

Review

Kinetic Models of Wood Biomass Drying in Hot Airflow Systems

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Abstract: In the field of convective drying, several models have been proposed by different research groups, both theoretical and empirical. However, research on theoretical mathematical models has been superficial and needs to be extended. Empirical models present difficulties in their implementation in other research. It is suggested that further research should focus on obtaining models adaptable to different species and environmental conditions. The aim of this work was to analyse the current state of research on the drying process and mass transfer. It is concluded that drying is a mathematically complex process that must be modelled with differentiated equations in two stages: constant drying rate stage and decreasing drying rate stage. The modelling of the constant drying phase can be based on the convective mass transfer equation, although the prediction of the coefficient with analogies to heat transfer has deviations in biomass. Modelling of the variable rate drying phase should focus on the variation of water diffusivity in porous materials or vapour permeability as a function of material moisture and temperature. A database of homogenised equations particularised for each material needs to be generated to predict drying rates and times under predetermined convection conditions. This represents a scientific challenge and suggests that research in drying kinetics still needs development.

Keywords: drying kinetics; drying time; biomass; bioenergy; biomass treatment; biofuels



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1. Introduction

Drying is the process of removing moisture from a material to a desired level. This serves various purposes, including its use in the production of solid biofuels. However, although it is a frequent process, its mathematical modelling for the prediction of energy and time spent in the process has not been fully developed due to the dependence of multiple factors and process variants [1–3]. The porosity and chemical structure of biomass means that the water particles it contains are subject to capillarity and electrostatic forces, such as hydrogen bonds and van der Waals forces [4]. The variability of biomass structures means that general values cannot be given to the parameters of mathematical models for predicting biomass drying speed. This chapter aims to review the proposals made by different researchers, proposing a standardised assessment procedure that is as close as possible to the physical reality.

Generally, before starting the drying process for the production of solid biofuels, the material is prepared by shredding or grinding. Shredding is the fragmentation of the material to a particle size of a few centimetres (3 to 5 cm). Grinding involves a reduction in the particle size to less than 3 mm. After size reduction, the material can be directly combusted or transformed into other biofuels. The shredded materials can be transformed

into charcoal. The ground material can be used for the production of pellets or briquettes. Although there are probably experiments on drying small particles, it is usual to carry out drying on chipped or crushed material, with a particle size greater than 3 cm. Obviously the small particle size increases the mass transfer surface, but the handling of these particles is more difficult.

After particle size reduction, several drying methods are available. Common methods include the following:

- Air drying: This is the most commonly used method. It involves the use of air to evaporate moisture from the material. The air stream can be forced or natural. The air absorbs the water particles by diffusion and convection [4].
- Vacuum drying: A reduced negative pressure on the surface is used to accelerate the evaporation process. This pressure influences the diffusion of particles inside the pores of the biomass and thus increases the rate of mass transfer [5].
- Radiation drying: In this process, radiant energy is absorbed by the material, which causes the water to evaporate. Electromagnetic radiation can come from various sources, such as electric radiators, infrared lamps, microwaves, or other sources of radiant energy [6]. When the radiation reaches the wet material, some of the energy is absorbed and converted into heat. This heat causes the water to evaporate, allowing it to escape from the material in the form of steam. Radiation drying can be selective, as different materials have different absorption capacities, which affects the speed and efficiency of the drying process. For example, the material may be transparent to microwaves, which will interact exclusively on water molecules, where the heat of evaporation is generated [7].
- Freeze-drying: This involves freezing the material and then removing the water by sublimation under vacuum conditions.

