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Assessment of Drying Temperature and Initial Moisture on Beans and Corn Seeds Drying Kinetics and Transport Properties

Avaliação da Temperatura de Secagem e Umidade Inicial na Cinética de Secagem e Propriedades de Transporte de Sementes de Feijão e Milho

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The purpose of this study is to assess the drying temperature and initial moisture content on beans and corn seeds drying kinetics and transport properties. It was verified that the best empirical lumped models fitting whereas obtained by Approximation of Diffusion and Hii, Law and Cloke models. This was expected because the fitting tends to improve as the model has more parameters. However, despite having only two parameters, the Page model showed good fitting in all conditions analyzed, therefore, this generalized model could predict experimental data with a maximum global deviation of around 10.0 %. The distributed parameter model assessed moisture content distribution inside the grain, which could predict experimental data with an overall deviation of around 10.0 %. Results indicated that both drying temperature and initial moisture have a significant influence on drying rates and mass transfer coefficients and verified that it is not advisable to neglect the influence of the initial moisture content and its distribution along the position inside the material for beans and corn seeds drying studies.
Keywords: empirical models, distributed parameters, generalized model.

O objetivo deste estudo é avaliar a temperatura de secagem e o teor de umidade inicial na cinética de secagem e propriedades de transporte em sementes de feijão e milho. Verificou-se que o melhor ajuste de modelos empíricos concentrados foi obtido pelos modelos de Aproximação de Difusão e Hii, Law e Cloke. Isso era esperado porque o ajuste tende a melhorar conforme o modelo tem mais parâmetros. No entanto, apesar de ter apenas dois parâmetros, o modelo de Page apresentou bom ajuste em todas as condições analisadas, portanto, este modelo generalizado conseguiu prever dados experimentais com um desvio global máximo em torno de 10,0 %. A distribuição do teor de umidade no interior do grão também foi avaliada pelo modelo de parâmetros distribuídos, que pode prever dados experimentais com um desvio global em torno de 10,0 %. Os resultados indicaram que tanto a temperatura de secagem quanto a umidade inicial têm influência significativa nas taxas de secagem e nos coeficientes de transferência de massa e verificaram que não é aconselhável desprezar a influência do teor de umidade inicial e sua distribuição ao longo da posição no interior do material para estudos de secagem de sementes de feijão e milho.
Palavras-chave: modelos empíricos, parâmetros distribuídos, modelo generalizado.

1. INTRODUCTION

Beans and corns are one of the main grains produced worldwide, being widely used for oil, fuel, and flour production, beyond being consumed directly by humans and animals. These grains are produced seasonally, however, there is demand for these materials throughout the year, requiring storage [1].

To carry out the storage, the moisture content of beans must be reduced from 16 – 20 % on a dry basis (d.b.) to 12 – 14 % (d.b.) and corn from 25 – 28 % (d.b.) to 12.5 – 14 % (d.b.), to preventing the growth and reproduction of microorganisms, reducing storage and processing costs, extending the useful life of the grain or seed, in addition to increasing its value. The drying process can be applied to remove the moisture content in the beans and corn [2-7].

Nowadays, the most used method for carrying out the drying of grains from the harvest is convective drying. During this process, heat and mass transfer occur simultaneously, and the heat supplied from the air to the wet product is due to convection, which is necessary for the evaporation of the moisture content present on the surface of the grain [3].

Currently, several researchers perform simulation models of grain drying, to design new drying systems or improve existing systems. Normally, semi-theoretical and empirical models are used to design dryers [3, 8].

Regarding the semi-theoretical models of drying agricultural products, these are based on moisture diffusion, considering that there is resistance to water diffusion in the outer layer of the material. They are usually derived from Fick's second law [8-10].

In the case of empirical models, they normally provide good results about the drying behavior, being constituted by a direct relationship between the average moisture content and the drying time. Some researchers have verified the application of semi-theoretical and empirical models performing thin layer drying for agricultural materials, these materials being: turmeric, *Mentha spicata*, garlic, pomegranate peel, lemon, *Jatropha curcas* seeds, green peas, apple, raspberries, and kiwi [11-20].

Among the factors that influence the applied models of conventional thin layer drying, there are air temperature, which influences drying rates, material thickness, which may affect drying kinetics, and initial moisture content, which may affect drying rates [8, 21]. However, several drying lumped parameter models neglect the influence of moisture content distribution on drying rates, being this moisture profile related to the initial moisture content of the material in contact with ambient air.

Due to this, the objective of this work is to assess the drying temperature and initial moisture content on beans and corn seeds drying kinetics and transport properties. Empirical lumped parameter models of drying kinetics for beans and corn seeds were fitted based on experimental data of moisture content over time, and they were generalized in the function of air temperature and initial moisture content. Distributed parameter models were also fitted to assess the influence of the initial moisture content on the drying kinetics and to estimate the moisture profile along the position inside the seed.

2. METHODS AND MATERIALS

2.1 Drying

The beans and corn used in this article were donated by a local farmer (Apucarana, Brazil) and stored at room temperature without the incidence of light for a period of 2 months, until the completion of drying. The initial moisture content of beans after the storage is around 14 % (d.b.) and of corn seeds around 9 % (d.b.). The moisture content of beans was obtained during drying at temperatures of 40, 60, and 80°C, and for the corn seed the temperatures used were 40, 55, and 70°C, in duplicate, using a conventional laboratory oven (Nova Ética). For this procedure, 100.00 g of beans and corn were placed in a thin layer. For beans and corn, experiments were conducted for 120 minutes and 90 minutes, respectively.

2.2 Moisture determination

Samples remained in the oven for each predetermined temperature and time condition, and the evaporated water was measured by the variation of the mass sample every 5 minutes. In sequence, samples remained in the oven at 105°C for 24 hours to determine the moisture content.

2.3 Lumped parameter models

For the mathematical modeling of the beans and corn drying process, the global mass balance equation was applied with a single seed as the system. The variation in the mass of water in the seed was considered equal to the rate of evaporated water over time.

Using the lumped parameter model, the output of water of the material is obtained by multiplying the mass flow (N_{water}) and the grain surface area (As_{grain}) (Equation 1).

$$dm_{water}/dt = -N_{water}As_{grain} \quad (1)$$

The mass flow of evaporated water can be estimated by Equation 2:

$$N_{water} = K_s(Y_s - Y_{se}) \quad (2)$$

K_s is the convective mass transfer coefficient, Y_s is the moisture content of the material on a dry basis (d.b) and Y_{se} is the moisture content at equilibrium (d.b). Replacing the Equation 2 in 1 and writing the variable m_{water} in terms of moisture content, Equation 3 is obtained.

$$dY_s/dt = -K_s(Y_s - Y_{se})As_{seed}/m_{ss} \quad (3)$$

It is possible to rewrite Equation 3 in the function of the global mass transfer coefficient (K), described by Equation 4.

$$K = K_sAs_{seed}/m_{ss} \quad (4)$$

Equation 4 can also be expressed as the model proposed by Lewis (1921) [22] (Equation 5).

$$dY_s/dt = -K(Y_s - Y_{se}) \quad (5)$$

Equation 5 can be used in studies of grains and seeds thin layer drying. For the conventional drying process, some researchers assume empirical expressions to obtain the parameters of the drying kinetics, and these expressions are solutions to the model proposed by Lewis (1921) [22]. Some models applied to the conventional drying kinetics are described in Table 1.

Table 1: Mathematical models.

