

THIN LAYER DRYING CHARACTERISTICS OF AMARANTH GRAINS IN A NATURAL CONVECTION SOLAR TENT DRYER

E. K. Ronoh, C. L. Kanali, J. T. Mailutha and D. Shitanda

Biomechanical and Environmental Engineering Department, College of Engineering and Technology, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya

E-mail: eriqueron2002@yahoo.com

Abstract

This study aimed at determining thin layer drying characteristics of amaranth grains in a natural convection solar dryer. Initially, temperature distribution in the dryer was evaluated using nine discrete points spread in two planes (Planes 1 and 2). Planes 1 and 2 were set at 0.75 and 1.5 m above the concrete base of the dryer. The drying characteristics were determined by drying the grains at two levels (Layers 1 and 2) in the dryer. The control treatment involved drying the grains in the open sun. The mean temperatures and standard deviations for Plane 1 ranged from 38.2–38.4°C and 6.8–7.3°C, respectively. The corresponding values for Plane 2 were in the range of 38.8–39.2°C and 6.6–6.9°C, respectively. At 5% level of significance, there was no significant difference in temperature distribution within and between the planes. Further, the grains dried in the dryer attained an equilibrium moisture content of 7% d.b from an initial value ranging from 61.3–66.7% d.b after 4.5 hours of drying as opposed to 7 hours for the open sun. The effective moisture diffusivity of the grains ranged from 5.49×10^{-12} – 6.20×10^{-12} m²/s. The findings demonstrate the potential of natural convection solar tent dryers in enhancing drying of amaranth grains in vertical layers.

Key words: Solar tent dryer, thin layer, amaranth grains, temperature, moisture diffusivity

1.0 Introduction

Drying is defined as the removal of moisture from a product, and in most practical situations the main stage during drying is the internal mass transfer. Drying is one of the cheap and common preservation methods for biological products (Shitanda and Wanjala, 2003). Successful drying depends on: enough heat to draw out moisture, without cooking the grain; dry air to absorb the released moisture; and adequate air circulation to carry off the moisture. When drying grains, the key factor is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the grain. If the temperature is too low in the beginning, microorganisms may grow before the grain is adequately dried (Vizcarra Mendoza *et al.*, 2003).

Amaranths are drought-tolerant crops and are susceptible to partial shatter losses especially when harvested at a moisture content less than 30% dry basis (d.b) (Prim, 2003; Gupta, 1986). Harvesting of amaranth grains must be done at moisture content of 30% d.b or higher which requires necessary artificial drying to safe storage moisture level. Storage of grain at a moisture content that is higher than the equilibrium moisture level of about 10% d.b leads to mould growth and the grains become unfit for human consumption (Abalone *et al.*, 2006). To ensure safe preservation of amaranth grains, they must be dried to equilibrium moisture content which requires good drying techniques. These grains are mostly dried in the rural areas in thin layers either in the open sun or in a solar dryer (Abalone *et al.*, 2006). Thin layer drying is the process of removal of moisture from a porous media by evaporation, in which drying air is passed through a thin layer of the material until the equilibrium moisture content is reached (Omid *et al.*, 2006).

The open sun drying method has disadvantages such as lack of temperature control, intensive labour and contamination from dust, foreign materials, rodents and bird droppings (Basunia and Abe, 2001). The best alternative, especially when amaranth is produced on commercial basis, is to provide affordable drying methods such as a natural convection solar tent dryer. This type of solar dryer is affordable in the rural set-up, saves labour, ensures good quality of material being dried and facilitates faster drying of grains especially under favourable conditions (Whitfield, 2000). The present work aimed at analyzing thin layer drying characteristics of amaranth grains in a natural convection solar tent dryer. The specific objectives were to analyze the distribution of temperature in the solar tent dryer, and to determine the thin layer drying characteristics of amaranth grains in the solar tent dryer.

