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Adjustments of mathematical models for drying maize seeds on cobs

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Abstract. The present study aimed to select the mathematical models that best fit the drying kinetics of maize seeds on the cob. A 50- and 150-cm maize layer was used in the dryer for four airflows: 5. 10, 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$ was used for stationary drying. The ears were dried in four prototypes of stationary perforated false-bottom dryers with a diameter of 0.92 m, height of 1 m and axial fan. The temperature of the drying air was controlled at the base of the dryer chamber using a thermostat. The mathematical models were analyzed via linear regression. The model of Page and Handerson & Pabis was used. The results showed that the Page model was more satisfactory for predicting the data for the 50 cm layer of ears than the Henderson & Pabis model was for predicting the data for the 150 cm layer. However, both models can be used to represent the drying phenomenon of maize seeds on cobs.

Keywords: Drying kinetics, corn seeds, air flow, mathematical modeling.

Introduction

Drying in spikes can only be performed in stationary dryers, which must be properly operated to avoid excessive drying of the lower layers and allow the upper layer to dry quickly so that there is no loss of seed quality. Thus, some precautions are necessary regarding the factors that may influence the drying process, such as air flow, temperature and ear layer thickness (Villela & Peske, 2000).

The seed layer is highly important because the thicker it is, the greater the pressure loss and the smaller the amount of air that will pass through the seeds, thus requiring greater air flow. The thickness of this layer should not exceed 150 cm in drying silos with a false bottom (Aguirre & Peske, 1992; Baudet, 1992; Villela & Peske, 2000).

Grain drying is an extremely important postharvest resource. The grains can be harvested early before they reach the recommended moisture content for storage, reducing the probability of quality-related losses. The proper execution process results in the conservation of the grains for a long time, without changing their physical, chemical and biological properties, for later commercialization (Maldaner et al., 2021).

The moisture gradient between the seeds located in the different layers of the column, far from the air entry zone, depends on the relative humidity, temperature, air flow, moisture content, seed mass thickness and ability to transfer water from the seeds to the air. The gradient decreases with decreasing temperature and seed mass thickness, as well as with increased air flow (Brooker et al., 1974).

The drying process involves drying the tissues of the grains/seeds. To simulate how the process occurs, mathematical models are used that satisfactorily represent the loss of water content of the product throughout the period necessary for drying until the appropriate final moisture is obtained, according to Goneli et al. (2014). .

The drying of seeds in fixed layers is not uniform, with a significant difference in the final moisture content of the seeds located at different distances from the inlet of the drying air, either near the base or the central tube of the dryer silos. There was a tendency for the seeds located closer to the air intake site to have lower moisture contents than the seeds located farther away. Reducing the layer thickness decreases the moisture gradient between seeds (Brooker et al., 1974; Dalpasquale et al., 1987; Cardoso et al., 1999; Lacerda Filho et al., 1999).

In drying silos with a radial air distribution, the reduced thickness of the seed layer, associated with favorable aerodynamic characteristics, causes the static pressure to be low, allowing the use of airflows close to 30 m ^{3}.min $^{-1}$.t $^{-1}$.

The air flow must be sufficient not to become saturated before leaving the seed mass; it can be increased until it is able to absorb all the water evaporated from the seeds. From that point on, the movement of water from the interior to the surface of the seeds becomes the main factor influencing the drying time.

Mathematical models of air flow, heat and mass transfer have also been studied in models of mixed grain flow dryers, according to researchers (Mondal et al., 2019; Duc & Hyuk et al., 2020). The feasibility, design and optimization of the product for commercial use in drying systems are usually studied through mathematical modeling, using thin-layer drying of the product as a principle and making use of a mathematical model that accurately describes water loss. agricultural products (Sousa et al., 2011). In this context, Mabasso et al. (2022) also conducted a study to simulate the drying process of cowpea seeds.

