Modeling Thin Layer Drying of Amaranth Seeds under Open Sun and Natural Convection Solar Tent Dryer

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ABSTRACT

Thin layer drying studies of amaranth (*Amaranthus cruentus*) seeds were carried out under open sun and natural convection solar tent dryer. The ambient temperature and relative humidity ranged from 22.6–30.4 °C and 25–52 %, respectively, while the inside temperature and relative humidity in the solar dryer ranged from 31.2–54.7 °C and 22–34 %, respectively. Fresh amaranth seeds with the average moisture content of 64 % (dry basis) were dried under both conditions for seven hours to the final moisture content of about 10 % (dry basis). A non-linear regression analysis was used to develop drying models for amaranth seeds. The models were compared using the coefficient of determination (R^2), root mean square error (RMSE) and the reduced chi-square (χ^2) in order to determine the one that best represented thin layer drying characteristics of amaranth seeds. The results show that the Page model satisfactorily described the drying of amaranth seeds with R^2 of 0.9980, χ^2 of 0.00016 and RMSE of 0.01175 for bottom layer and R^2 of 0.9996, χ^2 of 0.00003 and RMSE of 0.00550 for top layer of the drying rack. Similarly, the Page model attained R^2 of 0.9965, χ^2 of 0.00027 and RMSE of 0.01540 for the open sun. This shows that there was a good agreement between the predicted and actual moisture changes in drying of amaranth seeds under both conditions.

Keywords: Thin layer, open sun, solar tent dryer, amaranth, drying models, natural convection

1. INTRODUCTION

The grain amaranth is indigenous to Kenya but many communities are ignorant of its significance in health and food security hence there is need to promote the use of this grain in alleviating hunger. Kenyan farmers in regions with marginal rainfall plant amaranth rather than maize because there is less risk of a crop failure with amaranth (Gupta, 1986). Amaranth is a small size (one millimeter in diameter), nearly spherical, attrition-resistant seed with high nutritional value. Amaranth grows vigorously, tolerates drought, heat, and pests, and adapts readily to a wide range of environments (Abalone *et al*., 2006). The leaves can be cooked like spinach, and the seeds can be germinated into nutritious sprouts. The leaves can be cooked like spinach, and the seeds can be germinated into nutritious sprouts. Amaranth seeds are ground into flour, popped like popcorn and cooked into porridge. While amaranth is not a staple food in Kenya, it is still grown and sold as healthy food.

The potential of both grain and vegetable amaranth as a food resource has been reviewed extensively by many researches (Abalone *et al*., 2006; Bressani, 1988). The increasing interest in the international community in its growth and use lies in its seeds which contain proteins between 16 and 18 % and have high lysine content. Amaranth grain, cultivated in family scale, is exposed to ambient air and naturally dries. When amaranth is cultivated on a large scale (25-800 acres), heavy field losses occur as the crop easily shatters the seeds when dry. In order to reduce the field losses, amaranth can be harvested with moisture content of about 30 % (dry basis) or more with necessary artificial drying to reduce the moisture level to about 10 % (dry basis) to assure safe preservation (Abalone *et al.*, 2006). Drying is one of the cheap and common preservation methods for biological products (Shitanda and Wanjala, 2003). Solar drying is a good alternative for farmers in Kenya and other developing countries as the dryers can generate relatively high air temperatures and low relative humidity, both of which are conducive to improved drying rates.

Solar drying is actually a form of convective drying, in which the air is heated by solar energy in a solar collector. Due to the elliptical orbiting of the earth around the sun, the distance between the earth and the sun fluctuates annually and this makes the amount of energy received on the earth's surface (I'_{sc}) to fluctuate annually in a manner given by Eq. 1 (Sukhatme, 2003), where I_{sc} is the solar constant valued at 1367 W/m^2 and n is the day of the year.

$$I'_{sc}=I_{sc}\left(1+0.033\cos\left(\frac{360n}{365}\right)\right) \quad (1)$$

The direct solar radiation reaching a unit area of a horizontal surface in the absence of atmosphere I_b can be expressed as in Eq. 2 (Al-Ajlan *et al.*, 2003), where φ is the latitude (degrees), β is the angle of inclination of surface from horizontal (degrees), δ is the angle of declination (degrees) and ω is the hour angle (degrees) given by Eq. 3 (Sukhatme, 2003) where H_r is hour of the day in 24 hour time. The diffused radiation I_d can be estimated as direct radiation incident at 60^o on the collector surface (Sukhatme, 2003). The total solar radiation I_t incident on the horizontal surface is therefore given by adding the direct and diffused components of solar radiation.

$$I_b= I'_{sc}\left(\sin\left(\varphi-\beta\right)\sin\delta+\cos\,\delta\cos\omega\cos\left(\varphi-\beta\right)\right) \quad (2)$$

$$\omega=15(12-H_r) \quad (3)$$

The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behaviour, and for optimizing the drying parameters. Many researches on the mathematical modeling and actual studies have been conducted on the thin layer drying processes of various agro-based products such as rough rice (Basunia and Abe, 2001), green pepper, green bean and squash (Yaldiz and Ertekin, 2001). However, very little information is available on thin layer drying behaviour of amaranth seeds (Abalone *et al.*, 2006). The study was therefore undertaken to model the thin layer drying of amaranth seeds under open sun and natural convection solar tent dryer.