The duration of the process varies according to the method used, the type of material, porosity, and the required moisture level. During the drying process, it is important to control several parameters such as particle size, temperature, relative humidity, air velocity, and vacuum pressure if applicable. It is important to note that the drying process can be critical in the energy balance of biofuel production. Energy efficiency is an important consideration during the design and implementation of industrial drying systems [8]. This is why mathematical modelling for the prediction of process time and quality becomes a scientific challenge that needs to be worked on. Several works suggest that further research should focus on obtaining models adaptable to different species and environmental conditions to improve the applicability of empirical studies. This need parallels the findings observed in the study of Kahrizsangi et al. (2015) [9] where it was demonstrated that environmental factors significantly influence dust generation in vibrated cohesive powders.

On the other hand, drying is also a process widely used in the agri-food and pharmaceutical industry, for example, for drying foodstuffs or wood, and it is for this reason that in-depth knowledge of it becomes necessary in order to optimise it.

Thus, the technical difficulties of predictive modelling of drying processes have led to the development of empirical curves, which, although they allow the results of the process to be obtained with relative simplicity [10,11], only allow their application in the conditions given at the time and place of the experimentation, thus not being able to transport the process to other conditions and obtain the same results.

On the other hand, a significant group of researchers have tried to model drying on the basis of mass transfer phenomena. In this respect, there are two trends in the scientific literature: on the one hand, those who model drying based on diffusivity by Fick's Law (Equation (1)) and mass convection (Equation (2)) [4,12]; on the other hand, those who consider a simplified mass transfer model where the drying speed is proportional to the

difference between the moisture of the material at each instant and the moisture of the material at equilibrium (Equation (3)) [12–17].

$$\dot{m}_w = D_w \cdot \rho_{air} \frac{(\omega_{sat} - \omega_{air})}{L} \quad (1)$$

$$\dot{m}_w = h_m \cdot \rho_{air} \cdot (\omega_{sat} - \omega_{air}) \quad (2)$$

$$\dot{m}_w = K \cdot (x - x_e) \quad (3)$$

where \dot{m}_w is the mass flow rate of water particles in the drying process ($\text{g water m}^{-2} \text{s}^{-1}$), D_w is the mass diffusivity ($\text{m}^2 \text{s}^{-1}$), L is the distance where the difference in humidity in the air occurs (m), h_m is the convective mass transfer coefficient (m s^{-1}), ρ_{air} is the density of the air at the average process temperature ($\text{g} \cdot \text{m}^{-3}$), ω_{air} is the absolute humidity of the air and ω_{sat} is the humidity of the saturated air at the material surface ($\text{g water} \cdot \text{g}^{-1} \text{air}$), K is the overall mass transfer resistance ($\text{g solid m}^{-2} \text{s}^{-1}$), x is the humidity of the material at a given instant, and x_e is the humidity of the material at equilibrium.

However, these models do not work accurately due to a number of influencing factors, such as material porosity, pore size distribution, capillarity, and electrostatic forces. These factors mean that the diffusivity within the material is not constant, and hence neither is the transfer at the solid–air interface [18].

Various mass transfer models attempt to predict the value of h_m from the Sherwood number, which in turn depends on the Reynolds number and the Schmidt number following correlations analogous to those used in the heat transfer model, where Nusselt's number is replaced by Sherwood's number, and Prandtl's number is replaced by Schmidt's number. However, one of the most important limitations of these models is that these numbers depend mainly on the properties of the air flow used in the drying process, but they also depend on the diffusivity, which in most materials is not well determined, since it is not constant but variable with humidity for a given porous structure [19,20]. This represents a scientific challenge that has not yet been addressed in sufficient depth. An interesting study for determining this variability of diffusivity is the one presented by [21]. They present a patented prototype for this purpose.

Table 1 shows a set of works that report the variability of diffusivity with humidity. However, they do not provide equations but rather graphs for their determination.