In particular, when drying with heated air, flows lower than 6 m ^{3}.min $^{-1}$.t $^{-1}$ may excessively prolong the drying time, whereas flows above 20 m ^{3}.min $^{-1}$.t $^{-1}$ may become uneconomical. The air flows become variable and depend on the region, the type and time of storage and the seed species (Villela & Peske, 2000).

Materials and Methods

A batch of 768 kg of corn (*Zea mays* L.) seeds from the triple hybrid Pioneer 3027 on a cob with an initial moisture content of 30% was used. Before drying, the initial moisture content of the seed lot was determined. After drying, the spikes were threshed manually to obtain the seed samples, which were then evaluated for quality.

Four prototypes of the Vitória stationary dryer, with a perforated false bottom, 0.92 m diameter, 1 m height, 1 m height, axial fan with a single-phase induction motor, 1/6 hp power, 1680 rpm and 60 Hz. In each of the prototypes, tubes made of metal sheets 30 cm in diameter and 200 cm in height were placed, with five sampling points distributed vertically, 25 cm equidistant from each other, with the first point being located 50 cm from the dryer base and the last one 50 cm from the top.

The tubes were fully loaded with spikes. Analog thermometers were placed at these points to determine the temperature of the drying air in the seed mass.

Drying was performed until the seeds on the top reached an average moisture content of 13%.

A constant temperature of 30+1 °C was used for each prototype. The air heating was obtained by means of electrical resistances installed in the aeroduct connected to the plenum of each dryer. The temperature of the drying air was controlled at the base of the dryer chamber using a thermostat.

The air flows were obtained via an axial motor-fan assembly to blow air through the layer of corn on the cob. The different airflows, equal to 5, 10, 15 and 20 m3.min $^{-1}$.t $^{-1}$, were obtained by means of a regulating mechanism to control air flow. The specific flow rates were calculated for each prototype on the basis of the area, air inlet velocity and volumetric weight of corn on the cob (450 kg.m $^{-3}$). The air velocities were determined via a thermoanemometer - Hot Wire Anemometer, brand LT Lutron - model AM4204. The correction of each air flow as a function of the mass of corn cobs used in the study was performed.

At the end of the drying process, samples were collected at different heights of the seed layer in the dryer and spaced 10 cm vertically from the base. The first height was 10 cm from the bottom of the dryer, and the last height was 150 cm. After collection, the moisture content of the seeds was determined via the oven method at 105 + 3 °C for a period of 24 h, according to the SAN (Brasil, 1992).

To adjust the mathematical models, the experimental data of the drying process for the two layers and the four airflows used in the study were subjected to linear regression analysis via Excel 2013 software.

Mathematical modeling:

The drying kinetics data were represented by the semiempirical models of Henderson & Pabis (1961) and Page (49) to verify which model fits the real behavior of moisture loss over time. The choice of the best fit was performed via the coefficient of determination (R ^{2}) and the root mean square deviation (MFD).

The mathematical models used to predict the drying process are described below:

Page:

$$RU = exp(-k.t^{n})$$

Henderson & Pablos:

$$RU = a.exp(-k.t)$$

Estimated:

$$RU = exp(b.t)$$

where RU is the moisture ratio (dimensionless); t is the drying time (h); k is the drying constant (h $^{-1}$); and a, b, and n are the coefficients of the (dimensionless) models.

$$DQM = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left(RU_{pre} - RU_{exp}\right)^{2}}$$

where MFD is the mean square deviation; RUpre is the predicted moisture ratio; RUexp is the experimental moisture ratio; and N is the number of experimental data.

Through the data observed in the experiment, it was possible to calculate the values of the moisture content ratio through the equation below:

$$RU = \frac{X - X_{e}}{X_{i} - X_{e}}$$

where RU is the moisture ratio (dimensionless), X is the equilibrium moisture content of the product (bs), Xi is the initial water content of the product (bs), and X is the water content at any point on the drying curve (ds).