2. MATERIALS AND METHODS

2.1 Experimental Solar Dryer

The schematic diagram of the natural convection solar tent dryer used in this study is shown in Figure 1(a). The dryer consisted of a chimney, the main structure with a door and a concrete base. The main structure measured 1.85 m wide, 2.73 m long and 2.55 m high. The top part of this structure was semi-circular in shape with a radius of 0.5 m and was entirely covered with a polyvinyl chloride (PVC) material. The dimensions of the door were 0.6 m wide and 1.8 m high. A detailed diagram illustrating locations of drying trays in a drying rack is shown in Figure 1(b). Flat and angled iron bars were used to fabricate these trays, and a fine wire mesh was placed at the top of each layer. The entire system was completely sealed from light in order to preserve light sensitive nutrients in the drying material. For air circulation purposes, a protruding chimney was provided at the top center of this structure.

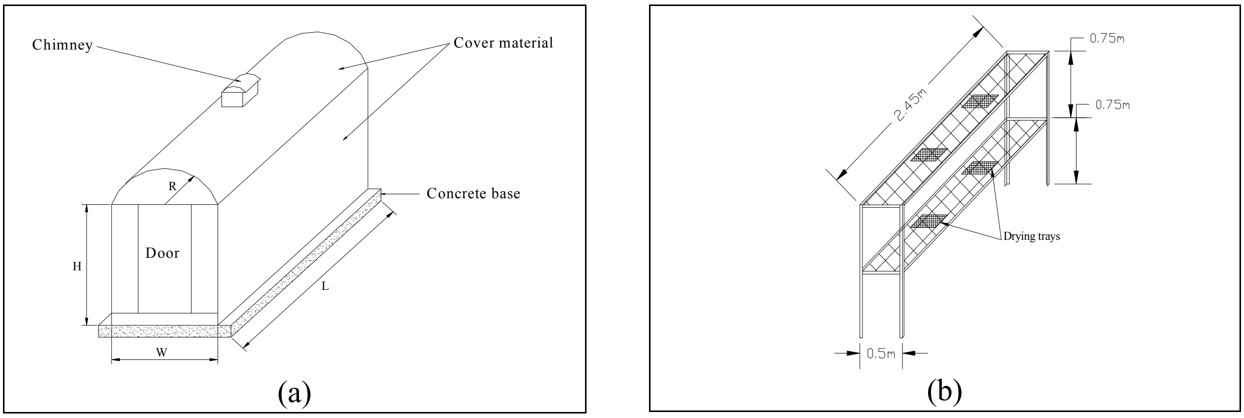

Figure 1. Schematic diagram of a natural convection solar tent dryer (a), and the arrangement of drying trays in two layers (b). In this figure: W = 1.85 m; L = 2.73 m; H = 2.05 m; R = 0.5 m.

2.2 Sample Preparation and Drying Conditions

Amaranth seeds were planted at the Horticultural farm of Jomo Kenyatta University of Agriculture and Technology (JKUAT) in order to obtain freshly harvested grains for the drying experiment. JKUAT is located in Juja (37.05^o E longitude, 1.19^o S latitude and at an altitude of 1550 m above sea level). The mean annual temperature of Juja is 18.9 ^{o}C with mean annual maximum and minimum temperatures of 26.1 and 13.6 ^{o}C, respectively. The relative humidity ranges from 15 to 80 % (Uluko *et al*., 2006). *Amaranthus cruentus* seeds were planted during the month of October 2008 in an experimental plot (6 m×3 m) and in rows spaced at 0.5 m. The seeds were planted in holes spaced at 0.2 m within a row in finely prepared loam soil which was packed to assure good seed-to-soil contact. The rains were not adequate during this period and water was therefore artificially applied to ensure good germination. Germination took three to four days and the weeding process between rows was done after two weeks from germination. The plants were thinned after three weeks of germination in order to leave three plants per hole. This was followed by another thinning after two more weeks which left one plant per hole in order to provide sufficient air and sunlight to the crop (Gupta, 1986). Fresh amaranth seeds were harvested with moisture content of approximately 64 % (dry basis) after 90 days. The harvesting involved detaching seeds from the seed heads and cleaning them manually to remove any foreign material before drying.