2.0 Theoretical Considerations

2.1 Theory of Solar Drying

Solar drying is a form of convective drying, in which the air is heated by solar energy in a solar collector. Solar energy is an important and economical source of renewable energy, particularly during energy crises, when the costs of fossil fuel and electricity increase (Saravacos and Kostaropoulos, 2002). The amount of solar energy reaching the earth's surface is expressed in terms of the solar constant I_{sc} . The I_{sc} is valued at 1367 W/m^2 and is the quantity of energy received from the sun per unit area in a unit time on the earth's surface perpendicular to the sun's rays at a mean distance ($1.496 \times 10^8 \text{ km}$) of the earth from the sun (Sukhatme, 2003). 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 to fluctuate in a manner given by Equation 1 where, I'_{sc} is the solar energy flux on the earth's surface at the n^{th} day of the year, n is 1 on 1st January, and 366 on 31st December.

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

The direct solar radiation, I_b , reaching a unit area of a horizontal surface on the earth in the absence of the atmosphere can be expressed by Equation 2 (Sukhatme, 2003). In this equation, I'_{sc} is solar energy flux on the earth's surface at the n^{th} day of the year (W/m^2), ϕ is latitude (degrees), δ is angle of declination (degrees), ω is hour angle (degrees), and β is angle of inclination of the surface from horizontal surface of the earth.

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

The angle δ can be evaluated from the expression presented in Equation 3. On the other hand, ω is computed by Equation 4 (Sukhatme, 2003), where H_r is the hour of the day in 24 hour time.

$$\delta = 23.45 \sin \left(360 \left(\frac{284 + n}{365} \right) \right) \dots\dots\dots(3)$$

$$\omega = 15(12 - H_r) \dots\dots\dots(4)$$

The diffuse radiation, I_d , is that portion of solar radiation that is scattered downwards by the molecules in the atmosphere. During clear days, the magnitude of I_d is about 10 to 14% of the solar radiation received at the earth's surface. I_d can be estimated as direct radiation incident at 60° on the collector surface by Equation 5 (Sukhatme, 2003), where C is the diffuse radiation factor. The total solar radiation, I_t , incident on the horizontal surface such as the collector plate of a solar dryer is therefore obtained by adding the direct and diffuse components of solar radiation as shown in Equation 6. The total solar radiation is of great importance for solar dryers since it captures the required components of solar energy that is harnessed in the dryer.

$$I_d = CI_b \cos 60^\circ = 0.5CI_b \dots\dots\dots(5)$$

$$I_t = I_b (1 + 0.5C) \dots\dots\dots(6)$$

The total solar radiation harnessed by the dryer provides the heat energy incident on the collector surface, Q_i , which is necessary for the drying process. This heat energy is expressed in Equation 7, where A is the area of the energy collector (m^2) and τ is the transmissivity of the collector material.

$$Q_i = I_t A \tau \dots\dots\dots(7)$$

2.2 Moisture Transfer under Thin Layer Drying

The theoretical equations of moisture transfer in grains are transient in nature and their solutions are not easy. Several approaches, including separating the moisture transfer equations for moisture movement in and around the grain, have been suggested. The equation for thin layer drying of grains is given by Equation 8 as reported by Brooker *et al.* (1992). In this equation, M is the moisture content (% d.b) at drying time t (hours), M_e is the equilibrium moisture content (% d.b), k is the drying rate constant (h^{-1}) and $M = M_o$ (initial moisture content, % d.b) at $t = 0$. Integration of Equation 8 with constant of integration equal to unity yields Equation 9 (Lahsasni *et al.*, 2004).

$$\frac{\partial M}{\partial t} = k (M - M_e) \dots\dots\dots(8)$$

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \quad (\text{for } t > 0) \dots\dots\dots(9)$$

The ratio on the left hand side of Equation 9 is referred to as moisture ratio (MR). During solar drying, the values of M_e are relatively small compared to M and M_o . In addition, the relative humidity of the drying air varies continuously. Therefore, Equation 9 can be simplified to Equation 10 (Uluko *et al.*, 2006).