Results and Discussion

Table 1 shows the values of the parameters of the Page, Henderson & Pabis models, adjusted to the experimental data of the drying curves of maize seeds on the cob under different airflows of 5, 10, 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$. In addition to the observed and estimated data, Table 1 shows the coefficients of determination (R^2) and root mean square deviations (MDD) for the 50 cm seed layer thickness. Among the models tested, the Page model with two parameters presented the lowest R2 values and the highest DQM values for all airflows used compared with the Henderson & Pabis model. On the other hand, it better fits the observed data. In the Henderson & Pabis model, R ^{2} values are considered good but lower than the R ^{2} values of the estimated data.

The DQM values for the Page and Henderson & Pabis models used in all airflows were very similar, demonstrating that there is a dispersion of the data with characteristics of great homogeneity. However, the Page model resulted in the best fit model, since the MFD values were lower than those of the other models.

In the estimated data, the DQM result was higher than that of the other methods, demonstrating that the homogeneity of the data was impaired when the 50 cm layer was used.

Analyzing the behavior of Page's semitheoretical model, it appears that the parameter k was greater for the higher air flow used in the drying process, whereas the parameter n was greater for the lower air flow and lower for the largest flow. The k parameter of the semitheoretical model of Henderson & Pabis increased for an airflow of 20 m ^{3}.min $^{-1}$.t $^{-1}$. The parameter a of the same model decreased with increasing airflow.

Table 1. Fitting parameters of the models of drying kinetics of maize grains on the cob, coefficients of determination (R ^{2}) and root mean square deviations (MDD) for a 50 cm layer.

Adjustments/Models	Air flows ($m^3.min^{-1}.t^{-1}$)	Parameters		R^2		MFD	
	-	a	b	k	n	-	-
Observed Data	5	-	-	-	-	0,8123	-
	10	-	-	-	-	0,7572	-
	15	-	-	-	-	0,8082	-
	20	-	-	-	-	0,6645	-
Estimated Data	5	-	-0,0104	-	-	0,9732	0,1048
	10	-	-0,0109	-	-	0,9704	0,1185
	15	-	-0,0115	-	-	0,9675	0,1107
	20	-	-0,0137	-	-	0,9549	0,1532
Page Data	5	-	-	0,1423	0,4061	0,7599	0,0210
	10	-	-	0,1631	0,3886	0,7358	0,0156
	15	-	-	0,1607	0,3982	0,7407	0,0296
	20	-	-	0,2891	0,3060	0,6111	0,0227
Data from Henderson & Pabis	5	0,7735	-	0,0073	-	0,9234	0,0610
	10	0,7379	-	0,0072	-	0,8876	0,0717
	15	0,7615	-	0,0081	-	0,9285	0,0653
	20	0,6499	-	0,0084	-	0,8588	0,0925

Figure 1 shows the drying curves of maize seeds on the cobs under air flows of 5, 10, 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$ for the 50 cm layer, with adjustments according to the models of Page, Henderson & Pabis and with the observed and estimated data. The curve generated from the Page model fit the observed data well, better than the Henderson & Pabis model did, regardless of the coefficient of determination, although the Henderson & Pabis model had higher R2 results than the Page model did. For the authors of Costa et al. (2022), the fitted Page model can be used precisely to predict the drying of hardy maize cultivars in thin layers and can also be coupled with other differential equations in the study of thick drying layers. On the other hand, other studies on drying kinetics resulted in model fits with nonsignificant parameter estimates (Quequeto et al., 2019).

Table 2 shows the values of the parameters of the Page, Henderson & Pabis models, adjusted to the experimental data of the drying curves of maize seeds on the cob under different airflows of 5, 10, 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$. In addition to the observed and estimated data, Table 2 shows the coefficients of determination (R ^{2}) and root mean square deviations (MDD) for the 150 cm seed layer. Both the Page and Henderson & Pabis two-parameter models tested, as well as the estimated and observed data, presented coefficients of determination (R ^{2}) greater than 0.92%, indicating a satisfactory representation of the behavior of the drying process for the 150 cm layer.