The study on thin layer drying of amaranth seeds was conducted in an open area near the Agricultural Processing Engineering Laboratory of Biomechanical and Environmental Engineering Department, JKUAT in the month of December 2008. A sample of approximately 50 g was evenly spread on a drying tray (0.25 m×0.25 m) to form a single layer. Two layers were used in the drying rack, i.e. top and bottom layers. Data acquisition involved recording ambient temperature and relative humidity, and temperature and relative humidity inside the dryer, and the moisture content of the grains. The data were recorded at 30 minutes intervals from 9:00 to 16:00. The capacity and sensitivity of Shimadzu electronic balance (LIBROR EB-4300D, Japan) used were 600 g and 0.01 g, respectively. The ambient and inside temperatures were taken using thermocouples which relayed data to a Thermodac electronic data-logger (ETO Denki E, Japan) with ±1°C accuracy, while relative humidity (RH) was recorded using a digital thermo-hygrometer sensor (HC-520, Hong Kong) with ±5% accuracy within 20 and 99 % RH. The solar radiation data was evaluated from electronic world satellite solar maps and Eqs. 1–3 gave the hourly computed solar radiation values.

2.3. Prediction Accuracy of Thin Layer Models

The collected moisture data were used to plot graphs of moisture content against drying time, and to evaluate Eq. 4, which is based on the theory of thin layer drying (Uluko *et al*., 2006). The drying rate (DR) was taken to be approximately proportional to the difference in moisture content between the product being dried and equilibrium moisture content at the drying air state, as given by Eq. 5, where M_t is moisture content at time t, M_{t+dt} is moisture content at time $t+dt$ and dt is time of successive measurements (Omid *et al*., 2006). For mathematical modeling, the thin layer drying equations in Table 1 were tested to select the best model for describing the drying curve of amaranth seeds.

$$\mathrm{MR} = \mathrm{e}^{-kt} \tag{4}$$

$$\mathrm{DR} = \frac{\mathrm{M}_{t+dt} - \mathrm{M}_t}{dt} \tag{5}$$

Table 1. Mathematical models widely used to describe the drying kinetics

S/No.	Model*	Model name	References
1	MR = exp(-*kt*)	Newton	Yaldiz and Ertekin (2001)
2	MR = exp(-kt^n)	Page	Abalone *et al.* (2006)
3	MR = exp[-(*kt*)^n]	Modified Page	Omid *et al.* (2006)
4	MR = *a*exp(-*kt*)	Henderson and Pabis	Chhninman (1984)
5	MR = *a*exp(-*kt*) + *c*	Logarithmic	Yagcioglu *et al.* (1999)
6	MR = 1 + *at* + *bt*^{2}	Wang and Singh	Wang and Singh (1978)

* *a, b, c* and *n* are drying coefficients, *t* is drying time (hours) and *k* is drying constant (h^{-1})

Modeling the drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analyses. Regression analyses were done using the GenStat statistical tool. The coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were used to determine the quality of the fit. The higher the value of

R^2, and the lower the values of χ^2 and RMSE, the better goodness of fit is observed (Yaldiz and Ertekin, 2001; Sarsavadia *et al.*, 1999).

Diffusivity is used to indicate the flow of moisture leaving the material during drying. In the falling rate period of drying, moisture is transferred mainly by molecular diffusion. Moisture diffusivity is influenced mainly by moisture content and temperature of material. For a drying process in which the absence of a constant rate is observed, the drying rate is limited by the diffusion of moisture from the inside to the surface layer, represented by Fick's law of diffusion. Assuming that the amaranth seeds can be approximated with spheres, the diffusion is expressed by Eq. 6 (Konishi *et al.*, 2001) where D_e is the effective moisture diffusivity (m^2/s) and r_a is the radius of amaranth seed (m).

$$\frac{\partial M}{\partial t} = D_e \left(\frac{\partial^2 M}{\partial r_a^2} \right) \quad (6)$$

For the transient diffusion in a sphere, assuming uniform initial moisture content and constant effective diffusivity throughout the sample, the analytical solution of Eq. 6 yields Eq. 7.

$$MR = \frac{M - M_e}{M_o - M_e} = \left(\frac{6}{\pi^2} \right) \exp\left[-D_e t \left(\frac{\pi^2}{r_a^2} \right) \right] \quad (7)$$

The effective moisture diffusivity (D_e) is determined by applying logarithms to Eq. 7 to obtain a linear relation of the form shown in Eq. 8. Therefore, a plot of ln(MR) versus time result in a straight line, and the diffusivity may be determined from the slope (slope = $-D_e\pi^2/r_a^2$).

$$\ln(MR) = \ln\left(\frac{6}{\pi^2} \right) - \left(D_e \frac{\pi^2}{r_a^2} \right) t \quad (8)$$