Table 1. Works that report the variability of diffusivity with humidity in different wood biomasses.

| | |
|---|------|
| Mass diffusivity of low-density fibreboard determined under steady- and unsteady-state conditions: Evidence of dual-scale mechanisms in the diffusion | [19] |
| Moisture diffusion coefficient of reaction woods: compression wood of <i>Picea abies</i> L. and tension wood of <i>Fagus sylvatica</i> L. | [20] |
| Characterization of sorption behavior and mass transfer properties of four central africa tropical woods: Ayous, Sapele, Frake, Lotofa | [22] |
| Experimental determination of the convective heat and mass transfer coefficients for wood drying | [23] |
| Modification of mass transfer properties in poplar wood (<i>P. robusta</i>) by a thermal treatment at high temperature | [24] |
| Comparison of moisture diffusion coefficients for pine, oak and linden wood | [25] |

A key aspect in modelling the drying process is the value of the *Biot* number in mass transfer (4), where h_m is the coefficient of mass transfer by convection, D_w is the diffusivity, and L_c is the characteristic length. This number relates the rate of mass transfer by diffusion within the material and mass transfer by convection at the surface.

$$Biot = \frac{h_m \cdot L_c}{D_w} \quad (4)$$

A large *Biot* number would indicate that the rate of water transfer at the surface is significantly higher than the mobility of water through the material. This would lead to the appearance of moisture gradients. Shallower layers of material would have lower moisture than deeper layers. A high *biot* number is associated with a high convective mass transfer coefficient together with a large characteristic length. A small *biot* number implies a high diffusivity of water through the material, associated with a low convective mass transfer coefficient and small particle sizes. Then, the moisture variation in the drying process can be considered homogeneous without the occurrence of gradients.

The occurrence or not of moisture gradients in the materials during the drying process makes modelling very difficult. On the other hand, there is no general agreement on the value of the *biot* number from which models that consider these gradients, or models that consider uniform moisture during the process, should be used.

A major problem with mass transfer models is that they are influenced by the temperature at which the process takes place and by the latent heat consumption in the change of state. Therefore, models must be developed with these considerations in mind.

The aim of this work has been to analyse the current state of the art of published research on the wood biomass drying and mass transfer process.

2. Air Drying Process

In order to know in depth how the research on wood drying is going at the moment, it is first necessary to understand the process. Drying is actually a mass transfer, i.e., the exchange of mass between two systems due to two processes, diffusion inside the material and convection at the surface [26]. Diffusion is the result of the random movement of molecules at the microscopic level and is caused by the difference in water concentration, causing a movement of these particles from areas of high concentration to areas of low concentration [27]. In convection, in addition to the movement of molecules at the microscopic level, there is the mass movement of water at the macroscopic level, due to the action of a moving fluid on the surface of a mass [26,27].

In the case of forced hot air drying, where an air stream provides the surface heat for evaporation and subsequently carries away the detached particles, surface diffusion could be qualified as a minor process, because the mass exchange it produces is so low that it becomes negligible, with convection reigning in the process.

In a process of drying of a surface of free water deposited on a container, [28–34], and Sherwood and Comings (1933) [35] determined the conditions for calculating D_w and h_m from Reynolds number and Schmidt number to make Equations (1) and (2) applicable, but consider their values constant during the process. In general, their determinations remain applicable as long as the porous mass is saturated with water. However, once the humidity is less than saturation, the models need to be adapted, since D_w and h_m vary with humidity and temperature. On the other hand, they do not consider heat transfer phenomena, which are closely linked to mass transfer phenomena in a drying process.

In order to address these considerations, researchers have dealt with drying in two ways. On the one hand, some research teams have opted for a line based on obtaining equations that describe the process from data obtained experimentally through drying graphs (empirical research) and, on the other hand, they have opted to delve deeper into the mathematical model that describes the process by obtaining parameters with physical significance (theoretical predictive research).

3. Empirical Investigation of the Process

Some experimental investigations, such as those of Babiak and Kudela (1995) [36], show different drying phases. First is the constant-rate period, when the moisture content is above the fibre saturation point (*FSP*). After this point, a period starts where the drying rate decreases rapidly, called the 'falling-rate period'. When the moisture content reaches the equilibrium point, the drying rate reaches zero.