Model	Equation	References
Newton	MR= exp(-kt) (6)	Lewis (1921) [22]
Page	MR= exp($-kt^n$) (7)	Simal et al. (2005) [23]
Henderson and Pabis	MR= aexp(-kt) (8)	Henderson and Pabis (1961) [24]
Logarithmic	MR= aexp(-kt)+c (9)	Yaldiz et al. (2001) [25]
Midilli	MR = aexp($-kt^n$)+bt (10)	Midilli (2002) [26]
Two term	MR = aexp($-k_0t$)+bexp($-k_1t$) (11)	Colson and Young (1990) [27]
Approximation of Diffusion	MR = aexp(-kt)+(1-a)exp(-kbt) (12)	Sobukola et al. (2007) [28]
Hii, Law and Cloke	MR = a exp($-kt^n$)+cexp($-gt^n$) (13)	Hii et al. (2009) [29]

MR is the moisture ratio (Ys-Yse)/(Y_0-Yse), and Y_0 is the initial moisture content of the beans and corn. After obtaining the drying kinetics for the experimental data, a general equation was adjusted, considering the influence of the initial moisture of the material and the drying temperature.

2.4 Distributed parameter models

To assess the influence of the initial moisture on drying kinetics, the technique of distributed parameters model can be used, in which the moisture profile of the grain and seed is estimated along the position inside the material [21].

In this technique, the factors that can be evaluated are the influence of the moisture profile inside the material on drying rates, in addition to diffusion assessment. This technique can be described by using Fick's Second Law of Diffusion in spherical coordinates (Equation 14), in which D was considered to be constant, the bean considered a sphere, and corn, which is an ellipsoid, was considered as a sphere using the equivalent diameter ratio, and they have a symmetrical moisture distribution [21, 30]:

$$\frac{\partial \mathrm{Y_s}}{\partial t} = D\left(\frac{2}{r}\frac{\partial \mathrm{Y_s}}{\partial r} + \frac{\partial^2 \mathrm{Y_s}}{\partial r^2}\right) \quad (14)$$

r corresponds to the radius of the material. To solve Equation 14, an initial homogeneous distribution of moisture (Equation 15) was assumed, in addition to two boundary conditions. It was also assumed symmetry at the center of the material (r = 0) (Equation 16), and the diffusive flow is equivalent to the convective flow at the surface of the material, during the entire drying process [21, 30]:

$$\mathrm{Y_s}(\mathrm{r}, 0) = Y_0 \quad (15)$$

$$\frac{\partial \mathrm{Y_s}}{\partial r} = 0 \qquad t > 0 \quad (16)$$

$$-\rho_{DC} D\frac{\partial X}{\partial r} = \rho_a Kc(Y_R - Ys_e) \qquad t > 0 \quad (17)$$

Kc is the convective mass transfer coefficient, ρ_{DC} is the density of the dry grain and seed, ρ_a is the air density and X_R is the moisture content on the surface of the material.

To solve Equation 14, a new differential equation can be obtained at the grain center, employing L'Hospital's rule (Equation 18). This new equation is used due to the indeterminacy of the quotient (2/r) when r → 0 [21].

$$\frac{\partial X}{\partial t} = 3D\left(\frac{\partial^2 X}{\partial r^2}\right) \quad (18)$$

The non-dimensionalization technique was applied to facilitate the numerical solution due to the high difference of the order of magnitude between radius and time [21]:

$$t^* = t/t_{max} \quad (19)$$

$$r^* = r/R \quad (20)$$

R corresponds to the value of the radius on the surface of the bean and corn and t_{max} is the maximum value of the drying time.

2.5 Statistical analysis

Statistical analysis performed to verify the fitting of the models were the reduced chi-square (γ^2), mean squared error (MSE), root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), and modeling efficiency (EF), represented by Equations 21 to 25, respectively.

$$\gamma^2 = \sum\left(\mathrm{Ys_{exp}} - \mathrm{Ys_{cal}}\right)^2/(\mathrm{N_o} - \mathrm{N}_c) \quad (21)$$

$$\mathrm{MSE} = \sum\left(\mathrm{Ys_{exp}} - \mathrm{Ys_{cal}}\right)^2/\mathrm{N_o} \quad (22)$$

$$\mathrm{RMSE} = \left(\sum\left(\mathrm{Ys_{exp}} - \mathrm{Ys_{cal}}\right)^2/\mathrm{N_o}\right)^{\frac{1}{2}} \quad (23)$$

$$\mathrm{NRMSE} = \mathrm{RMSE}/(\mathrm{Ys}_{\mathrm{max}} - \mathrm{Ys}_{\mathrm{min}}) \quad (24)$$

$$\mathrm{EF} = \left(\sum\left(\mathrm{Ys}_{\mathrm{exp}} - \overline{\mathrm{Ys}}_{\mathrm{exp}}\right)^2 - \sum\left(\mathrm{Ys}_{\mathrm{cal}} - \mathrm{Ys}_{\mathrm{exp}}\right)^2\right) / \sum\left(\mathrm{Ys}_{\mathrm{exp}} - \overline{\mathrm{Ys}}_{\mathrm{exp}}\right)^2 \quad (25)$$

N_0 corresponds to the number of observations, N_c the number of constants of the model, $\overline{\mathbf{Ys}}_{\mathbf{exp}}$ the value of the average experimental moisture content on a dry basis, Ys_{max} and Ys_{min} the values corresponding to the maximum and minimum moisture content on dry basis observed, respectively.

For the γ^2, MSE, RMSE, and NRMS parameters, the best adjustment occurs when their values are closest as possible to 0. As for EF, the best value corresponds to the one nearest to 1.0 [31].

2.6 Equilibrium moisture content

To determine the equilibrium moisture content of beans and corn as a temperature function, 10 crucibles with samples distributed in a monolayer were used. Each crucible was weighed together with the material at room temperature and the samples remained in a kiln for a period of 9 days. Each day, the temperatures were increased to 30, 40, 50, 60, 70, 80, 90, 100, and 105 °C, successively, and the measures were carried out to quantify the mass of the samples, thereby determining the equilibrium moisture as a function of temperature. The final temperature employed was 105 °C, to ensure that all water contained in the grain and seed was evaporated. It is known that equilibrium moisture content is also a function of air humidity. However, experiments were conducted under conditions of similar air absolute moisture content.

3. RESULTS AND DISCUSSION

3.1 Mathematical fits for beans

The mean values of the statistical parameters for the lumped parameter models fitting at different drying conditions for beans are shown in Table 2.

Table 2: Statistical parameters for kinetic models of bean drying.

Model	γ^2	MSE	RMSE	NRMSE	EF
Newton	3.27E-05	3.14E-05	4.39E-03	5.54E-02	9.55E-01
Page	3.80E-06	3.49E-06	1.52E-03	2.14E-02	9.94E-01
Henderson and Pabis	1.85E-05	1.70E-05	3.28E-03	4.25E-02	9.75E-01
Logarithmic	3.32E-06	2.92E-06	1.34E-03	2.15E-02	9.92E-01
Midilli	1.71E-05	1.44E-05	2.86E-03	3.58E-02	9.77E-01
Two term	7.96E-06	6.68E-06	1.84E-03	2.56E-02	9.87E-01
Approximation of Diffusion	**8.11E-07**	**7.11E-07**	**7.17E-04**	**1.12E-02**	**9.98E-01**
Hii, Law and Cloke	**4.18E-07**	**3.28E-07**	**4.71E-04**	**7.65E-03**	**9.99E-01**

According to Table 2, it was verified through the statistical analyses that the best fits (in bold) were obtained by the Approximation of Diffusion and Hii, Law and Cloke models. These results are expected, as these models have a high number of constants, and the fit tends to be better as the number of constants in the model increases [32-35]. In addition, it was verified that the Newton model was the least adequate, as it has values farther from 0 for the statistical parameters of γ^2, MSE, RMSE, and NRMSE and a lower value of EF.

However, despite having only two parameters, it can be seen that Page's model showed a good fitting, and it can be the model chosen to carry out the generalization, being able to predict experimental data as a function of air temperature and initial moisture of beans.

This model was chosen because it has a good statistical fitting, and as the number of parameters increases the influence of the initial moisture content of the sample and the drying temperature is considered. The dependence of Page's model parameters, both as a function of initial moisture content and temperature, can be observed in Figure 1.