$$MR = \frac{M}{M_o} = e^{-kt} \dots\dots\dots(10)$$

Another important parameter that should be considered during drying is diffusivity which is used to indicate the flow of moisture out of the material being dried (Vizcarra-Mendoza *et al.*, 2003). Therefore, it is important that this parameter is established during drying of grains such as amaranth. 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 the 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 (Crank, 1975). Assuming that amaranth grains can be approximated to spheres, the diffusion is expressed by Equation 11 (Konishi *et al.*, 2001), where D_e is the effective moisture diffusivity (m^2/s) and r_a is the radius (≈ 0.0005 m) of amaranth grain.

$$\frac{\partial M}{\partial t} = D_e \left(\frac{\partial^2 M}{\partial r_a^2} \right) \dots\dots\dots (11)$$

For the transient diffusion in a sphere, assuming uniform initial moisture content and a constant effective diffusivity throughout the sample, the analytical solution of Equation 11 yields Equation 12.

$$MR = \frac{M - M_e}{M_0 - M_e} = \left(\frac{6}{\pi^2} \right) \exp \left[-D_e t \left(\frac{\pi^2}{r_a^2} \right) \right] \dots\dots\dots (12)$$

The effective moisture diffusivity is determined by applying logarithms to Equation 12 to obtain a linear relation of the form shown in Equation 13. Therefore, a plot of $\ln(MR)$ versus time yields a straight line, and the diffusivity is determined from the slope (slope = $-D_e \pi^2 / r_a^2$).

$$\ln(MR) = \ln \left(\frac{6}{\pi^2} \right) - \left(D_e \frac{\pi^2}{r_a^2} \right) t \dots\dots\dots (13)$$

3.0 Materials and Methods

3.1 Description of the Solar Tent Dryer

Figure 1 shows the schematic diagram of the natural convection solar tent dryer used in this study. 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 is semi-circular in shape with a radius of 0.5 m and the entire structure is covered with a polyvinyl chloride (PVC) material. The PVC material is preferred because it filters radiations such as ultraviolet, which can destroy light sensitive nutrients in the material being dried (Leon *et al.*, 2002). The chimney measuring 0.2 m long, 0.2 m wide and 0.4 m high is provided at the top center of the dryer to enhance natural convective air circulation. The dimensions of the door are 0.6 m wide and 1.8 m high. The solar tent dryer was placed on a concrete base measuring 1.95 m wide, 2.83 m long and 0.075 m high. The concrete base was provided in order to collect grains easily in case of spillage, to concentrate heat harnessed in the dryer, and to avoid water draining into the dryer.

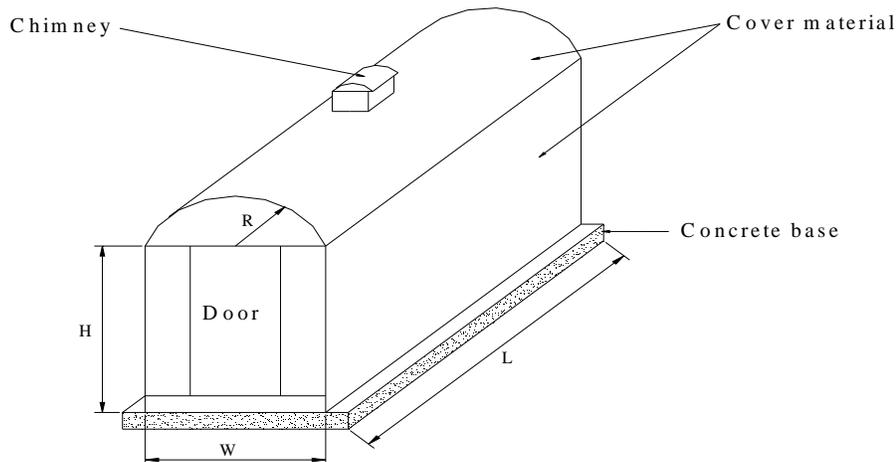


Figure 1: Schematic of the natural convection solar tent dryer. In this figure: $W = 1.85$ m; $L = 2.73$ m; $H = 2.05$ m; $R = 0.5$ m