The definition of the FSP has been much debated so far. Zelinka et al. (2016) [37] defined a new process point (based on thermodynamic solutions) different from the FSP, called critical moisture content x_c , which is the most accurate in establishing the transition point from the period of constant drying rate to the period with decreasing drying rate.

In the research of Inoué et al. (2010) [38], studying the effects of dry and wet bulb temperature on the drying times of materials in convective processes with forced air at ambient conditions, forced hot air and superheated steam, they indicated that the critical humidity of the material was not a fixed characteristic of the material, but depended on the air temperature and the drying rate in the constant period. The constant drying rate was calculated from the heat transfer, using Equation (5), where h is the combined heat transfer coefficient of convection and radiation (W/m^2K), T_{bh} is the wet bulb temperature, T is the dry bulb temperature (K), and λ_w is the specific latent heat of evaporation at process temperature (J/kg).

$$\dot{m}_w = \frac{h \cdot (T - T_{bh})}{\lambda_w} \tag{5}$$

Inoué et al. (2010) [38] proposed a linear regression model for the calculation of critical humidity (x_c), obtaining a coefficient of determination $R^2 = 0.97$.

$$x_c = 0.063829 \cdot \dot{m}_w - 0.00168 \cdot T_{bh} + 0.250371$$

In doing so, they concluded that the critical moisture point is low at high wet bulb temperatures and constant at low temperatures. This study of the critical moisture content of the material studied is very important, as it can be very useful in helping to determine the end point of the drying process. Once the critical moisture content has been predicted for the period with constant drying rate, Chanpet et al. (2020) [39] describe the kinetics as follows:

$$\dot{m}_w = -\frac{m_0}{A} \frac{dx}{dt} \quad \text{ó} \quad \frac{dx}{dt} = -\dot{m}_w \frac{A}{M_0} = -k_l$$

$$x = x_0 - k_l t = x_0 - \dot{m}_w \frac{A}{M_0} t$$

where \dot{m}_w is the drying rate (g water/s m²), m_0 and A are the dry mass (g) and its moisture transfer area (m²), and x is the moisture of the solid on a dry basis.

For the period with decreasing drying rate, Chanpet et al. (2020) [39] define the drying kinetics as follows:

$$\dot{m}_w = -\frac{m_0}{A} \frac{dx}{dt} = K(x - x_e) \quad \text{for } \omega < \omega_s$$

$$\frac{dx}{x - x_e} = -K \frac{A}{m_0} dt$$

$$\ln \frac{x - x_e}{x_c - x_e} = -K \frac{A}{m_0} t$$

$$\frac{x - x_e}{x_c - x_e} = e^{-K \frac{A}{m_0} t}$$

where x_c is the critical moisture content that separates the period with constant drying rate from the period with decreasing drying rate, and x_e is the moisture at equilibrium. The first term of the equation is called the MR Moisture Ratio [40], such that:

$$MR = \frac{x - x_e}{x_c - x_e}$$

There are extensive studies relating the variation of moisture ratio (MR) with time in a drying process, such as, [17,41–47]. All of them used empirical models, shown in Table 2,

which are applicable in the drying period of decreasing speed, obtaining their coefficients for particular conditions.

Table 2. Models for calculating the moisture ratio (MR) in drying processes.

| Model Name | Model Equation | Reference |
|----------------------|--|-----------|
| Page | $MR = \frac{x-x_e}{x_0-x_e} = \exp(-k, t^n)$ | [48] |
| Henderson y Pabis | $MR = \frac{x-x_e}{x_0-x_e} = a * \exp(-k, t)$ | [49] |
| Logarithmic | $MR = \frac{x-x_e}{x_0-x_e} = \exp(-k, t) + c$ | [50] |
| Two-term exponential | $MR = \frac{x-x_e}{x_0-x_e} = \exp(-k, t) + (1 - a)\exp(-k, a, t)$ | [51] |
| Diffusion approach | $MR = \frac{x-x_e}{x_0-x_e} = \exp(-k, t) + (1 - a)\exp(-k, b, t)$ | [52] |