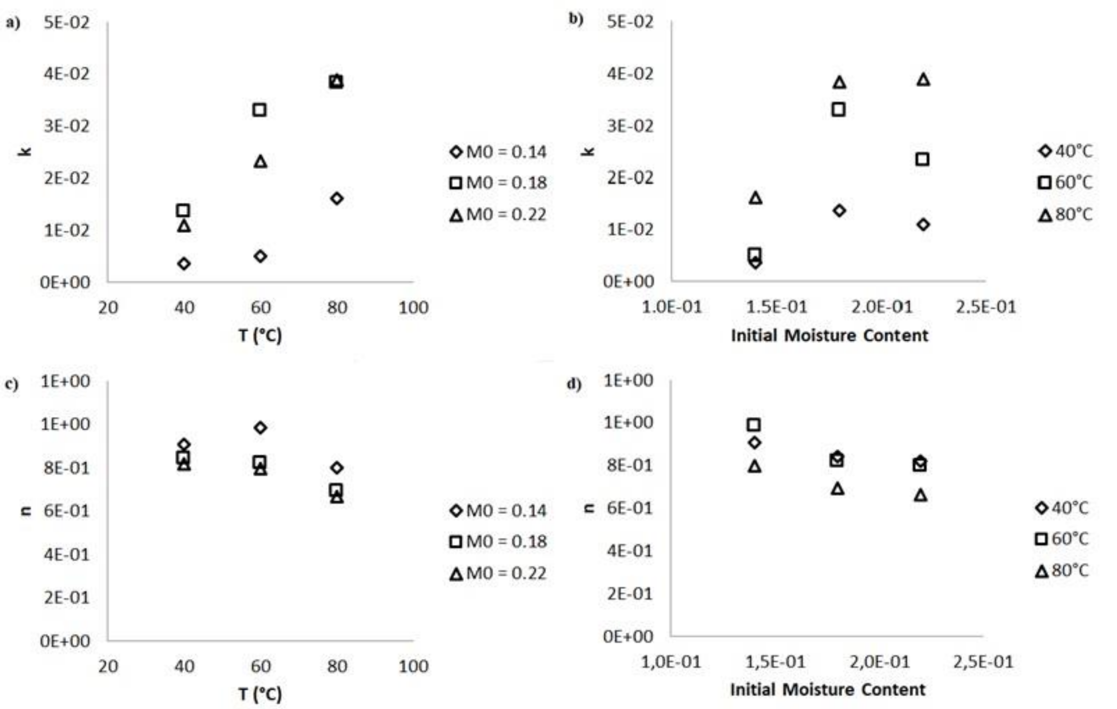

Figure 1: Dependence of Page model parameters as a function of initial moisture content and temperature for bean grain.

Figures 1. a and 1. c demonstrate a variation of the parameters k and n with the drying temperature, and Figures 1. b and 1.d show that there is also a variation of the parameters with the initial moisture content of the beans. The parameters k and n were adjusted as a function of the temperature and the initial moisture content, being presented by Equations 26 and 27 for beans:

$$k = A_1 + A_2T + A_3Y_0 + A_4TY_0 \quad (26)$$

$$n = A_5 + A_6T + A_7Y_0 + A_8TY_0 \quad (27)$$

T corresponds to the drying temperature and Y_0 to the initial moisture content of the material. The values obtained from the statistical parameters for the generalized model of Page are shown in Table 3, and the adjusted values of parameters k and n are described in Equations 28 to 29.

Table 3: Statistical parameters for the generalized model of Page for beans.

Model	γ^2	MSE	RMSE	NRMSE	EF
Generalized model of Page	2.44E-05	1.73E-05	4.16E-03	7.42E-02	8.87E-01

$$k = -4.74.10^{-2} + 1.72.10^{-4}T + 2.53.10^{-1}Y_0 + 1.03.10^{-3}TY_0 \quad (28)$$

$$n = 2.32 - 1.43.10^{-2}T - 7.66Y_0 + 6.67.10^{-2}TY_0 \quad (29)$$

Considering the values obtained from the statistical parameters, it can be verified that the generalized model of Page presented good fitting, which indicates that it can be applied to the simulation and optimization of drying of beans in a thin layer. Figure 2 shows the graph of the experimental and predicted data for the generalized model of Page, in which experimental data could be predicted with a maximum overall deviation lower than 10.0 %.

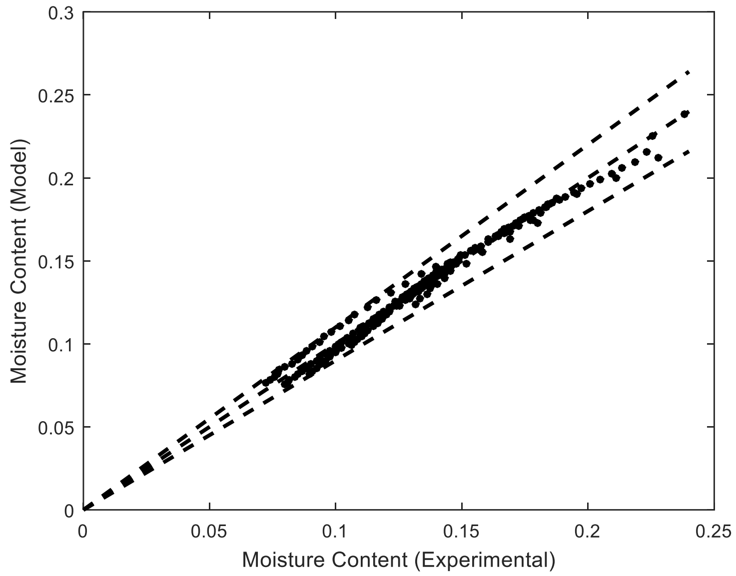

Figure 2: Predicted and experimental data for general Page model for beans. Maximum overall deviation of approximately 10.0% compared to the experimental data.

As the Page model's parameters were influenced by initial moisture content, it can indicate that the distribution of moisture content may influence drying rates. Initially, it can be assumed that the moisture content is evenly distributed throughout the interior of the material, from the surface to its center, as samples were in equilibrium with ambient air.

However, the longer the drying time, the more unsaturated the grain surface becomes, resulting in a grain with a greater amount of moisture in its center in comparison to its surface [21, 35]. This difference in moisture content along the material influences drying kinetics, causing a decrease in drying rates, namely the diffusion of water inside the material enhances its influence on drying rates over time. In this context, at this moment, the velocity that the water takes to achieve the grain surface is the phenomenon that controls the process.

These results can be verified in Figure 3, which shows the drying rates for different moisture contents. For samples with different initial moisture content, it can be observed that they do not present the same drying rates when comparing the same moisture content level. This can be observed since curves do not overlap each other during most of the drying process.

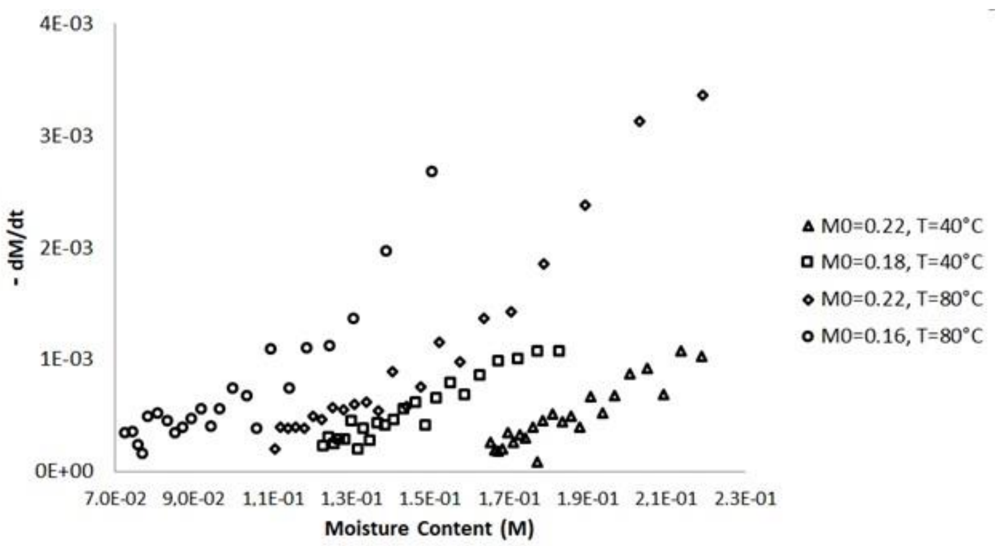

Figure 3: Drying rates for beans at temperatures of 40 and 80 °C.

