasification and pyrolysis), is dependent on internal fluid diffusivity, which is closely related to the dynamic porosity of each material.

A straightforward method we recently published for the quantitative comparison of fluid diffusivity in porous solids [1] is now applied to the determination of the dynamic porosity of sawdust of different species to be considered as energy asset.

Qualitative discussion of the model

The method is based on the kinetic features of drying curves. Loosely-bound water located at particle surfaces evaporates according to zeroth-order kinetics because its vapour pressure remains constant during the time of total coverage of the surface. This constant kinetic regime holds for as long as water molecules arrive at the particle surface as fast as evaporation takes place. This constant rate is independent of the chemical nature of the substrate, and similar to the rate of evaporation of free liquid surfaces.

“Dry islands” on the surface eventually appear once a critical degree of drying is achieved (x_c), and the rate now depends on the residual moisture content and the air-particle interfacial fluxional area. This second stage is due to H₂O-substrate molecular interactions and internal transport limitations. A third stage is often observed at high degrees of drying, when the surface is dry and the evaporation plane slowly gets its way through the matrix up to the surface.

It is tenable that materials with higher x_c values (longer constant-rate periods) correspond to high dynamic porosity. This issue has also been dealt with by Yiotis *et al.* [2] through 3-D-pore network model simulations and by Songok *et al.* [3] on the influence of coating on the drying of paper.

Thus, we present results on x_c and specific effective fluxional area values for 14 types of finely ground saw dust studied at 50 °C. Kinetic results are also discussed as a criterion for energy-cost of drying.

Materials and methods

Materials

The samples were obtained from different sawmills in Costa Rica. *Pinus caribea* sample from La Chonta Sawmill, Cartago. The rest of materials were provided by Inmobiliaria MxM, Maderas Garabito, Maderas Fallas, and Corporación Agrícola Del Monte, all sawmills located in the province of Limón. They were air dried, reduced in size down to finely divided saw dust, and kept in sealed plastic bags.

Drying kinetics and data treatment

All experiments were carried out in laboratory environment kept at 60 ± 5 % relative humidity and 87 kPa barometric pressure.

The solid samples were soaked overnight with tap water. Shortly before the gravimetric measurements, the materials were filtered out (Büchner funnel) and pressed between paper towels to obtain free-flowing solids.

10-g samples were spread loosely on the balance dishes, and mass loss monitored at 50 °C by using Ohaus MB35 Halogen Moisture Analysers. Crude *mass - time* data pairs were subjected to

linear least-square fitting for the set of numbers for which a linear correlation is significant with a $r = 0.9990$. The $-dm/dt$ value corresponds to the initial rate of surface evaporation and the range of validity allows the calculation of x_c . All experiments were carried out in triplicate. Additional runs were carried out when necessary.

The effective surface fluxional area of the samples was calculated from the initial constant rate and the previously determined rate of water evaporation at 50 °C and 87 kPa ($11.37 \text{ mmol s}^{-1} \text{ m}^{-2}$).

All numerical results are given with the magnitude of a standard error from the mean.

Energy-cost of drying

It is possible to obtain energy-cost information from drying kinetics and the operation conditions of the moisture analysers. These instruments run at 110 V and consume 4 A [4].

Thus for a given experiment, the total electrical energy used equals to the amount $110 \text{ V} \times 4 \text{ A} \times \text{time}$. The fraction of electrical energy actually used for the evaporation of water was obtained as the ratio of the evaporation thermal energy of M grams of water ($M \times 2259 \text{ J g}^{-1}$) to the total electrical input. M is the difference between the initial mass of the sample and the final mass of the dried sample. An empirical regression equation was obtained as a function of M :

$$\text{Energy fraction} = 1.091 \times 10^{-3} + 3.520 \times 10^{-4} M - 1.466 \times 10^{-5} M^2$$

Since the heating power is constant and evaporation takes place against a stagnant gaseous surrounding (no significant haulage air currents), the thermal energy needed to achieve the various degrees of drying is solely dependent on the process kinetics.