An example of empirical research is the work of [53], who tested all the empirical models in Table 1 for the calculation of rubber drying kinetics with a hot air dryer. From each, the parameters of the constants were obtained for particular cases. The model that best adapted to the experimental data obtained in the drying of rubber was that of Henderson and Pabis, for which they found that for a drying temperature of 90 °C, the value of *k* is equal to 0.0008, and that of *a* is equal to 1.038 (with an *R*² = 0.9963 and a mean square error of 0.00015). However, the coefficients *a* and *k* are influenced by the process temperature in such a way that, as the temperature increases, the drying rate is also higher. They also indicated that the physical properties of the rubber might vary, and the equations obtained might not be applicable to different rubbers. In addition, the conditions of their experimentation might not make this model applicable to other drying processes with different test conditions.

Ananias et al. (2020) [54] proposed an estimation of the value of the overall mass transfer resistance (*K*) through the equation:

$$\frac{1}{K} = \alpha_0 \exp\left(\frac{c_0}{T_K}\right)e + b_0 \exp\left(\frac{c_0}{T_K}\right)v^{-P} \exp\left(\frac{-z}{x_{FSP} - x_e}\right)$$

where *x*_{FSP} − *x*_e is the difference between the saturation point of the fibres and the moisture content at equilibrium for a specified air temperature and relative humidity. *T*_K is the temperature in degrees Kelvin (K), *e* is the thickness of the solids to be dried, and *v* is the air velocity. The parameters of this equation particularised for spruce (*Picea abies*) and beech (*Fagus sylvatica*) wood establish the model:

$$\frac{1}{K} = 0.12 \exp\left(\frac{2683}{T_K}\right)e + 23.9 \exp\left(\frac{2683}{T_K}\right)v^{-0.8} \exp\left(\frac{\frac{HR}{100} - 1}{x_{FSP} - x_e}\right)$$

Note that the overall mass transfer resistance only depends on the process temperature, fibre saturation moisture, and moisture at equilibrium. The fibre saturation moisture *x*_{FSP} could be close to the critical moisture *x*_c.

Mierzwa and Musielak (2023) [55], in order to compare the effectiveness of different drying methods from a kinetic point of view, evaluated the drying constant β. For this, they assumed that the evaporation rate of the dried material is proportional to the difference between the mass at one instant *m* and the mass at wet equilibrium *m*_e:

$$\frac{dm}{dt} = -\beta \cdot (m - m_e)$$

where *m*_e is the equilibrium in the bulk sample. Thus, they obtained the following solution to the above equation:

$$m = m_e + C \cdot e^{-\beta t}$$

obtaining the value of the drying constant *C* experimentally.

Chandra and Talukdar (2013) [56] continued their line of research by modelling drying processes of porous and wet materials from experimental data. In this case, hot air drying of potato sheets of predefined dimensions ($4 \times 2 \times 2 \times 2$ cm) was studied, with the dryer air temperatures varying between 40, 50, 60, and 70 °C. The air speed was always 2 m/s. Since 1965, researchers have reached a number of interesting conclusions. The first of these was that, in the first instants of the process, the drying rate is very fast, since the moisture content is high, so at the beginning, the material loses the free water from its surface, for which little energy is required, which is quickly provided by the hot air hitting the object. The density of the material is directly proportional to the moisture content of the material, so the higher the moisture content, the higher the density. When a drying process is carried out, the more the drying process progresses over time, the lower the moisture content of the material and, therefore, the lower the density. To reach this conclusion, Chandra and Talukdar (2013) [56] related the experimentally measured density to the correlation equation created by [57]:

$$\rho = A_1 + A_2 \cdot e^{A_3 x^2}$$

where A_1 , A_2 , and A_3 are constants at a drying temperature of 40 °C (1.08, 0.3, and -0.325 , calculated from a non-linear regression) and x is the moisture content of the material. On the other hand, Mierzwa and Musielak (2023) [55] compared convective microwave drying with hybrid infrared drying.