For example, for beans, at 80ºC, samples with an initial moisture content of 22% present a lower drying rate at a moisture content of 15%, in comparison to samples with an initial moisture content of 16% at 15% of moisture content. Samples initially with 16% at 15% of moisture content present higher levels of moisture content near the surface than samples initially with 22% at 15% of moisture content.

In this context, these results indicate that models that neglect the effect of moisture content distribution may not be adequate to be applied to studies that consider different initial moisture content that they were fitted, as presented by Defendi et al. (2016) [21], with soybeans**.** Therefore, the distributed parameters models can be applied to verify the influence of the initial moisture content on the drying kinetics, in addition to estimating the moisture profile along the position inside the grain [13].

Considering that the diffusivity value (D) (Equation 14) is constant throughout the material, $\rho_a Kc = 4.5.10^{-2}$ kg/m²s [21], the equivalent radius of 3.63 mm, and that the material is a sphere that has a symmetrical moisture distribution from the center to the surface, D values were adjusted for all drying conditions (Table 4), and the drying kinetics of the distributed parameter model and the moisture distribution profiles within the material over time were arranged in the Figures 4 and 5, respectively [21].

Table 4: Diffusivity values and statistical analysis for the eight drying conditions for beans.

Drying Condition	D (m²/s)	γ2	MSE	RMSE	NRMSE	EF
1 - 40 °C Y_0 = 14 % (d.b.)	8.88E-12	2.76E-06	2.54E-06	1.59E-03	9.09E-02	9.10E-01
2 - 40 °C Y_0 = 18 % (d.b.)	5.28E-11	2.43E-05	2.24E-05	4.73E-03	8.16E-02	9.27E-01
3 - 40 °C Y_0 = 22 % (d.b.)	2.97E-11	2.98E-05	2.74E-05	5.24E-03	8.44E-02	9.24E-01
4 - 60 °C Y_0 = 19 % (d.b.)	6.83E-11	1.52E-05	1.40E-05	3.74E-03	4.76E-02	9.71E-01
5 - 80 °C Y_0 = 14 % (d.b.)	5.22E-11	2.06E-05	1.90E-05	4.35E-03	6.87E-02	9.44E-01
6 - 80 °C Y_0 = 17 % (d.b.)	1.06E-10	1.58E-05	1.45E-05	3.81E-03	4.02E-02	9.79E-01
7 - 80 °C Y_0 = 19 % (d.b.)	7.99E-11	2.91E-05	2.68E-05	5.17E-03	5.27E-02	9.66E-01
8 - 80 °C Y_0 = 24 % (d.b.)	8.74E-11	3.82E-05	3.51E-05	5.93E-03	4.63E-02	9.73E-01

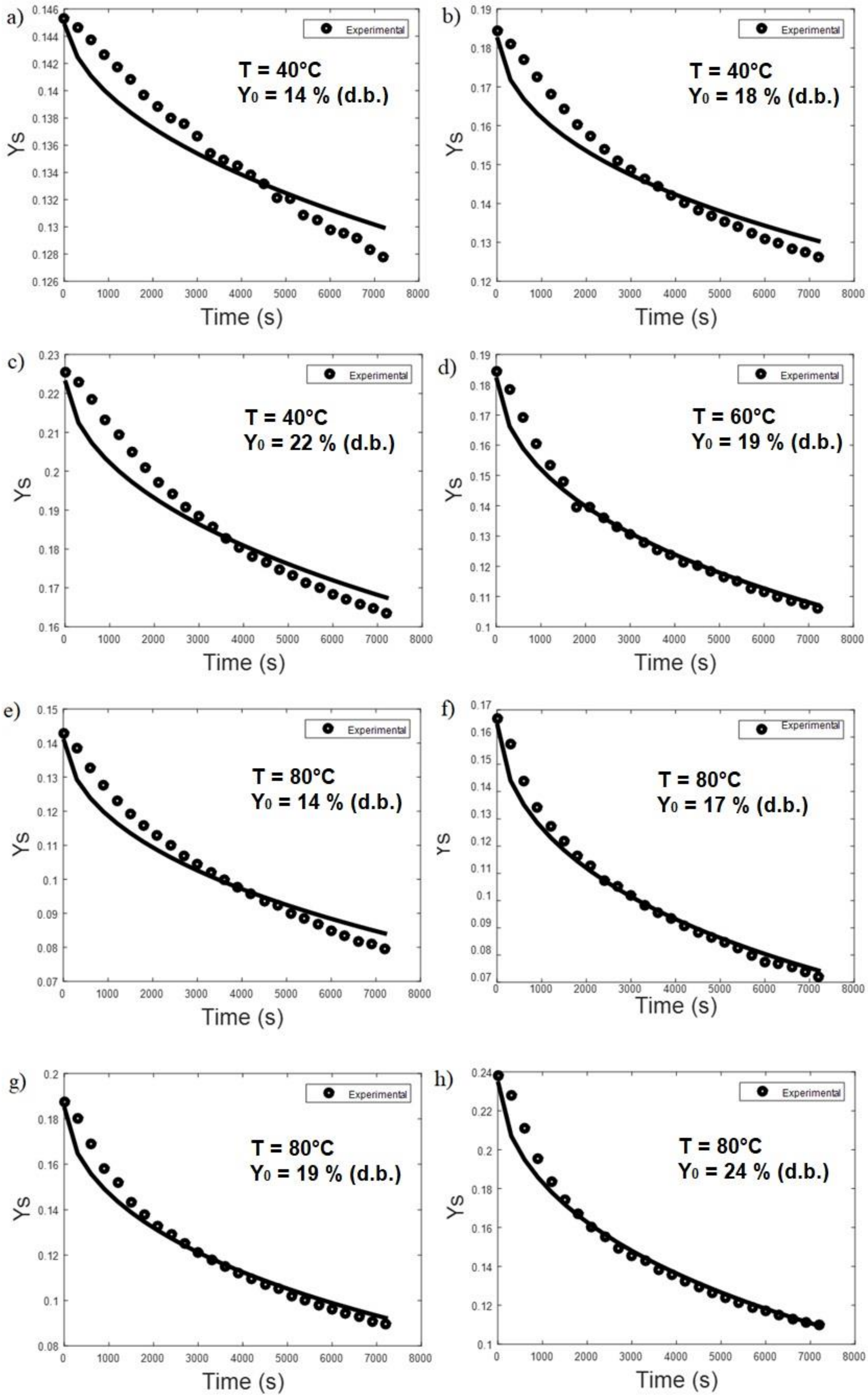

Figure 4: Beans drying kinetics with distributed parameter model. (a) Condition 1; (b) Condition 2; (c) Condition 3; (d) Condition 4; (e) Condition 5; (f) Condition 6; (g) Condition 7; (h) Condition 8.