3. RESULTS AND DISCUSSION

Before modeling the thin layer drying of amaranth seeds, drying conditions (viz., temperature, relative humidity and solar radiation) and moisture content data were acquired between 9:00 and 16:00 at intervals of 30 minutes under open sun and in a natural convection solar tent dryer. These data were monitored within the dryer at two levels (i.e., bottom layer and top layer) and in the open sun. Figure 2 compares the temperatures developed in the open sun and inside the solar tent dryer at two levels on a typical day of December 2008. The inside temperatures corresponded to top and bottom layers placed at 0.75 m from each other and the ground surface in the solar tent dryer. The temperatures inside the solar tent dryer were higher than those in the open sun (27.8±2.6 ^oC) throughout the drying period. The results also show that the temperatures developed in the top layer were always higher (48.9±4.8 ^oC) than those developed in the bottom layer (39.5±3.8 ^oC). This was perhaps due to the closeness of the top layer to the solar energy harnessing surface of the cover material. The inside temperatures were highest between 12:30 and 13:30. The difference between the inside and open sun temperatures (margin: 12.8–24.3 ^oC) was also high during this time. Figure 2 also indicates that solar radiation has a direct effect on open sun and solar dryer temperatures. The mean value of ten-year (1996–2005) solar radiation data obtained from world satellite map (NASA) was approximately 6 kW/m^2 and slightly lower than the sum of calculated hourly results (1.6±0.3 kW/m^2).

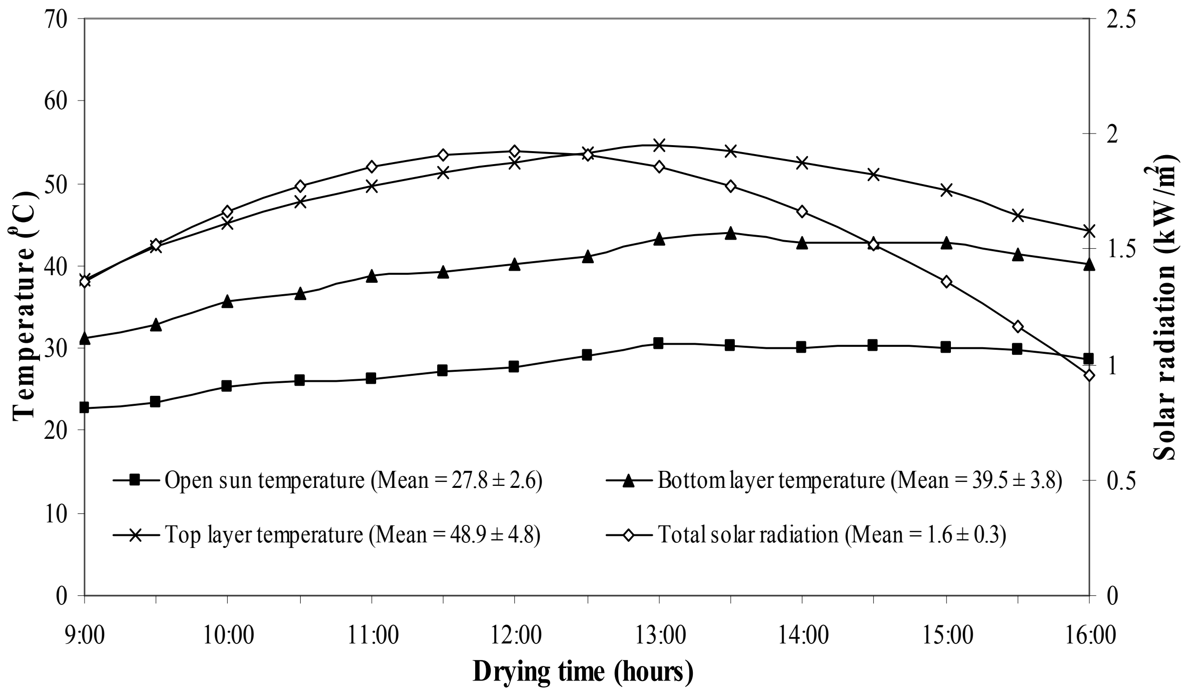

Figure 2. Comparison of temperature and total solar radiation with time in the solar tent dryer and the open sun on a typical day of December 2008.