4. Theoretical Predictive Research

Theoretical predictive research attempts to perform modelling based on the equations of mass and energy balances, together with mass and heat transfer models. The modelling must consider three balances:

Water mass balance

$$\dot{m}_{air} \cdot (\omega - \omega_{air1}) = m_s \cdot (x - x_e)$$

Energy balance in the air

$$\dot{m}_{air} \cdot [(Cp_{air} \cdot T + \omega \cdot (\lambda + Cp_{steam} \cdot T)) - (Cp_{air} \cdot T_1 + \omega_{air1} \cdot (\lambda + Cp_{steam} \cdot T_1))] = K \cdot A \cdot h_w \cdot (x - x_e) + h \cdot A \cdot (T - T_b)$$

Biomass energy balance

$$m_s \cdot (Cp_b + x \cdot Cp_w) \frac{dT_b}{dt} + m_s \cdot \lambda \cdot \frac{dx}{dt} = \dot{m}_{air} \cdot [(\lambda + Cp_v \cdot T_e) \cdot (\omega - \omega_{air1}) + (Cp_{air} + \omega Cp_v) \cdot (T - T_e)]$$

$$\dot{m}_w = \frac{m_s}{A} \cdot \frac{dx}{dt} = K \cdot (x - x_e)$$

T is the air temperature and T_b is the biomass temperature. The unknown variables are ω , T , x , T_b . Salinas et al. (2015) [58] and Pang (2007) [59] already warn that to simulate and model wood drying, it is necessary to implement strong simplifications of the process and the factors that govern it, such as, for example, considering the wood to be dried as a continuous medium, eliminating the heterogeneity of the material, or making the air temperature of the air stream constant during the drying process.

Some authors have designed kinetic models of drying based on mass transfer processes. Tremblay et al. (2000) [23], using an experimental method, sought to determine the convective heat and mass transfer coefficient in *Pinus resinosa* A. based on moisture content, establishing the difference in water potential between the wood surface and the air as the driving force for heat and mass exchange. Their conclusions were that the coefficient varies as a function of air velocity, the higher the velocity, the higher the coefficient, and it is constant up to wood surface moisture content values close to 80%.

Other authors designed drying models based on [60,61], developed by [62–69]. Their models are based on the conservation of energy to model the drying of a pine particle of infinite cylindrical geometry as a porous medium. To do so, they use the following equation:

$$\varepsilon_g + \varepsilon_s + \varepsilon_{fw} + \varepsilon_{bw} = 1$$

where the sum of the volume fractions of each phase (gas mixture: g , solid: s , free water: fw , and bound water: bw) equals 1. Thus, they investigated nine physical properties (effective thermal conductivity, specific heat capacity, intrinsic permeabilities of gas and liquid, relative permeabilities of gas and liquid, capillary pressure, diffusivity of bound water, and effective diffusivity of water vapour) and the transport coefficients of the model. They concluded that these properties showed a noticeable impact on the predicted drying time, of which intrinsic gas permeability was the most influential in the model.

Chávez et al. (2021) [3] developed a model capable of simultaneously simulating mass and heat transfer at low temperature in small wood masses of *Pinus radiata* D. Don. species, predicting the mechanical stresses during the drying process. In particular, the values of the local heat transfer coefficient (h) were calculated by Colburn's Analogy, which allowed finding the values in terms of convective mass coefficients k_r (radial) and k_t (tangential), respectively (Sánchez-Escalona et al., 2020) [70].

$$h_m = k_r \left(\frac{K_w}{D_{air}} \right) \left(\frac{Sch}{Pr} \right)^{-\frac{1}{3}}$$

where h_m is the local mass transfer coefficient (water), k_r is the radial conductivity, K_w is the permeability, D_{air} is the diffusivity, Sch is the Schmidt number, and Pr is the Prandtl number.