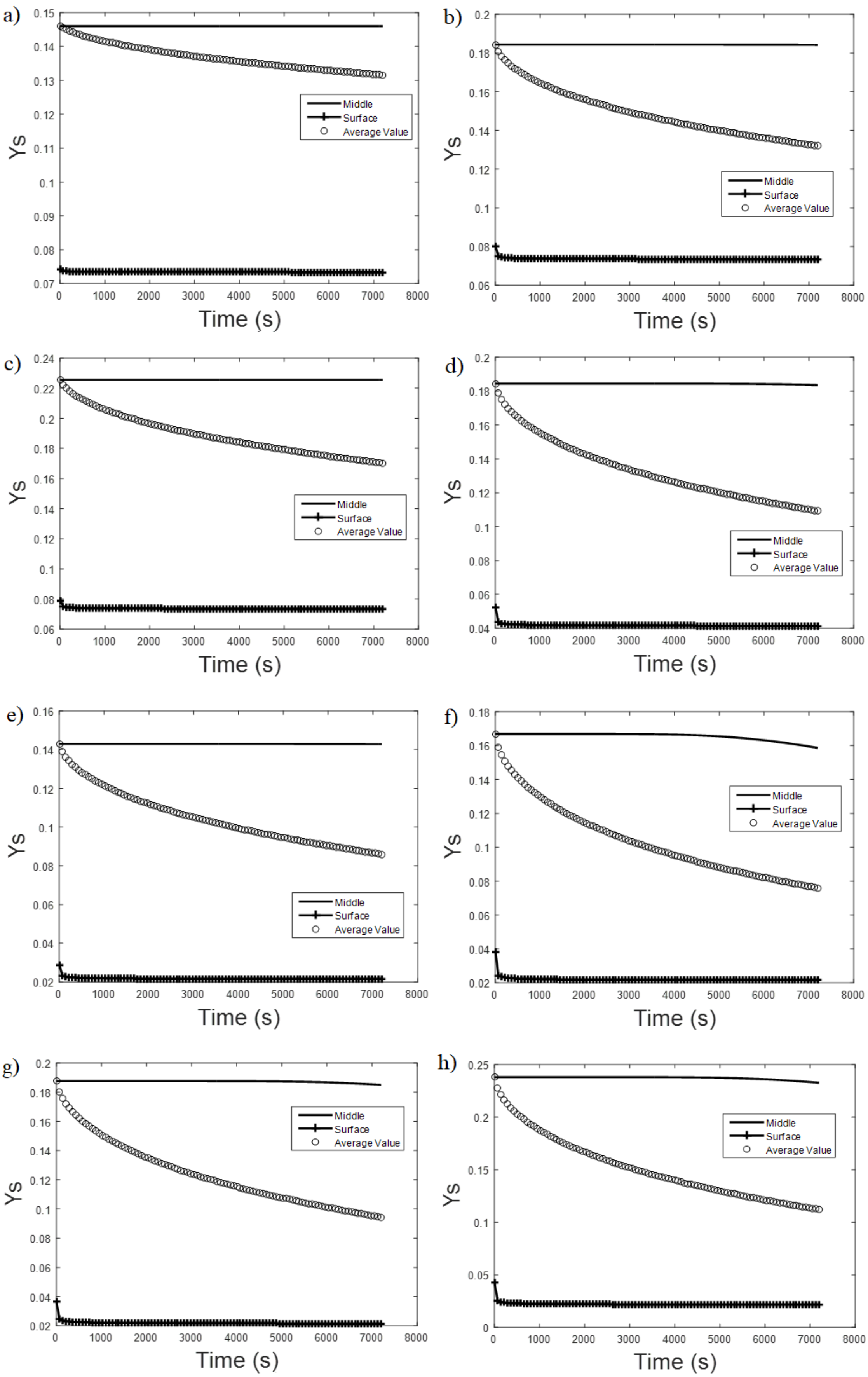

Figure 5: Moisture distribution profiles within the bean. (a) Condition 1; (b) Condition 2; (c) Condition 3; (d) Condition 4; (e) Condition 5; (f) Condition 6; (g) Condition 7; (h) Condition 8.

It can be seen from Figure 4 and Table 4 that for all drying conditions, the model of distributed parameters was fitted adequately, and the best conditions were for high drying temperatures and high initial moisture content. Figure 6 shows the graph of the experimental and predicted data for a model of distributed parameters, in which experimental data could be predicted with a maximum overall deviation lower than 10.0 %.

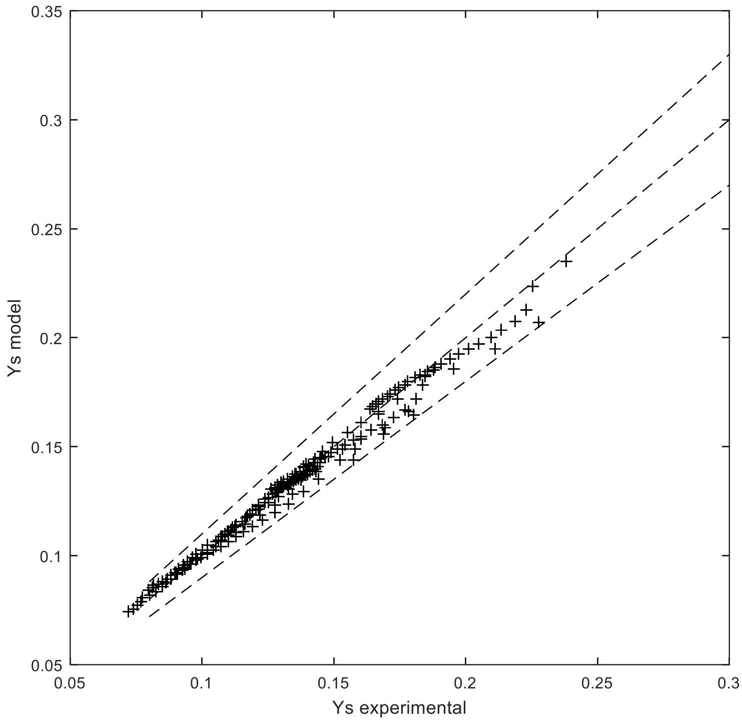

Figure 6: Predicted and experimental data for a model of distributed parameters for beans. Maximum overall deviation of approximately 10.0% compared to the experimental data.

In Figure 5, the profiles of moisture distribution within the material can be verified. For beans, in the drying condition in which the lowest temperature is used and the beans have a lower initial moisture content (Figure 5. a), lower moisture removal from the material was verified, with the average moisture value being close to the moisture content contained from the center of the material. As for the drying conditions with higher temperature and higher initial moisture contents (Figure 5. g and 5. h), greater moisture removal from the material occurred, due to the average moisture values being far from the moisture content in the middle of the material, where the greatest amount of moisture is contained.

In addition, it was verified based on the profiles of moisture distribution within the material, that the center of the material is where there is the highest moisture content of the material. This is expected, because drying first removes the moisture located on the surface of the material, requiring diffusion of the moisture content contained in the center of the material to its surface.

It can also be observed in Figures 4 and 5 that there is a difference in the moisture content along the position inside the grain. These profiles demonstrate that it is necessary to evaluate the moisture distribution inside the grain to predict a drying kinetic model with greater precision. Therefore, this work verified that it is not advisable to neglect the influence of the initial moisture content and its distribution along the position inside the material for beans drying studies.

3.2 Mathematical fits for corn seeds

The mean values of the statistical parameters for the lumped parameter models fitting at different drying conditions for corn seeds are shown in Table 5.

Table 5: Statistical parameters for kinetic models of corn drying.

Model	χ^2	MSE	RMSE	NRMSE	EF
Newton	1.08E-05	1.02E-05	2.54E-03	6.04E-02	9.39E-01
Page	4.03E-06	3.61E-06	1.11E-03	1.77E-02	9.95E-01
Henderson and Pabis	8.10E-06	7.24E-06	1.97E-03	4.04E-02	9.75E-01
Logarithmic	3.05E-06	2.57E-06	1.37E-03	3.64E-02	9.75E-01
Midilli	3.64E-05	2.87E-05	2.74E-03	3.69E-02	9.76E-01
Two term	5.79E-05	4.88E-06	1.32E-03	2.40E-02	9.89E-01
Approximation of Diffusion	**1.30E-06**	**1.09E-06**	**6.48E-04**	**1.23E-02**	**9.97E-01**
Hii, Law and Cloke	**1.24E-06**	**9.14E-07**	**6.39E-04**	**1.37E-02**	**9.97E-01**

According to Table 5, it was verified through the statistical analyses that the best fits (in bold) were obtained by the Approximation of Diffusion and Hii, Law and Cloke models, being the models similar to those obtained for beans. It can be seen that these models were suitable for fitting the drying kinetics of grains and seeds.