3.2 Analyzing the Distribution of Temperature in the Solar Tent Dryer

Prior to determining the thin layer drying characteristics of amaranth grains, it was necessary to monitor how temperature were distributed in the dryer. Traditionally, grains are dried in solar dryers in single layers (Basunia and Abe, 2001). The need for enhancing output and efficiency, and for minimizing cost requires that grains be dried in a series of layers. To determine the suitable positions of these layers, it is necessary that the temperature

distribution in the solar tent dryer be evaluated. In this study, the evaluation was carried out by monitoring temperatures at different locations in the x,y,z-plane in the dryer, the origin being the centre of the ground surface inside the solar tent dryer. The positions for recording temperature distribution were defined by discrete points (x_i, y_j, z_l) as shown in Figure 2, on which m_1 vertical lines, n_1 lateral lines and p_1 horizontal lines were distributed. The discrete points were located at intersections of the lines and the coordinates were established from Equations 14–16. In these equations, W, L and H are the width, length and height of the main structure (Figure 1), respectively.

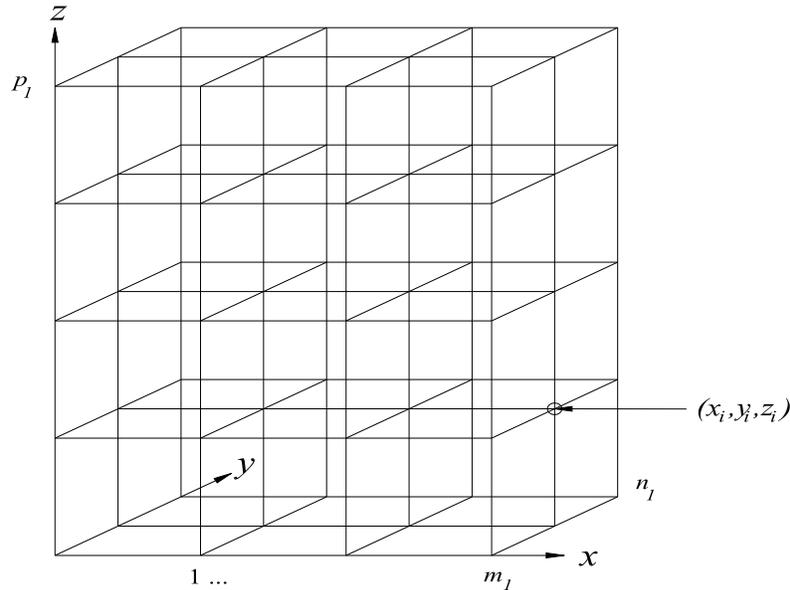


Figure 2: Discretization of temperature distribution points in the solar tent dryer

$$x_i = (i - 1) \frac{W}{(m_1 - 1)} \Big|_{i=1 \text{ to } m_1} \dots\dots\dots (14)$$

$$y_j = (j - 1) \frac{L}{(n_1 - 1)} \Big|_{j=1 \text{ to } n_1} \dots\dots\dots (15)$$

$$z_l = (l - 1) \frac{H}{(p_1 - 1)} \Big|_{l=1 \text{ to } p_1} \dots\dots\dots (16)$$

Figure 3 shows two planes (Planes 1 and 2) in the solar tent dryer on which nine discrete points on each plane were located for monitoring temperature distribution. These points were defined in such a way that Plane 1 was considered to be in the positive x-direction and at a vertical distance of 0.75 m from the ground surface ($z = 0.75$ m). Plane 2 was set at 0.75 m higher from the Plane 1 ($z = 1.5$ m) to avoid shading and enhance air circulation. The spacing between the concrete base and Plane 1, and between Planes 1 and 2 of 0.75 m were subjectively set. The points along the two planes constituted the y coordinates.