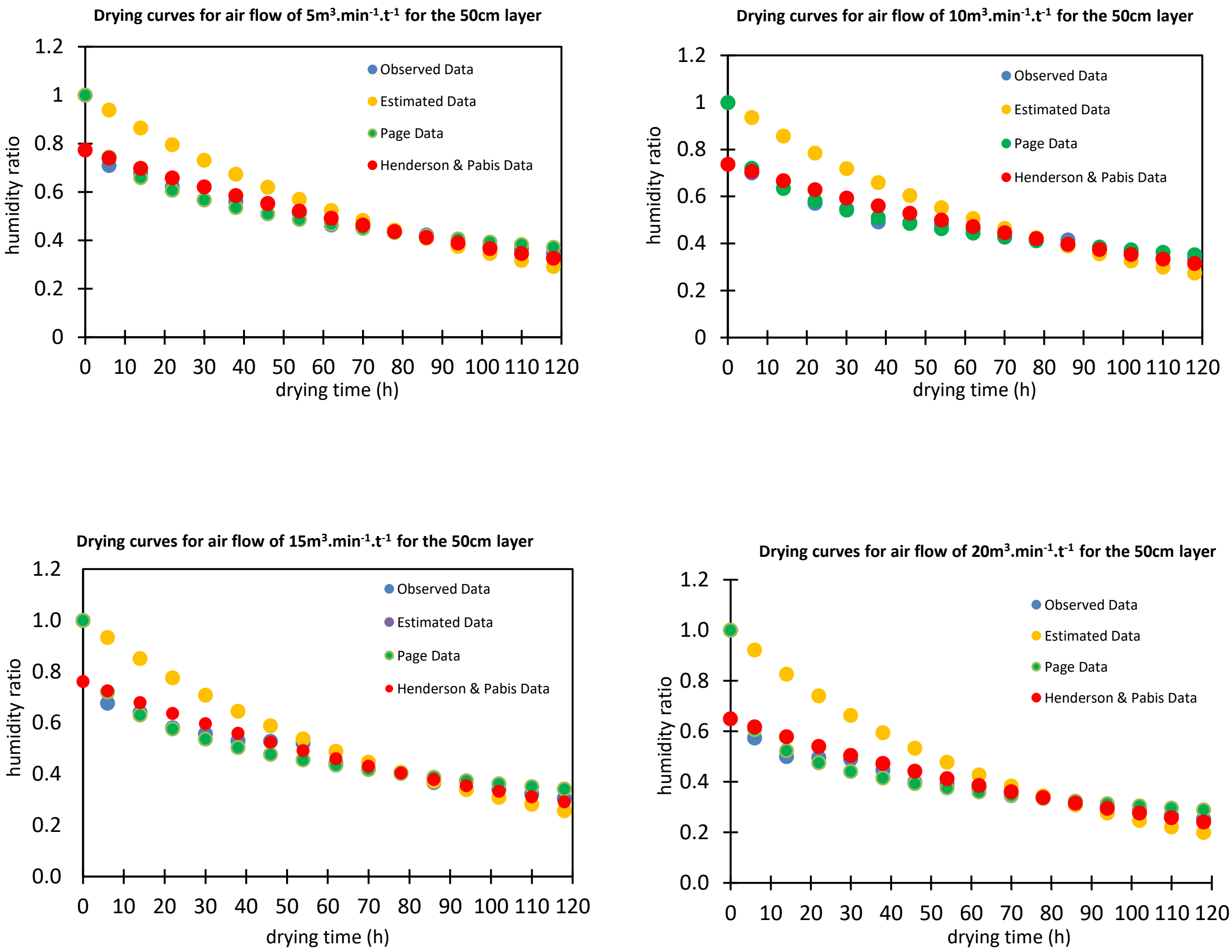

Figure 1. Drying curves via mathematical models at different airflows (5, 10, 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$) used for drying corn seeds on the cob to a layer of 50 cm.

The DQM values for the models and fits used in all airflows resulted in very similar values, demonstrating that there is a dispersion of data with characteristics of great homogeneity. However, the Henderson & Pabis model resulted in the best fit, as the DQM values were lower than those of the other models.