The relative humidity of the drying air in the solar tent dryer was lower (25.6±4.3 %) than that for the open sun (29.5±5.4 %) throughout the drying period as shown in Figure 3. At any given time, there was a decreasing trend in relative humidity for the two drying conditions (viz., solar tent dryer and open sun). When Figures 2 and 3 are compared, it is noted that at any given time an increase in temperature led to decrease in relative humidity. This indirect relationship has also been reported by Basunia and Abe (2001). Regression analyses relating the temperature (T_i) and relative humidity (Rh_i) inside the solar tent dryer to the open sun temperature (T_a) and relative humidity (Rh_a), and total solar radiation (I_t) yielded linear relationships as shown in Eqs. 9 and 10. The high R^2 values (>0.9) obtained imply that there is a strong correlation between the drying conditions inside the solar tent dryer and the open sun conditions.

$$T_i = 1.38T_a + 10.46\,I_t - 6.27 \qquad R^2 = 0.98 \qquad (9)$$

$$Rh_i = 0.75\,Rh_a - 0.02\,I_t + 0.07 \qquad R^2 = 0.99 \qquad (10)$$

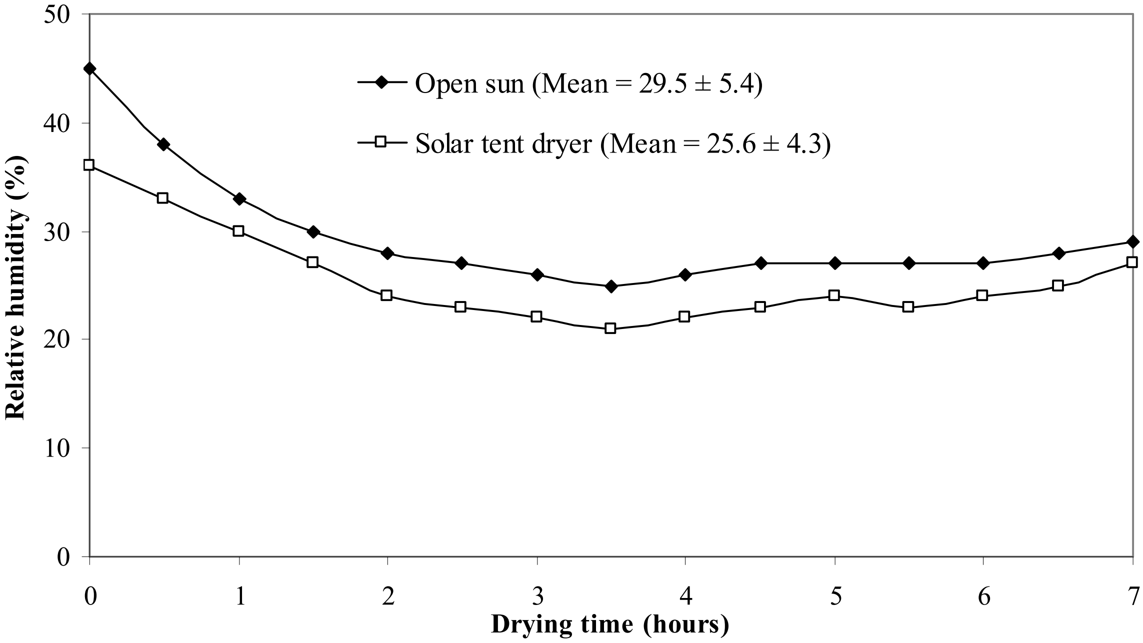

Figure 3. Comparison of relative humidity in the open sun and inside the solar tent dryer on a typical day of December 2008.

Figure 4 shows that the moisture content of amaranth seeds decreased exponentially with increase in drying time. The results show that under all the three drying conditions (viz., open sun, bottom layer and top layer) the rate of drying was highest within the first 2.5 hours of drying. Thereafter, the drying rate reduced significantly. This observation is common with most cereal grains as reported by Abalone *et al*. (2005) and Basunia and Abe (2001). As seen from the figure, there was no constant rate drying period and therefore the falling rate period prevailed in the entire thin layer drying process of amaranth seeds. It is also worth noting that the grains dried from an initial moisture content ranging from 61.3–66.7 % (dry basis) to an equilibrium moisture content of 7% (dry basis). It took 3.5, 4.5 and 6 hours to dry the seeds to the equilibrium moisture content for the top layer, bottom layer and open sun, respectively.