Results and Discussion

Drying kinetics. Figure 1 shows the kinetic profile for the drying process for the sawdust of *Enterolobium cyclocarpum* at 50 °C, 60 % relative humidity and 87 kPa. The data points correspond to three experiments combined. Note that the constant-rate (dx/dt) extends along the first quarter of the drying process.

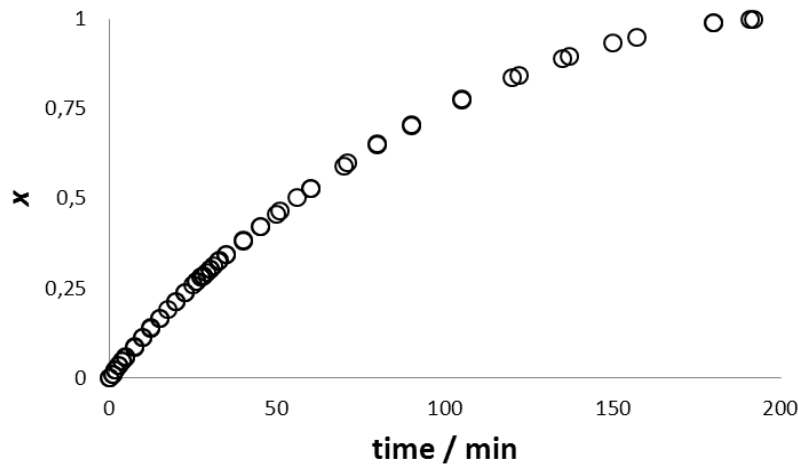


Figure 1: Drying curve of *E. cyclocarpum* sawdust at 50 °C, 60 % relative humidity and 87 kPa

Table 1 gives the x_c and specific fluxional areas of the 14 samples studied. Except for the case of *Lecythis ampla*, no statistically significant difference was found amongst

the 13 remaining biomasses. The mean x_c value resulted equal to 0.26 ± 0.03 (vs. 0.41 ± 0.02 , $p < 0.01$).

Table 1: x_c Parameter and specific effective fluxional areas for the lignocellulosic biomasses at 50 °C, 60 % relative humidity and 87 kPa

Sample	x_c	Specific fluxional area / m ² kg ⁻¹
Carapa guianensis	0.21 ± 0.01	1.0 ± 0.2
Vochysia guatemalensis	0.26 ± 0.03	1.5 ± 0.2
Lecythis ampla	0.41 ± 0.02	1.3 ± 0.1
Tectona grandis L. f.	0.21 ± 0.01	1.3 ± 0.3
Enterolobium cyclocarpum	0.28 ± 0.04	1.7 ± 0.1
Gmelina arborea	0.27 ± 0.03	1.5 ± 0.1
Cordia alliodora	0.27 ± 0.01	1.4 ± 0.2
Ficus werkleana	0.27 ± 0.01	1.876 ± 0.005
Cedrela odorata (orange tint)	0.31 ± 0.02	1.7 ± 0.1
Cedrela odorata (dark tint)	0.31 ± 0.02	1.56 ± 0.01
Pinus caribea	0.24 ± 0.02	1.4 ± 0.4
Samanea saman	0.28 ± 0.03	1.22 ± 0.05
Rollinia sp.	0.25 ± 0.03	1.2 ± 0.2
Hyeronima alchorneoides	0.25 ± 0.05	1.07 ± 0.08

This salient feature of *L. ampla* need not be considered surprising based on details of its anatomy that have been described in the literature [5, 7]. This species' sapwood has a high number of vascular fibres and high density of wide vessels (mean diameter = 150 µm). Its fresh wood is heavy (1.2 g cm⁻³ – 1.3 g cm⁻³) and contains a moisture content of 93 % - 96 %. Many of these

anatomical features must still be present in the water-saturated sawdust.

The specific effective fluxional areas were similar for all biomaterials (1.4 ± 0.2 m² kg⁻¹), a feature we have found common for most lignocellulosic materials. Table 2 shows the specific gravity of the materials studied in this work.