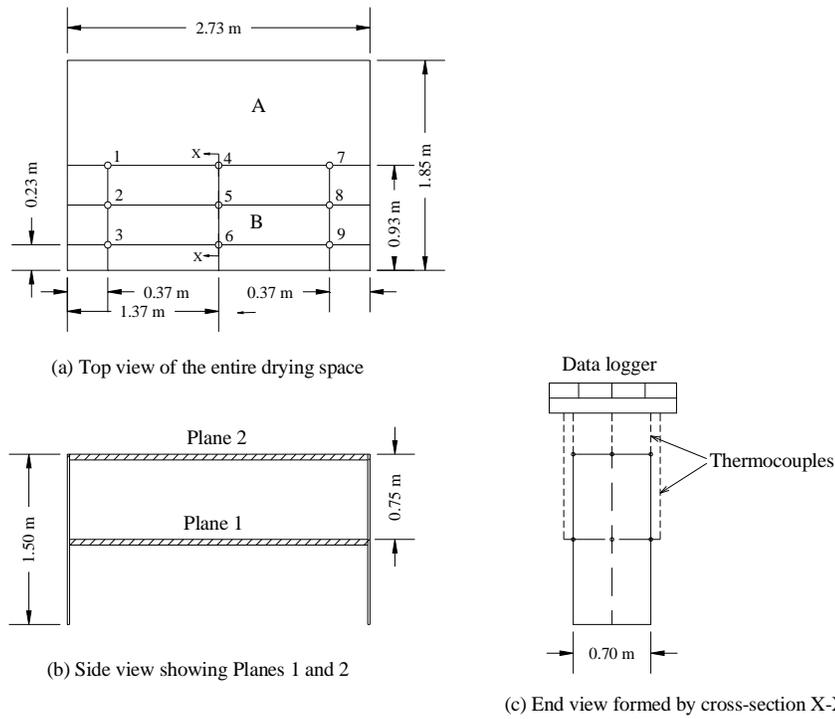


Figure 3: Schematic of temperature distribution acquisition system in the solar tent dryer

Temperature data were recorded using thermocouples which relayed the information to a Thermodac electronic data logger (ETO Denki E, Japan) with $\pm 1^{\circ}\text{C}$ accuracy. The data were acquired for three consecutive days for 10 hours on each day at intervals of one hour starting from 8:00 a.m. Preliminary tests conducted on temperature distribution in Sections A and B (see Figure 3(a)) established that the temperatures in the two sections were not significantly different. Hence, in this study temperatures were monitored only in Section B of the solar tent dryer. Analysis of variance (ANOVA) was conducted on the data using GenStat (Discovery Edition 3) statistical tool to determine whether or not there existed significant difference for temperature distribution within the same plane and between planes.

3.3 Determining the Thin Layer Drying Characteristics of Amaranth Grains

Two layers of drying trays were arranged in the dryer, each layer measuring 0.5 m wide, 2.45 m long and 0.75 m high as shown in Figure 4. Layer 1 is raised 0.75 m above the concrete surface while Layer 2 is at a height of 1.5 m. Flat and angled iron bars were used to fabricate these trays, and a fine wire mesh fixed at the top of each layer on which the grains were placed.