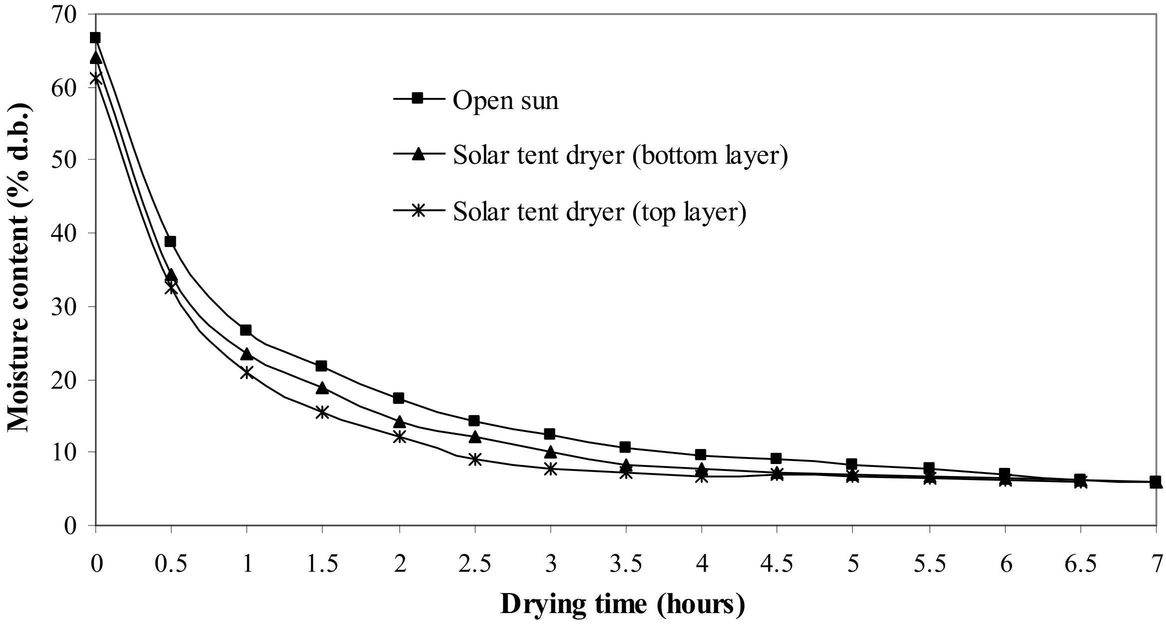

Figure 4. Drying curves for amaranth seeds under solar tent dryer and open sun.

Figure 5 shows that the drying rate decreased continuously with increasing drying time. The drying rate increased from open sun, bottom layer and top layer at any given time. However, the drying rates were not significantly different. These results are in agreement with the observations of earlier researchers based on thin layer drying of amaranth seeds (Abalone *et al*., 2006). In the falling rate period the material surface is no longer saturated with water and the drying rate is therefore controlled by diffusion of moisture from the interior of solid to the surface (Diamante and Munro, 1993). As expected, the decrease of relative humidity in the open sun and under the solar tent dryer increases the drying rate of the material because higher temperatures are developed.

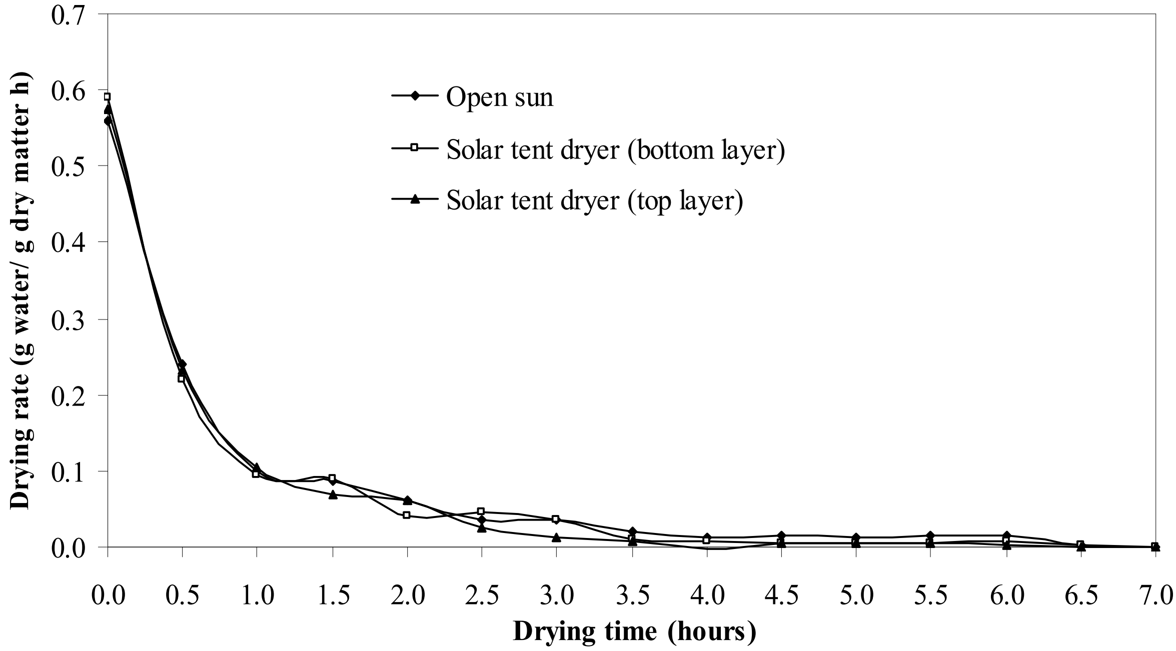

Figure 5. Drying rate as a function of drying time of amaranth seeds.