Table 2: Specific gravity of different dry wood samples [5 - 8]

Sample	Specific gravity
Carapa guianensis	0.42 - 0.53
Vochysia guatemalensis	0.33 - 0.41
Lecythis ampla	0.60 - 0.90
Tectona grandis L. f.	0.55 (duramen)
Enterolobium cyclocarpum	0.34 - 0.38
Gmelina arborea	0.42 - 0.64
Cordia alliodora	0.29 - 0.48
Ficus werkleana	0.30 - 0.32
Cedrela odorata (dark tint)	0.32 - 0.45 (duramen)
Pinus caribea	0.48 - 0.53
Samanea saman	0.45 - 0.53
Rollinia sp.	0.34 - 0.36
Hyeronima alchorneoides	0.60 - 0.65

The specific gravity of dry *L. ampla* wood is greater than the mean value for the rest of the materials: 0.75 vs. a mean value of 0.44 ± 0.09 ($p < 0.01$). High values of specific gravity are correlated with thicker xylem walls.

Drying energy cost. Data such as those in figure 1 can be transformed into energy-cost curves, according to the numerical procedure explained in section *Energy-cost of drying*. Thus, thermal energy is given to achieve different degrees of moisture reduction. The case of *E. cyclocarpum* is shown in figure 2

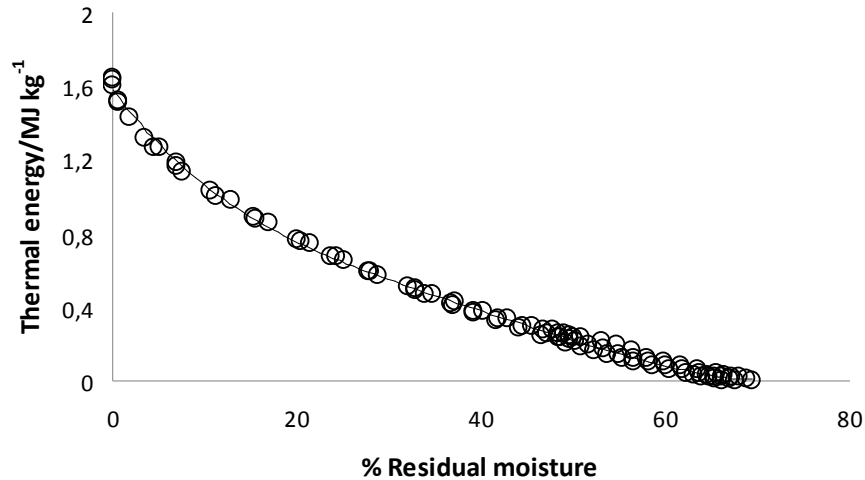


Figure 2: Energy cost for drying *E. cyclocarpum* sawdust at 50 °C, 60 % relative humidity and 87 kPa

All samples give similar values of slope during the first constant-rate stage, as expected from the molecular interpretation of the drying process discussed in the introduction.

Table 3 gives the drying-energy cost for the samples at $x = x_c$ and $x = 1$. The ratio E_c/E_1 is the fraction of thermal energy needed to

achieve x_c (superficial evaporation). The amount $1 - (E_c/E_1)$ is more useful because it gives the fraction of drying energy needed to promote water evaporation during the decreasing-rate stage, when effects other than water volatility control the process: matrix porosity and pore constrictivity and tortuosity.

Table 3: Drying energy for the different sawdust samples at 50 °C, 60 % relative humidity and 87 kPa

Sample	$E_c / \text{MJ kg}^{-1}$	$E_1 / \text{MJ kg}^{-1}$	$1 - (E_c/E_1)$
Carapa guianensis	0.080 ± 0.006	1.0 ± 0.1	0.9 ± 0.1
Vochysia guatemalensis	0.16 ± 0.02	1.4 ± 0.1	0.9 ± 0.2
Lecythis ampla	0.21 ± 0.01	0.87 ± 0.03	0.76 ± 0.03
Tectona grandis	0.114 ± 0.003	1.23 ± 0.02	0.91 ± 0.03
Enterolobium cyclocarpum	0.22 ± 0.02	1.5 ± 0.2	0.8 ± 0.1
Gmelina arborea	0.17 ± 0.02	1.2 ± 0.2	0.9 ± 0.2
Cordia alliodora	0.126 ± 0.008	0.9 ± 0.1	0.9 ± 0.1
Ficus werkleana	0.16 ± 0.02	1.1 ± 0.1	0.9 ± 0.1