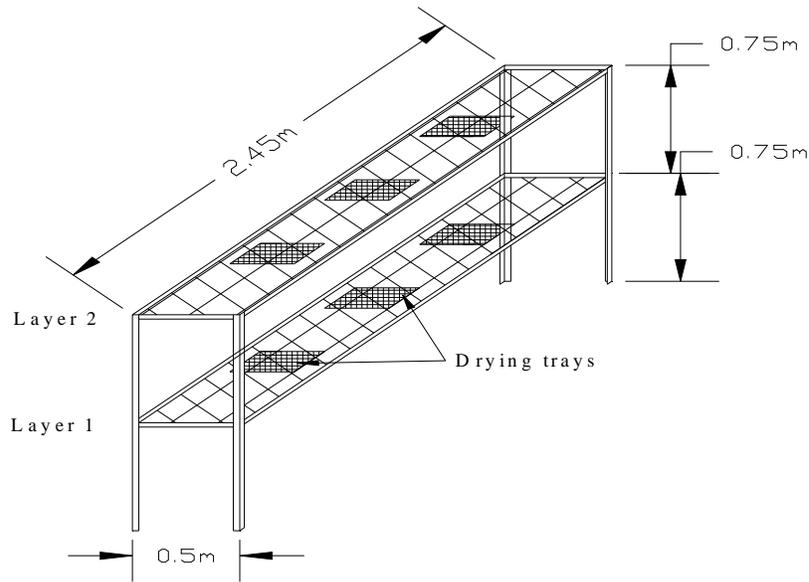


Figure 4: Schematic diagram showing the arrangement of drying trays in two layers

Data acquisition involved recording temperature and relative humidity values, and monitoring moisture content of the grains during drying in the solar tent dryer and the open sun. The data were recorded at 30 minutes intervals from 9:00 a.m to 4:00 p.m for three consecutive days. In order to determine the moisture content, grain samples were weighed in a drying dish of known weight and the wet weight recorded as W_t . The capacity and sensitivity of Shimadzu electronic balance (LIBROR EB-4300D, Japan) used were 600g and 0.01g, respectively. The samples were placed in a constant-temperature oven set at a temperature of 105°C for about 24 hours. The dried grains were removed from the oven and the dry weight, W_d , recorded. The percent dry basis moisture content M was then evaluated from the expression (Bala, 1997) given by Equation 17.

$$M = \frac{W_t - W_d}{W_d} * 100 \dots\dots\dots (17)$$

4.0 Results and Discussion

4.1 Temperature Distribution in the Solar Tent Dryer

The analysis of temperature distribution in the solar tent dryer was conducted on two planes (viz., Planes 1 and 2 as shown in Figure 4). Planes 1 and 2 are located at 0.75 and 1.5 m above the concrete base. Nine identical discrete points on each plane were utilized for monitoring the temperature. A total of 90 daily temperature data were obtained for each plane.

Results of the mean temperature distribution for Planes 1 and 2 are shown in Table 1. As seen from the table, the mean temperatures and standard deviations for Plane 1 ranged from 38.2–38.4°C and 6.8–7.3°C, respectively. The corresponding values for Plane 2 ranged from 38.8–39.2°C and 6.6–6.9°C, respectively. This shows that there was less variation in the temperature distribution within the planes. However, the temperatures for Plane 2 were slightly higher than those of Plane 1. This is because Plane 2 was closer to the solar energy collector surface. An ANOVA conducted at 5% level of significance shows that there was no significant difference in temperature distribution within Plane 1 (p -value, 0.999; $F_{critical}$, 2.055; $F_{computed}$, 0.002) and Plane 2 (p -value, 0.999; $F_{critical}$, 2.055; $F_{computed}$, 0.007) as the $F_{computed}$ values were lower than the $F_{critical}$ ones.

Table 1: Distribution of mean temperatures in the solar tent dryer

Temperatures (°C) developed at different discrete points in the solar tent dryer									
(a) Discrete points in Plane 1									
	1	2	3	4	5	6	7	8	9
Mean	38.2	38.4	38.3	38.2	38.4	38.3	38.2	38.4	38.3
Stdev	7.3	7.3	7.2	7.0	7.2	6.8	6.9	7.0	7.1
(b) Discrete points in Plane 2									
	10	11	12	13	14	15	16	17	18
Mean	39.1	39.2	38.8	39.2	38.9	39.2	38.9	39.2	38.8
Stdev	6.9	6.7	6.8	6.7	6.8	6.8	6.8	6.6	6.7