Similar to the fit performed for beans, it can be seen from the statistical analysis in Table 5 that Page's model presented a good fit, being used to generalize the drying kinetics as a function of air temperature and initial moisture of the seeds. The dependence of Page's model parameters can be seen in Figure 7.

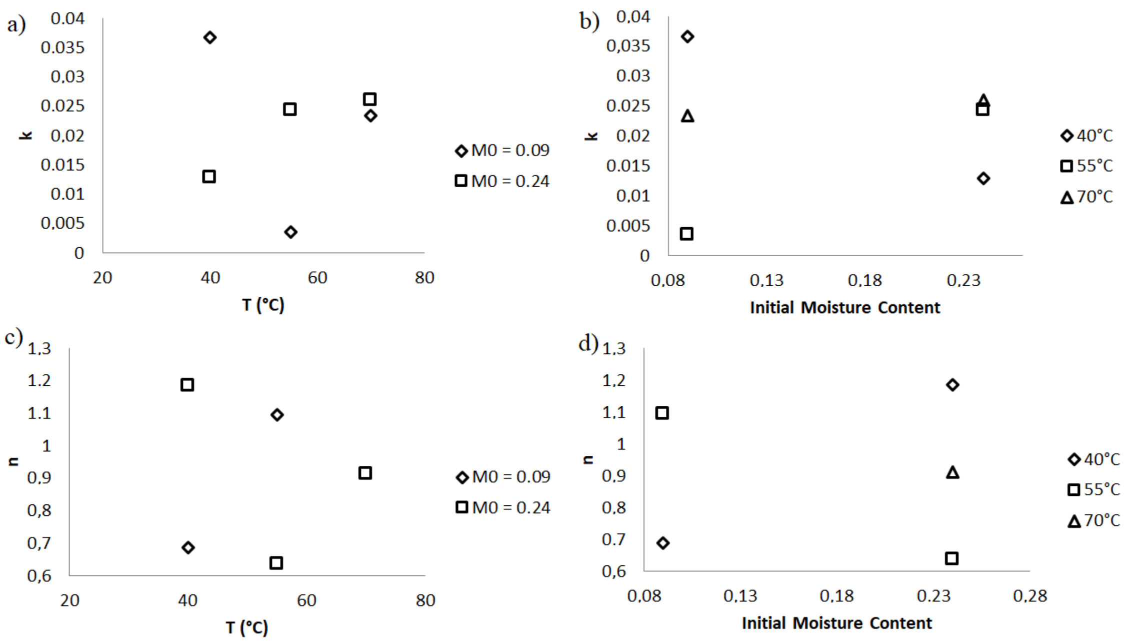

Figure 7: Dependence of Page model parameters as a function of initial moisture content and temperature for corn seed.

Figures 7. a and 7. c demonstrate a variation of the parameters k and n with the drying temperature, and Figures 7. b and 7.d show that there is also a variation of the parameters with the initial moisture content of the corn seeds. The parameters k and n were adjusted as a function of the temperature and the initial moisture content, being presented by Equations 30 and 31:

$$k = A_1 + A_2T + A_3Y_0 + A_4TY_0 + A_5T^2{Y_0}^2 \quad (30)$$

$$n = A_6 + A_7T + A_8Y_0 + A_9TY_0 + A_{10}T{Y_0}^2 \quad (31)$$

The values obtained from the statistical parameters for the generalized model of Page are shown in Table 6, and the adjusted values of parameters k and n are described in Equations 32 and 33.

Table 6: Statistical parameters for the generalized model of Page for corn seeds.

Model	γ²	MSE	RMSE	NRMSE	EF
Generalized model of Page	4.09E-05	1.94E-05	2.57E-03	3.83E-02	9.70E-01

$$k = -1.23.10^{-2} + 6.01.10^{-4}T - 4.11.10^{-2}Y_0 - 4.15.10^{-5}TY_0 + 2.42.10^{-5}T^2Y_0 \quad (32)$$

$$n = 6.20.10^{-1} - 2.65.10^{-3}T + 2.79Y_0 - 1.26.10^{-2}TY_0 + 8.91.10^{-3}T{Y_0}^2 \quad (33)$$

Considering the values obtained from the statistical parameters, it can be verified that the generalized model of Page presented good fitting, which indicates that it can be applied to the simulation and optimization of drying of corn seeds in thin layers. Figure 8 shows the graph of the experimental and predicted data for the generalized model of Page, in which experimental data could be predicted with a maximum overall deviation lower than 15.0 %.

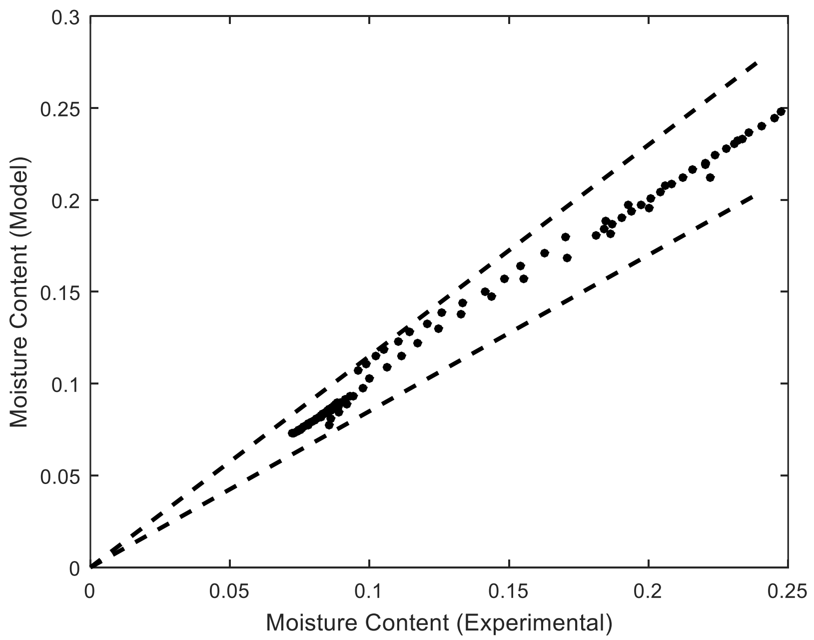

Figure 8: Predicted and experimental data for general Page model for corn seed. Maximum overall deviation of approximately 15.0% compared to the experimental data.

Similar to the fit performed for beans, the Page model parameters for corn seeds were also influenced by the initial moisture content, indicating that the distribution of moisture content can influence drying rates.

The results can be verified in Figure 9, which shows the drying rates for different moisture contents. For samples with different initial moisture content, it was again verified that they do not present the same drying rates when comparing the same moisture content level. This can be observed since curves do not overlap each other during most of the drying process.

