Some physical properties and thin-layer drying parameters of foxtail millet (*Setaria italic* L.)

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ABSTRACT

The purposes of present work were to determine some physical properties of foxtail millet as a function of moisture content in a range from 12 to 30% (dry basis), and to evaluate thin-layer drying of these grains for temperatures from 35 to 45 °C and air velocities from 0.5 to 1.5 m/s. The grains have dimensions equal to 2.82x2.03x1.54 mm, sphericity of 0.73, and apparent density of 1.180 g/cm³. The dimensions, surface area, sphericity, true, and apparent density did not vary significantly with the increase of moisture content, while the volume of seeds and their internal porosity increased linearly by about 7.6% and 22%, respectively. The reduction of moisture content of the seeds was investigated for fixed-beds of grains with thickness of 10 mm, characterizing thin-layer conditions. Thin-layer drying kinetics indicated that water vapor diffusion is the dominant mechanism of mass transfer during drying. The drying rates were not significantly affected by the temperature or air velocity in the range investigated. A statistical regression analysis applied to experimental data showed that the Page’s empirical model, with parameters k=0.047 and n=0.740, may be recommended to predict drying kinetics of foxtail millet. The data obtained here provides useful characterization of the grains as they include commonly required input parameters for design of equipment and modeling of processes involving foxtail millet and grains of similar characteristics.

Keywords: sphericity, true density, apparent density, drying, thin-layer.

INTRODUCTION

Foxtail millet (*Setaria italic* L.), also known as Italian millet, is among the world’s most important and ancient domesticated crops. It was staple food in the semiarid regions of East Asia and in the entire Eurasian continent before the popularity of rice and wheat, and is still important food in these regions today. In Brazil it is cultivated mainly in the South region and though the planted area is increasing, the production is not yet sufficient to supply the crescent internal demand. The grains have high nutritive value, with significant content of Fe, Ca, and proteins. These characteristics make them a valuable ingredient in the production of animal food for livestock and domestic birds. The cooked grains may be also consumed by humans, as an option to corn, soy or rice.

The knowledge of physical properties of millet seeds and how these properties are affected by the moisture content is important for design of suitable equipment to handling, transporting, processing, and storing the grains. Additionally, information on drying kinetics is necessary for design and prediction of drying equipment performance as drying is the most common preservation process applied to seeds. Therefore, the purposes of the present work are to investigate how the dimensions, volume, true and apparent densities, sphericity, and internal porosity of foxtail millet seeds are affected by the variation of moisture content, as well as to evaluate the thin-layer drying kinetics of grains at different temperatures and air velocities. A thin-layer thickness is defined as a thickness meeting the requirement that the temperature and relative humidity of the drying air does not change when passing through the grain layer in the drying process [1]. The data will be used to fit an empirical equation for estimate the drying time of seeds.

MATERIALS & METHODS

Foxtail millet seeds were obtained from local market in São Carlos, SP, Brazil, at moisture content of 13% d.b. and were cleaned manually to remove impurities. Because seeds at different moisture levels were required in the experiments, part of the seeds was submitted to a humidification process. The desired moisture levels were obtained by keeping the seeds in a closed chamber with a saturated atmosphere of water vapor, maintained at a temperature of 30°C. The moisture content of samples at each time was obtained through the oven method at 105.0±3.0 °C for 24h. All physical properties were determined at moisture contents in a range from 13 to 30%.

In order to determine the dimensions of the seeds, 3 groups of 10 seeds were randomly selected and the three main dimensions, namely minor diameter (thickness, T’), major diameter (length, L) and intermediate
diameter (width, W) were measured using a micrometer with an accuracy of 0.01 mm. The sphericity ($\phi$) was calculated as follows [2]:

$$\phi = \frac{(WT)^{1/3}}{L}$$

(1)

The measured dimensions were used to estimate the surface area (S) of the seeds [3]:

$$S = \frac{\pi BL^2}{2L - B}$$

(2)

where B is the geometric mean diameter, calculated from:

$$B = \left(\frac{WT}{1/2}\right)^{1/2}$$

(3)

The seed true density ($\rho_s$), defined as the ratio of the mass of the seed to the volume occupied by the seed excluding the volume of internal pores, was measured using Helium picnometry. The apparent density, defined as the ratio of the mass of the seed to the external volume occupied by a seed was determined using the liquid displacement technique for a sample containing 200 seeds. Hexane was used instead of water because it is absorbed by seeds to a less extent. A thousand grain mass was measured using an electronic scale to an accuracy of 0.001 g. From the calculated mass and volume of a unit seed, the apparent density ($\rho_{ap}$) was determined. The tests were carried out in triplicates, excepting by the analysis of true density, which was not replicated.