Analyzing the behavior of Page's semitheoretical model, the parameter k was greater for the lower air flow and lower for the higher air flow used in the drying process. According to Santos et al. (2020), the drying rate constant represents the effect of the external conditions under which the study was conducted. The values of the parameter n increased as the air flow increased. The k parameter of the semitheoretical model of Henderson & Pabis decreased with increasing air flow. The a parameter of the same model increased with increasing airflow from 5 to 20 m3.min $^{-1}$.t $^{-1}$.

Figure 2 shows the drying curves of maize seeds on the cobs under airflows of 5, 10, 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$ for a 150 cm layer, with adjustments according to the Page models. , Henderson & Pabis, curves with observed and estimated data. All curves generated from the Page, Henderson & Pabis models resulted in an excellent fit, especially for airflows of 15 and 20 m ^{3}.min $^{-1}$.t $^{-1}$. Significantly, the estimated data curves are practically superimposed, regardless of the airflow used from time zero to 120 hours. On the other hand, there are differences in the fits of the curves of the observed data, especially for airflows of 5 and 10 m ^{3}.min $^{-1}$.t $^{-1}$. Figure 2 shows the drying kinetics of maize seeds on cobs under different drying air flows. Regardless of the air flow used, the drying rate decreases with decreasing seed moisture loss until 80 h, after which a constant moisture loss rate begins throughout the period. time. A similar study involving drying kinetics in wheat was reported in the literature by Ramaj et al. (2021). To characterize the drying behavior, the authors used several semiempirical models, of which the Page model was favorable for adjusting the experimental data on the basis of statistical indicators. However, in a study of drying sorghum grains at different initial water contents and temperatures, Moura Silva et al. (2023) used six models, including the Page model and the Henderson & Pabis model; however, the Midilli model was the most satisfactory. When there are different drying conditions, the ideal approach is to use more adjustment models.

Table 2. Fitting parameters of the models of drying kinetics of maize grains on the cob, coefficients of determination (R ^{2}) and root mean square deviations (MDD) for a 150 cm layer.

Adjustments/Models	Air flows ($m^3.min^{-1}.t^{-1}$)	Parameters				R^2	MFD
	-	a	b	k	n	-	-
Observed Data	5	-	-	-	-	0,9297	-
	10	-	-	-	-	0,9734	-
	15	-	-	-	-	0,9799	-
	20	-	-	-	-	0,9865	-
Estimated Data	5	-	-0,0098	-	-	0,9761	0,0660
	10	-	-0,0081	-	-	0,9835	0,0268
	15	-	-0,00697	-	-	0.9877	0,0153
	20	-	-0,00643	-	-	0,9895	0,0218
Page Data	5	-	-	0,06451	0,5554	0,9963	0,0623
	10	-	-	0,0186	0,8070	0,9595	0,0258
	15	-	-	0,00315	1,1880	0,9663	0,0241
	20	-	-	0,00148	1,3374	0,9985	0,0218
Data from Henderson & Pabis	5	0,9252	-	0,0088	-	0,9391	0,0526
	10	0,9727	-	0,0078	-	0,9833	0,0231
	15	1,0073	-	0,0071	-	0,9919	0,0150
	20	1,0357	-	0,0069	-	0,9937	0,0158