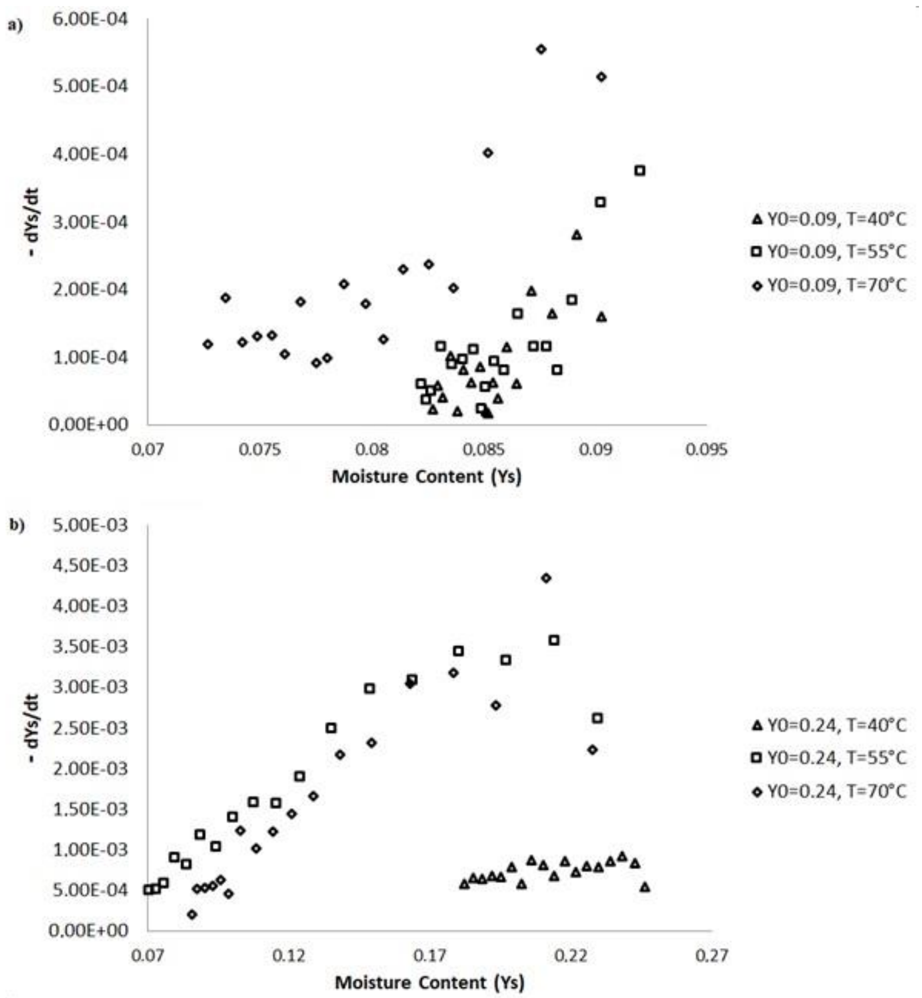

Figure 9: Drying rates for corn seeds with different moisture contents. (a) Low initial moisture content; (b) High initial moisture content.

For corn seeds, in the condition of $Y_0 = 0.09$, the maximum value of the drying rate was close to $6.00.10^{-4}$, and in the condition of $Y_0 = 0.24$, drying rates of approximately $4.50.10^{-3}$ were obtained, and this value corresponds to 7.50 times more than the maximum obtained for lower initial sample moisture values.

Again, it was found that models that neglect the effect of moisture content distribution may not be suitable to be applied to studies that consider different initial moisture contents to which they were adjusted [21].

Using the distributed parameter models, it was considered that the diffusivity value (D) (Equation 14) is constant throughout the material, $\rho_a Kc = 4.5.10^{-2}$ kg/m²s [21], the equivalent radius of 1.79 mm, and that the material is a sphere that has a symmetrical moisture distribution from the center to the surface, D values were adjusted for all drying conditions (Table 7), and the drying kinetics of the distributed parameter model and the moisture distribution profiles within the material over time were arranged for corn in the Figures 10 and 11, respectively [21].

Table 7: Diffusivity values and statistical analysis for the six drying conditions for corn seeds.

Drying Condition	D (m^2/s)	γ2	MSE	RMSE	NRMSE	EF
1 - 40 °C Y_0 = 9 % (d.b.)	2.15E-11	1.77E-07	1.58E-07	3.98E-04	4.97E-02	9.69E-01
2 - 40 °C Y_0 = 24 % (d.b.)	6.75E-12	6.97E-05	6.24E-05	7.90E-03	1.18E-01	8.55E-01
3 - 55 °C Y_0 = 9 % (d.b.)	5.61E-12	4.50E-08	4.03E-08	2.01E-04	1.85E-02	9.95E-01
4 - 55 °C Y_0 = 24 % (d.b.)	8.06E-11	3.61E-04	3.23E-04	1.80E-02	1.08E-01	8.83E-01
5 - 70 °C Y_0 = 9 % (d.b.)	7.51E-12	3.81E-07	3.41E-07	5.84E-04	3.05E-02	9.88E-01
6 - 70 °C Y_0 = 24 % (d.b.)	5.07E-11	1.83E-04	1.63E-04	1.28E-02	8.64E-02	9.24E-01

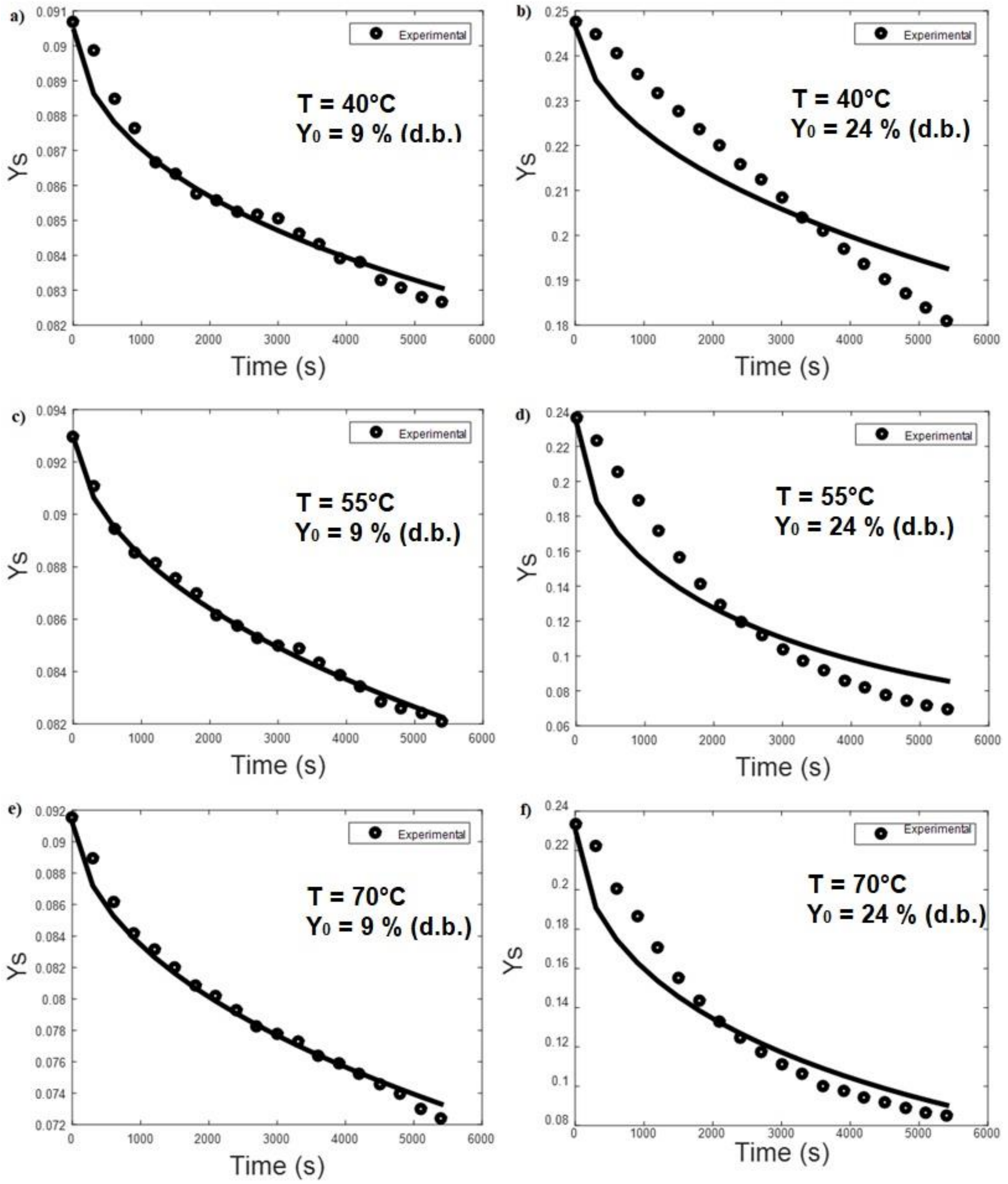

Figure 10: Corn seeds drying kinetics with distributed parameter model. (a) Condition 1; (b) Condition 2; (c) Condition 3; (d) Condition 4; (e) Condition 5; (f) Condition 6.