The seed porosity ($\varepsilon_s$) was estimated according to:

$$\varepsilon_s = 1 - \frac{\rho_{ap}}{\rho_s}$$

(4)

The investigation of thin-layer drying was carried out in a cylindrical cell, 50 mm in diameter and 10 mm high. This column was filled in with the grains and percolated by air flow, which was provided by a blower and heated by electrical resistances before entering the column. Tests were performed at air inlet temperatures of 35, 40 and 45 °C, and flow velocities of 0.5 and 1.5 m/s. Air temperatures at the inlet and outlet of the column were measured using type T thermocouples, the air flow rate was measured using an orifice flow meter previously calibrated. In each experiment, the weight of the small column was measured along time using an electronic scale to an accuracy of 0.001 g. Details of measuring systems may be found elsewhere [4]. The dimensionless moisture content was calculated as follows:

$$MR(t) = \frac{M(t) - M_{eq}}{M_0 - M_{eq}}$$

(5)

where $M(t)$ is the water content of sample at instant t, $M_0$ is the initial moisture content, and $M_{eq}$ is the equilibrium moisture content.

RESULTS & DISCUSSION

The behaviour of physical properties as a function of moisture content is depicted in Fig. 1, where the vertical bars indicate the relative mean deviations of each group of measurements. It is possible to observe that the properties showed weak dependence on the moisture content on the range of moistures investigated. Sphericity and apparent density stayed practically constant at values of 0.73±0.01, and 1.180±0.024 g/cm³. The linear dimensions increased about 3-4%; while the surface area and true density increased 7% and 5% respectively. To check statistical significance of these variations, a Student test-t was applied to each group of data. These tests indicated that the variations of dimensions were not statistically significant at a confidence level of 5%. Mean values of L, W, and T' are 2.82±0.05 mm, 2.03±0.05 mm, and 1.54±0.03 mm, respectively, and of surface area is 11.39±0.070 mm². As for the increase of true density, from 1.40 to 1.47 g/cm³, it has not been possible to check statistical significance once these tests have not been replicated. Considering the magnitude of errors involved in this measurement, this variation of only 5% is probably in
the range of experimental uncertainty. The seed porosity ($\varepsilon_s$), calculated from Eq. (4) increased from 16 to 29% due to the small variation of $\rho_s$.

The volume of seeds increased 6.4%, from 4.67 to 5.02 mm$^3$, a variation confirmed as statistically significantly at a 5% confidence level. In a range of moisture from 5 to 25 % (d.b.), Çalıṣır et al. [5] detected a linear increase of about 30% in the volume of rapeseeds. It is worthy noting that these authors have also detected a linear increase in the seed dimensions, of about 10% for length and of 9% for geometric mean diameter, which has not been observed in the present work for the foxtail millet seeds.

Figure1. Physical properties as function of moisture content ($U_{wa}$): (a) linear dimensions; (b) projected area; (c) apparent and true density; (d) sphericity; (e) seed porosity; (f) volume.
Based on preliminary tests, it was verified that thin-layer drying conditions were attained when the difference between inlet and outlet air temperatures were lower than 0.5 °C. This condition has been verified for all the experimental conditions of this work. Drying kinetic curves, for inlet air temperatures of 35 and 45 °C, and inlet air velocities of 0.5 and 1.5 m/s are shown in Figure 2. The results at 40 °C will not be showed, as they were similar to those obtained for the lower and upper temperature limits.

Figure 2. Dimensionless moisture content as a function of time for thin-layer drying of foxtail millet seeds at temperatures of (a) 35°C, and (b) 45°C.

Curves in Figure 2 show decreasing drying rates for all the conditions, which is a consistent behavior, once the drying of seeds is expected to be predominantly diffusive. No influence of air velocity was detected in the range investigated. The effect of temperature was also few significant, as the time required for reaching equilibrium conditions was similar at each temperature, of about 400 minutes. This may be probably attributed to the narrow range of temperature variation, of only 10°C.

Thin layer equations are useful to describe the drying phenomena in a united way, regardless of the controlling mechanisms [6]. Data of dimensionless moisture content as a function of time were fitted to the classical empirical correlations suggested in the literature for prediction of drying kinetics. As no dependence of temperature and air velocity was detected, all 115 experimental data were used in the fitting. The regression analysis was performed using the Statistica computer program. The correlation coefficient ($R^2$), the root mean square error (RMSE), and the reduced chi-square ($\chi^2$) were used as criteria for selecting the best fitting equation. Among the equations evaluated, those from Ezeike & Otten [7], Srzdenicki et al. [8] and Page [9] presented $R^2>0.990$ and RMSE minor than 10%, with low values of $\chi^2$. Though whichever of them might be recommended for predicting the drying kinetics of foxtail millet seeds, the correlation from Page [9] was selected because it requires only 2 parameters to be fitted. The parameters, $k=0.047\pm0.003$ and $n=0.740\pm0.015$, yielded $R^2=0.992$, RMSE=0.03325 and $\chi^2=0.000112$. The predictions may be compared to experimental data in Figure 3, which illustrates the good performance of Page’s correlation.
CONCLUSIONS

In a range of moisture content from 13 to 30 % (d.b.), the volume and porosity of foxtail millet seeds increased linearly with the increase in the moisture content. The linear dimensions, surface area, sphericity, and apparent densities did not vary significantly in this range of moisture. Thin-layer drying kinetics of seeds indicated that for inlet air temperatures from 35 to 45 °C and inlet air velocities from 0.5 to 1.5 m/s, approximately 400 minutes are necessary to reach the equilibrium moisture content of the seeds. The correlation of Page [9], with fitted parameters k=0.047±0.003 and n=0.740±0.015, may be recommended to predict drying kinetics in this range of temperature and air velocity.

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