Regression analyses were done for six thin layer drying models (viz., Newton, Page, Modified Page, Henderson and Pabis, Logarithmic and Wangh and Singh) by relating the drying time and moisture ratio in order to select the model that adequately describes thin layer drying of amaranth seeds. The acceptability of the model was based on $R^2 \cong 1$, and low values of χ^2 and RMSE. The model coefficients and parameters of error analysis under the natural convection solar tent dryer, and the open sun are presented in Tables 2–4. When all the six models are considered, the results show that the R^2 values obtained for the dryer at the top layer, bottom layer and open sun ranged from 0.834–0.999, 0.858–0.998 and 0.878–0.997, respectively. The corresponding values for the RMSE were 0.0055–0.1065, 0.0118–0.0979 and 0.0003–0.0095, respectively. Those for the χ^2 were 0.0000–0.0131, 0.0002–0.0111 and 0.0154–0.0908, respectively. Comparison of the six models shows that the Page model attained the highest R^2 (0.997–0.999) and the lowest RMSE (0.0003–0.0118) and χ^2 (0.0000–0.0154) values. This illustrates that, even though all the tested models satisfactorily predicted the thin layer drying of amaranth grains, the Page model performed better than the rest. Similarly, Figure 6 compares the moisture ratios predicted by the Page model and the actual values under both top and bottom layers of the solar tent dryer and in the open sun. The figure confirmed a good prediction of moisture ratio by the Page model during thin layer drying of amaranth seeds throughout the drying period. These results are in agreement with the observations by Abalone *et al*. (2006) for thin layer drying of amaranth seeds.

Table 2. Estimated parameters and comparison criteria for open sun drying

Model	Model coefficients and constants	R^2	RMSE	χ^2
Newton	$k = 0.7803$	0.963	0.0027	0.0500
Page	$k = 0.99$, $n = 0.8141$	0.997	0.0003	0.0154
Modified Page	$k = 0.99$, $n = 0.8141$	0.996	0.0003	0.0154
Henderson and Pabis	$a = 1.0235$, $k = 0.7803$	0.954	0.0036	0.0555
Logarithmic	$a = 0.7585$, $k = 0.7792$, $c = 0.0187$	0.949	0.0043	0.0589
Wang and Singh	$a = -0.3125$, $b = 0.0310$	0.878	0.0095	0.0908

Table 3. Estimated parameters and comparison criteria for solar tent drying (bottom layer)

Model	Model coefficients and constants	R^2	RMSE	χ^2
Newton	$k = 0.8341$	0.948	0.0594	0.0038
Page	k = 1.1494, $n = 0.8171$	0.998	0.0118	0.0002
Modified Page	$k = 1.1494$, $n = 0.8171$	0.997	0.0128	0.0002
Henderson and Pabis	$a = 0.8105$, $k = 0.8341$	0.960	0.0521	0.0031
Logarithmic	$a = 0.7333$, $k = 0.8446$, $c = 0.0053$	0.932	0.0679	0.0058
Wang and Singh	$a = -0.3249$, $b = 0.0334$	0.858	0.0979	0.0111

Table 4. Estimated parameters and comparison criteria for solar tent drying (top layer)

Model	Model coefficients and constants	R^2	RMSE	χ^2
Newton	$k = 0.8816$	0.936	0.0662	0.0047
Page	$k = 1.2969$, $n = 0.8219$	0.999	0.0055	0.0000
Modified Page	$k = 1.2969$, $n = 0.8219$	0.998	0.0097	0.0001
Henderson and Pabis	$a = 0.6337$, $k = 0.8816$	0.864	0.0966	0.0108
Logarithmic	$a = 0.7277$, $k = 0.9044$, $c = -0.0049$	0.927	0.0705	0.0062
Wang and Singh	$a = -0.3347$, $b = 0.0353$	0.834	0.1065	0.0131