Simo-Tagne et al. (2016) [22] modelled for two types of tropical wood (*Triplochiton scleroxylon* K. Schum. and *Terminalia superba* Engl. and Diels.) the heat and mass transfers during drying. For these calculations, they used mostly experimentally collected thermophysical data, the rest being obtained by literature review. The results obtained with their model were compared with those obtained by Luikov's model (1966) [71] and those obtained experimentally. The model was based on:

$$h_m = \frac{D_w \cdot Sh}{D_h}$$

where h_m is the mass transfer coefficient (water), D_w is the water diffusion coefficient caused by the moisture gradient, Sh is the Sherwood number [31–34,72], and D_h is the hydraulic diameter (consecutive distance between two rows of samples).

When comparing results between the model proposed by [73] and that of Luikov, it was found that, although both models showed the same evolution in the moisture content of the sample throughout the drying process, the differences in the evolution of temperature were wide. It should be noted that the proposed model did not take into account factors such as the hygroscopic and non-hygroscopic domains of the adult species [71].

This model is still used in recent studies of drying but needs to improve due to significant deviations [12].

Some authors have introduced a new factor to their research on the drying process, namely the porosity of the material. Thus, Inoué et al. (2009) [74] investigated the impact of pore size distribution on heat and moisture transfer in porous materials during drying. For this purpose, they used both theoretical and experimental approaches and estimated moisture transfer coefficients from them. Thus, the diffusivity of water (D_w) was estimated as:

$$D_w = \frac{\sigma_w}{\eta_w} Kx^3 = (1.604T - 394.3)Kx^3$$

where σ_w is the surface tension of water, η_w is the viscosity of water, and K is the transfer constant of water. Both σ_w and η_w depend on the temperature, while K depends on the pore structure. T is the temperature of the material.

Inoué et al. (2009) [74] analysed the trend that when the sum of convection and radiation heat at the surface of the material is greater than the conduction into the mass, evaporation of moisture at the surface of the material begins and the surface temperature increases. In the first period, the following equations are fulfilled. First, the heat used in the evaporation of water at the surface is equal to the heat received by convection plus the heat received by radiation minus the heat transferred to the interior of the part by conduction.

$$\dot{m}_w \cdot \lambda_w = q_{conv} + q_{rad} - k \left. \frac{dT}{dr} \right]_{r=R}$$

Only when the core temperature reaches the surface temperature does the evaporation rate \dot{m}_w become constant. On the other hand, the flux of water in the interior of the mass and the evaporated water at the surface is equivalent:

$$\dot{m}_{wi} = \dot{m}_w$$

$$D_w \cdot \rho_{solid} \cdot \varepsilon_w \left. \frac{dx}{dr} \right]_{r=R} = h_m \cdot \rho_{air} \cdot (\omega_{sat} - \omega_{air})$$

In the second stage, if there is no local moisture present at the surface (moisture content below critical), the internal water flux \dot{m}_{wi} cannot become equal to \dot{m}_w , and the evaporation plane δ moves inwards into the material. The value of \dot{m}_w decreases because the thermal resistance in the dry region of the material increases, starting the period of decreasing drying rate.

At this stage, the heat received by convection and radiation from the surface is equal to the heat dissipated by conduction into the mass. The plane of desiccation recedes inwards away from the surface. In this plane, a part of the heat received by conduction from the surface is transferred to the evaporating water, and another part is also transferred inwards by conduction.