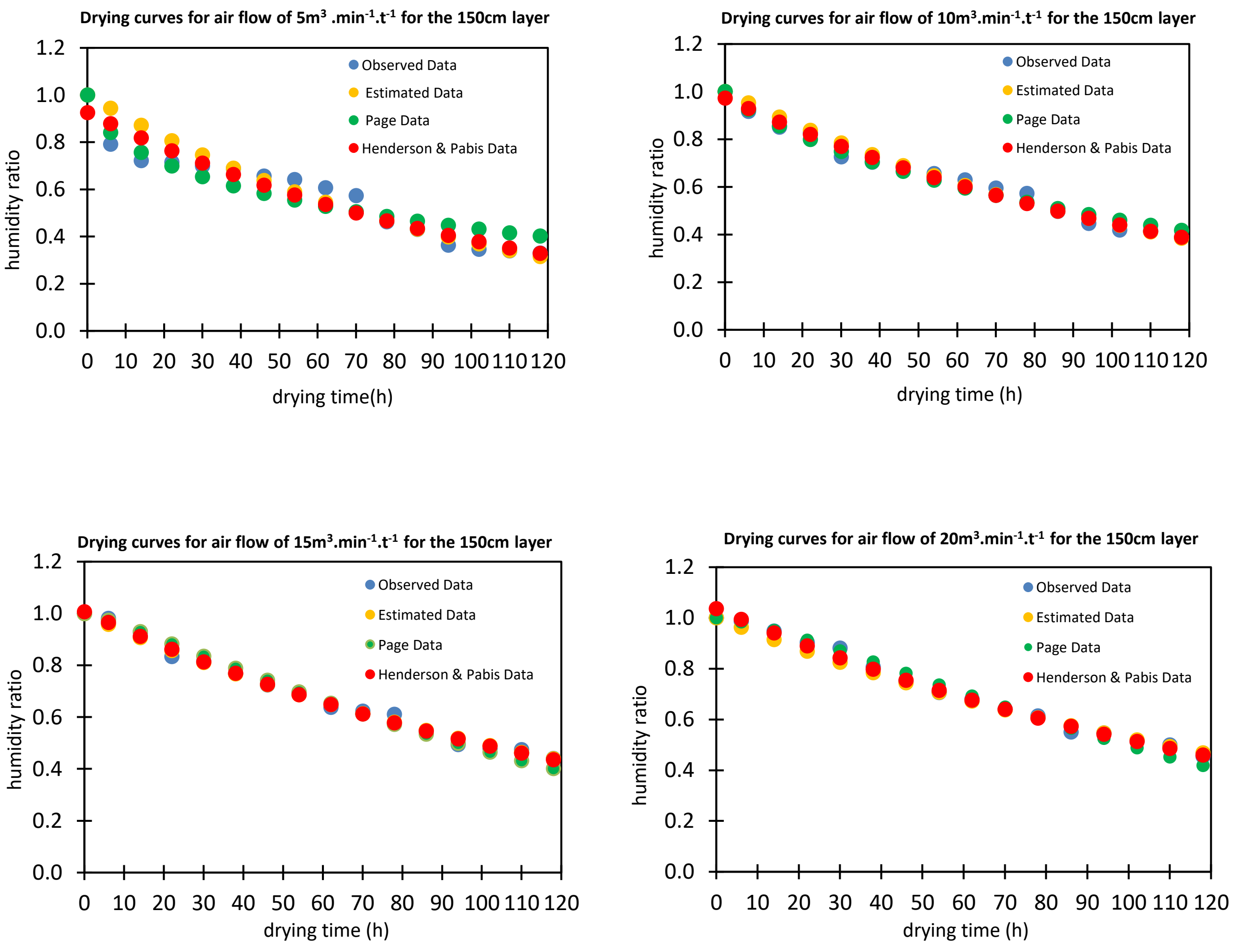

Figure 2. Drying curves of the mathematical models determined for the different air flows (5, 10, 15 and 20 m $^{-3}$.min $^{-1}$.ton $^{-1}$) used to dry maize seeds on the cob at the height of the 150 cm layer.

Conclusions

- The mathematical model of Page was viable, with satisfactory accuracy and a good fit to the observed data, under the conditions of the experiment for the 50 cm layer of maize seeds on the cob in all the airflow treatments used.

- In general, the fitted models effectively represent the phenomenon of drying maize seeds on cobs with reduced moisture.
- The mathematical model of Henderson & Pabis was viable, with satisfactory accuracy and a good fit to the observed and estimated data under the conditions of the experiment for the 150 cm layer of maize seeds on the cob in all airflow treatments used. .

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