Similarly, there was no significant difference in temperature distribution between the planes as the $F_{computed}$ was less than the $F_{critical}$ (p -value, 0.813; $F_{critical}$, 4.414; $F_{computed}$, 0.058). The above findings imply that one can achieve uniform drying of agricultural produce when drying in thin layers on any plane in the solar tent dryer. These results are in agreement with the observations reported by Mwithiga and Kigo (2006) in studying the temperature distribution in a solar dryer with limited sun tracking capability under similar conditions. Further, the results show that the dryer output can be doubled at minimal cost by drying the produce on two vertical layers in the solar tent dryer without compromising on the drying efficiency. However, when drying on different layers shading should be avoided and the spacing between the planes should be such that air circulation is not inhibited.

4.2 Thin Layer Drying Characteristics of Amaranth Grains in the Solar Tent Dryer

The drying characteristics of amaranth grains evaluated in this study comprised moisture content and effective moisture diffusivity. In order to determine these characteristics, temperature and moisture content data were acquired within the dryer at two levels (i.e., Layer 1 and Layer 2 as shown in Figure 4). Figure 5 compares the temperatures developed in the solar tent dryer and the open sun. It is seen from the figure that the temperatures in the dryer ($44.2 \pm 6.4^\circ\text{C}$) were higher than those in the open sun ($27.8 \pm 2.6^\circ\text{C}$) over the entire drying period. In addition, temperatures developed in Layer 2 were always higher ($48.9 \pm 4.8^\circ\text{C}$) than those in Layer 1 ($39.5 \pm 3.8^\circ\text{C}$). This is due to the fact that Layer 2 was closer to the solar energy harnessing surface than Layer 1. Figure 5 also shows that increase in solar radiation led to increase in temperature, indicating a direct relationship between solar radiation and temperature developed both in the dryer and the open sun.

Further comparison of temperatures developed in the dryer and the open sun during drying of amaranth grains was done using ANOVA at 5% level of significance. The results show that there was significant difference (p -value, 2.44×10^{-06} ; $F_{critical}$, 4.196; $F_{computed}$, 34.737) between temperatures developed in Layers 1 and 2. There seem to be a contradiction between the preceding results and those obtained in Section 5.1 that dealt with distribution of temperature in the dryer without drying the grains. The earlier results, unlike the current ones, showed no significant difference in temperatures between Layers 1 and 2. When grains were spread on Layer 2, they caused shading on Layer 1 and this may have resulted in significant lowering of temperatures on this layer. Similarly, the results show that there was significant difference (p -value, 1.26×10^{-17} ; $F_{critical}$, 3.220; $F_{computed}$, 112.963) between temperatures developed in the dryer and the open sun. This further confirms that solar tent dryers can effectively be used to harness solar energy for drying of agricultural products (Sacilik *et al.*, 2006; Abalone *et al.*, 2006)] such as amaranth grains.