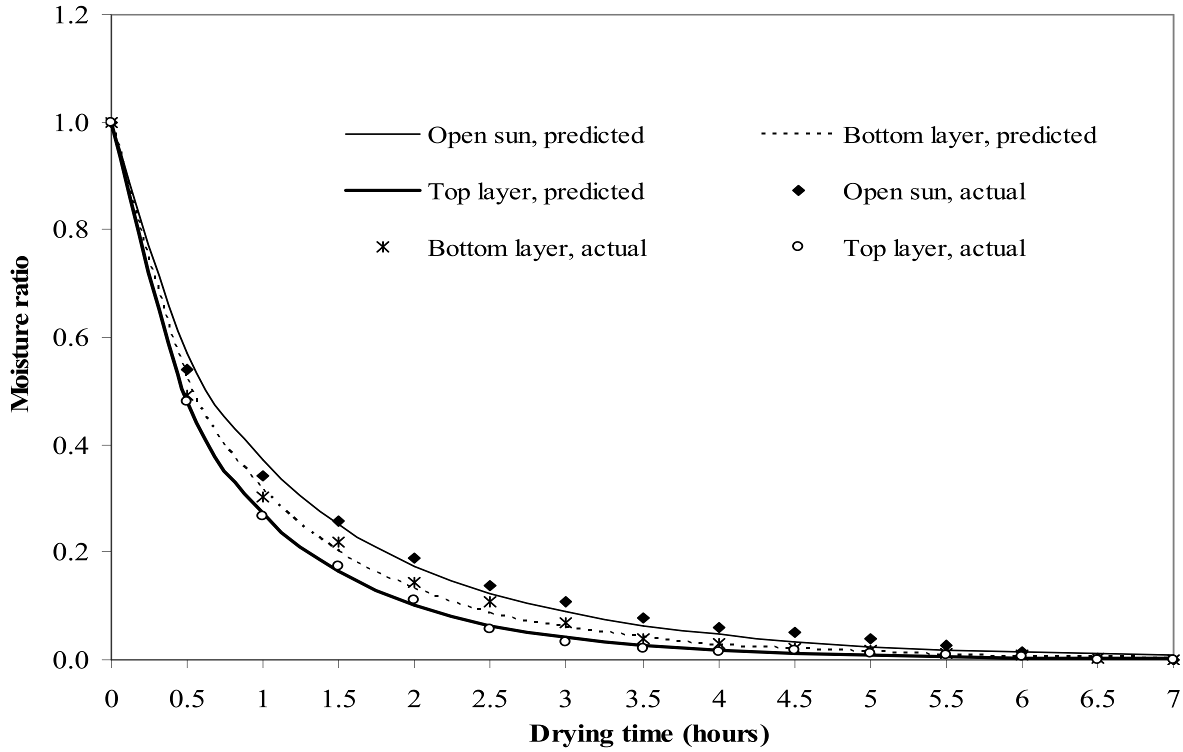

Figure 6. Comparison between the predicted moisture ratios using Page model and the actual values under open sun and in both top and bottom layers of the solar tent dryer.

The effective moisture diffusivities estimated from the drying data represent an overall mass transport property of moisture in the material, which may include liquid diffusion, vapour diffusion or any other possible mass transfer mechanism. The continuous decrease in moisture ratio with increase in drying time shows that the results can be interpreted using Fick's diffusion model (Konishi *et al*., 2001). Effective moisture diffusivity (D_e) was calculated using slopes derived from the linear regression of lnMR versus time data as defined in Eq. 9. The D_e values of amaranth seeds under open sun drying, solar tent drying on bottom and top layers were found to be 5.49×10^{-12} m^2/s, 5.88×10^{-12} m^2/s and 6.20×10^{-12} m^2/s, respectively. High temperature values developed at the top layer of the drying rack in the solar tent dryer led to highest D_e value and this represents the direct dependency of effective moisture diffusivity on temperature (Vizcarra Mendoza *et al*., 2003).

4. CONCLUSION

In this study, the drying behaviour of amaranth seeds was investigated under open sun and natural convection solar tent dryer. The solar tent dryer dried the amaranth seeds faster than the open sun. The drying of amaranth seeds occurred in the falling rate period where the drying rate decreased exponentially with increase in drying time. During the drying period, a strong correlation existed (R^2>0.9) between temperature and relative humidity in the solar tent dryer and the open sun, and total solar radiation. The temperatures developed in both top (48.9±4.8 ^oC)

and bottom (39.5±3.8 ^{o}C) layers of the dryer were always higher than those in the open sun (27.8±2.6 ^{o}C). In addition, the relative humidity values recorded in the dryer were lower (25.6±4.3 %) than those in the open sun (29.5±5.4 %).

To explain the drying behaviour of amaranth seeds, six mathematical drying models were fitted to the drying data. Comparison of the coefficient of determination, root mean square error and the reduced chi-square showed that the Page model was the most suitable in describing thin layer drying of amaranth seeds under open sun (R^2, 0.997; RMSE, 0.0003; χ^2, 0.0154) and on both bottom (R^2, 0.998; RMSE, 0.0118; χ^2, 0.0002) and top (R^2, 0.999; RMSE, 0.0055; χ^2, 0.0000) layers of the solar tent dryer. The effective moisture diffusivities for amaranth seeds ranged from $5.49\times10^{-12} - 6.20\times10^{-12}$ m^2/s.

5. ACKNOWLEDGEMENTS

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