$$q_{conv} + q_{rad} = k \left. \frac{dT}{dr} \right]_{r=R}$$

$$\dot{m}_{wi} \cdot \lambda_w = k \left. \frac{dT}{dr} \right]_{r=\delta^+} - k \left. \frac{dT}{dr} \right]_{r=\delta^-}$$

$$\dot{m}_{wi} = D_w \cdot \rho_{solid} \cdot \varepsilon_w \left. \frac{dx}{dr} \right]_{r=\delta}$$

$$\dot{m}_w = \frac{\delta^2}{R^2} \cdot \dot{m}_{wi}$$

Inoué’s great contribution is to establish a relationship between the water evaporated on the surface and the water evaporated inside the mass as a ratio of distances squared. In this way, they established relationships between moisture content and temperature, both at the surface and in the core of the material, and drying time. The heat transfer coefficient and the convective water transfer coefficient are calculated as follows:

$$h = \frac{k_{air}}{2R} \left(2.0 + 0.60 \cdot Re^{\frac{1}{2}} \cdot Pr^{\frac{1}{3}} \right)$$

$$h_m = \frac{D_w}{2R} \left(2.0 + 0.60 \cdot Re^{\frac{1}{2}} \cdot Sc^{\frac{1}{3}} \right)$$

5. Conclusions

The conclusions that can be drawn from the literature review are that drying is a mathematically complex process to model and that it is convenient to treat it with equations differentiated into two stages, one for the constant speed drying phase and the other for the decreasing speed drying phase. Although very commendable approximations have been proposed for both, it is a field that still requires further study because the variables involved are conditioned by the type of material (porosity), its humidity, temperature, and convective air conditions (speed, temperature, air humidity).

Modelling of the drying phase with constant velocity can be carried out from the convective mass transfer Equation (2). The use of the Reynolds number and Schmidt number for the calculation of the h_m coefficient with the analogies of the correlations used for heat transfer for the calculation of h , replacing the Prandtl number with the Schmidt number, requires revision, as they present deviations in the biomass, and are not applicable in the drying phase of decreasing velocity.

Suggestions for future research have been introduced in the conclusions and in the discussion of the models. One of the most important is to study the variation of diffusivity as a function of moisture content in porous structures, as well as the variation of the convection transfer coefficient. Some modern research is advancing in this sense, such as [21].

The modelling of the drying phase with variable speed should focus on the variation of D_w or K as a function of the humidity of the material and the temperature. There are initiatives in the measurement of these variables, for example, with patent P202330957 of the Universitat Politècnica de València [21,75]. For this purpose, it is necessary to assume:

$$D_w \cdot \rho_{solid} \cdot \varepsilon_w \left. \frac{dx}{dr} \right]_{r=R} = h_m \cdot \rho_{air} \cdot (\omega_{sat} - \omega_{air})$$

The variability of D_w or K in each material makes it necessary to generate a database of the specific equations for the calculation of these parameters for each type of material as a function of humidity and temperature, i.e., for different types of wood, food, leather, ceramics, minerals, etc. The generation of such a database to be able to predict drying speeds and drying times is a scientific challenge. This means that research into drying kinetics is not an extinct line, but it still requires further development.

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Abbreviations

| | |
|-----------------|---|
| A | Mass transfer area |
| D_w | Mass diffusivity |
| δ | Evaporation plane |
| ε_w | Material porosity |
| h | Convection heat transfer coefficient |
| h_m | Convection mass transfer coefficient |
| λ | Evaporation Enthalpy at 0 °C (Latent heat) |
| λ_w | Enthalpy of evaporation at one temperature (latent heat) |
| k | Thermal conductivity |
| K | Overall mass transfer resistance |
| L | Distance where the difference in humidity in the air occurs |
| m_s | Solid mass |
| \dot{m}_{air} | Airflow |

| | |
|----------------|--|
| \dot{m}_w | Evaporated water flow on an external surface |
| \dot{m}_{wi} | Evaporated water flow on an external surface |
| T | Air temperature |
| T_b | Biomass temperature |
| ω | Instantaneous air humidity |
| ω_{air} | Absolute air humidity |
| ω_{sat} | Absolute humidity of saturated air at the material surface |
| x | Solid material moisture |
| x_c | Critical humidity |
| x_e | Material moisture at equilibrium |
| x_0 | Initial material moisture |

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