Cedrela odorata (orange tint)	0.19 ± 0.02	0.99 ± 0.06	0.81 ± 0.08
Cedrela odorata (dark tint)	0.173 ± 0.001	0.96 ± 0.02	0.82 ± 0.04
Pinus caribea	0.118 ± 0.004	0.95 ± 0.01	0.88 ± 0.03
Samanea saman	0.136 ± 0.007	0.83 ± 0.01	0.84 ± 0.04
Rollinia sp.	0.12 ± 0.01	0.87 ± 0.06	0.86 ± 0.06
Hyeronima alchorneoides	0.084 ± 0.001	0.66 ± 0.04	0.87 ± 0.05

Water evaporation from *L. ampla* sawdust ($x_c = 0.41$) shows lower energy requirement to cope with the biomass internal transport features than the other 13 cases: 0.76 ± 0.03 vs. a mean of $0.87 \pm$

0.03 ($p < 0.01$). For the decreasing-rate period, an empirical regression equation can be obtained as suggested by the plotting of the data in figure 3:

$$(1 - E_c/E_1) = (1.07 \pm 0.01) - (0.79 \pm 0.05) x_c$$

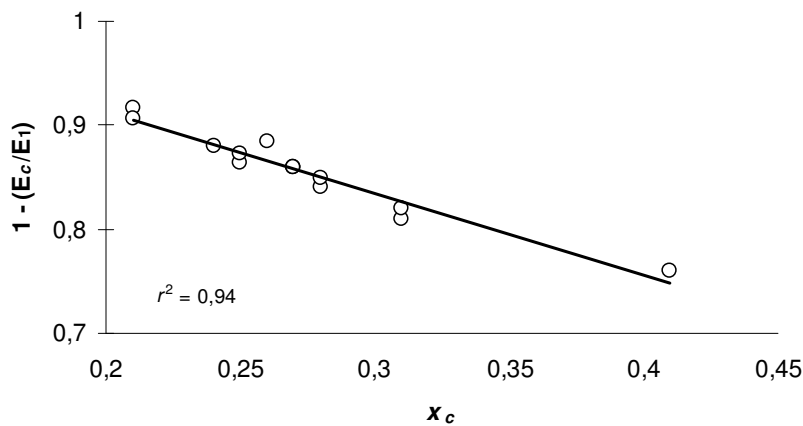


Figure3: Effect of dynamic porosity on the fraction of energy needed for the drying of sawdust samples at 50 °C, 60% relative humidity and 87 kPa

The physical meaning of this empirical correlation is immediate. The easier water diffusivity is in a given matrix, the lower energy requirement is needed to dry the material.

The results obtained could be considered to improve the management required for the use of forest biomasses. In this regard, a key issue is the supply chain optimisation which allows their transportation at lower cost, from the production place to the processing facility. Properties of lignocellulosic materials such as density and water content are fundamental elements to consider. In addition, a good understanding of the concept of dynamic porosity can lead to a better management of biomass in terms of economic efficiency and energy efficiency.

Moreover, measurements related with drying kinetics of forest biomasses represent a useful tool to decide about their pretreatment for a latter use. On this matter, information about dynamic porosity and specific fluxional area obtained from this simple methodology is valuable by itself, but can be also a great complement to more traditional information including chemical composition, cellulose crystallinity and degree of polymerization, particle size, pore size density and calorific power, amongst others.

Conclusions

The results justify the use of the dynamic porosity methodology as a tool to compare the drying energy requirements of porous materials, *e. g.* forest biomasses.

The methodology is simple to perform and allows understanding of macroscopic processing features, in terms of supramolecular idiosyncrasies of materials.

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