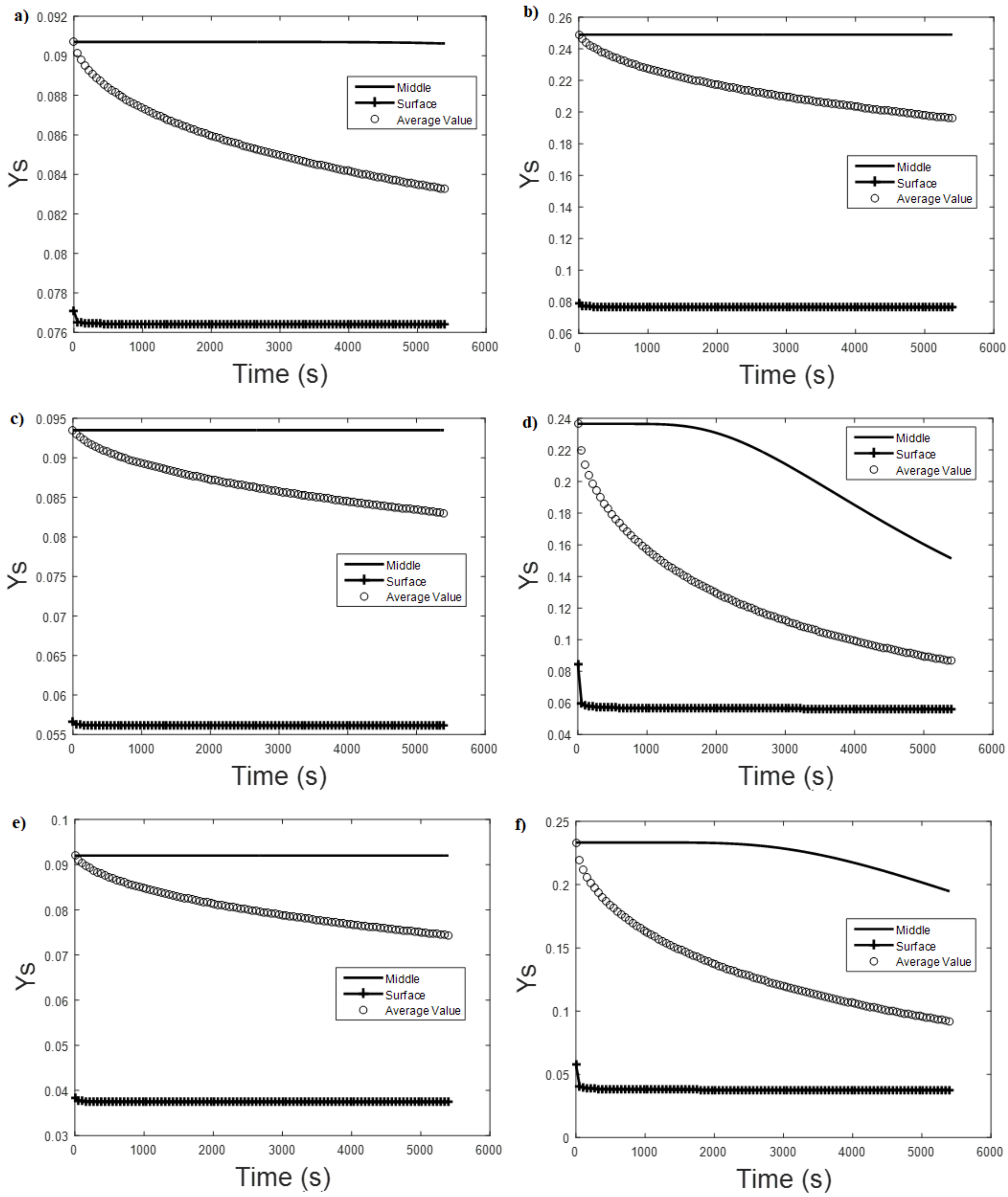

Figure 11: Moisture distribution profiles within the corn seed. (a) Condition 1; (b) Condition 2; (c) Condition 3; (d) Condition 4; (e) Condition 5; (f) Condition 6.

It can be seen from Figure 10 and Table 7 that for all drying conditions, the model of distributed parameters was fitted adequately, with the best conditions for corn it was found that the best conditions were for low moisture content and intermediate drying temperature (55 °C). Figure 12 shows the graph of the experimental and predicted data for a model of distributed parameters, in which experimental data could be predicted with a maximum overall deviation lower than 15.0 %.

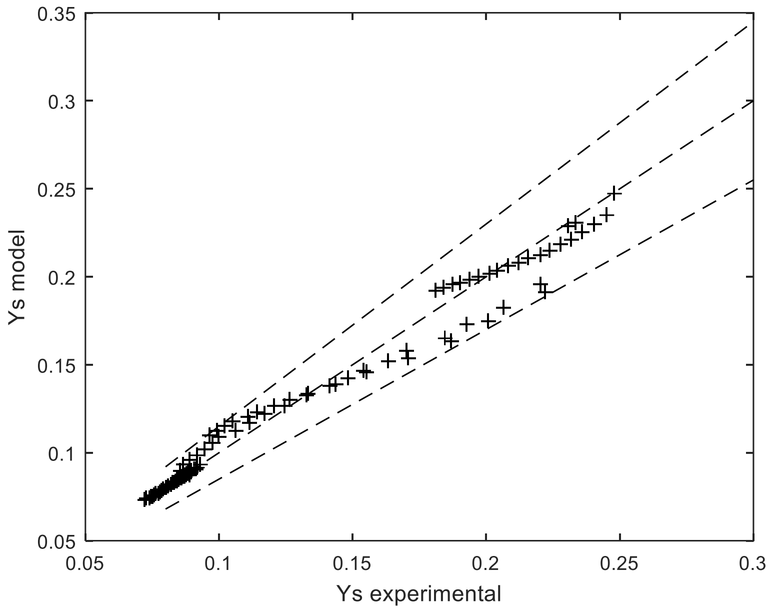

Figure 12: Predicted and experimental data for a model of distributed parameters for corn seeds. Maximum overall deviation of approximately 15.0% compared to the experimental data.

In Figure 11, the profiles of moisture distribution within the material can be verified. For corn seeds, the drying conditions with lower temperatures and lower initial moisture content (9 %) (Figures 11. a, 11. b, 11. c and 11. e), lower removals were obtained of corn seed moisture, and the average value of moisture content of the material is close to the moisture content contained in the middle of the material.

As for the conditions presented in Figures 11.d and 11. f, greater removal of the moisture content contained in the seed occurs, due to the average values of moisture of the material being distant from the moisture content contained in the middle of the material, where the largest amount of moisture is contained.

In addition, it was verified based on the profiles of moisture distribution within the material, it was found that similar to beans, the center of the material is where there is the highest moisture content of the material. This is expected, because drying first removes the moisture located on the surface of the material, requiring diffusion of the moisture content contained in the center of the material to its surface.

It can also be observed in Figures 10 and 11 that there is a difference in the moisture content along the position inside the seed. These profiles demonstrate that it is necessary to evaluate the moisture distribution inside the grain to predict a drying kinetic model with greater precision.

4. CONCLUSION

According to this work, it can be seen that the best fitted empirical models for drying both beans and corn are the Approximation of Diffusion and Hii, Law and Cloke models. However, despite having only two parameters, the Page model showed good fitting in all conditions analyzed, therefore, it was chosen to be generalized as a function of air temperature and grain initial moisture content. The generalized model could predict experimental data with a maximum overall deviation lower than 10.0% for beans and 15.0% for corn seeds.

It was also observed by the distributed parameter model that there is a difference in the moisture content along the position within the grain. These profiles demonstrate that diffusion of water inside the grain control the drying process, and that initial moisture content impacts drying rates. Therefore, this work verified that it is not advisable to neglect the influence of the moisture content and its distribution inside the material for modeling of beans and corn seeds drying purposes.

5. ACKNOWLEDGEMENTS

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