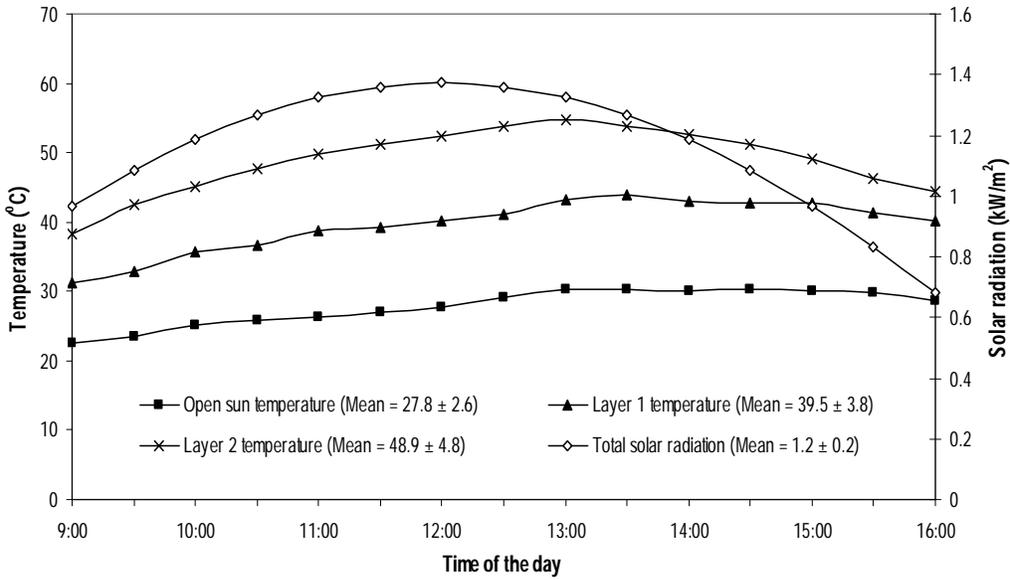


Figure 5: Comparison of temperature and total solar radiation with drying time in the solar tent dryer and the open sun

Figure 6 presents the relative humidity values recorded in the solar tent dryer and the open sun. The relative humidity values in the dryer were always lower ($25.6 \pm 4.3\%$) than those in the open sun ($29.5 \pm 5.4\%$) during the drying period. An ANOVA conducted on the results showed no significant difference between the relative humidity values for the dryer and the open sun (p -value, 0.039; $F_{critical}$, 3.220; $F_{computed}$, 3.497). The results obeyed the commonly observed behaviour that relative humidity decreases with increase in temperature (Basunia and Abe, 2001).

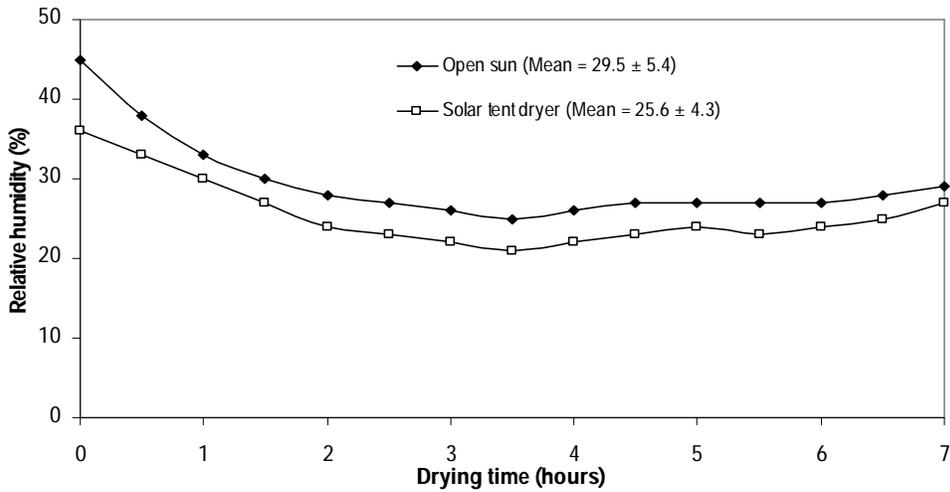


Figure 6: Comparison of relative humidity in the solar tent dryer and the open sun during drying of amaranth grains.

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 Equations 18 and 19. The high R^2 values (>0.95) obtained imply that there is a strong correlation between the drying conditions inside the solar tent dryer and the open sun conditions.

$$T_i = 1.38T_a + 14.66I_t - 6.27 \quad R^2 = 0.99 \dots \dots \dots (18)$$

$$Rh_i = 0.74Rh_a - 2.62t_i + 6.63 \quad R^2 = 0.96 \dots \dots \dots (19)$$

The drying curves of amaranth grains in Layers 1 and 2 of the solar tent dryer and the open sun are shown in Figure 7. The figure shows that the moisture content decreased continuously with increase in time. Many researchers (Basunia and Abe, 2001; Abalone *et al.*, 2005; Omid *et al.*, 2006) have noted the same observation, particularly, for cereal grains. The results show that under all the three drying conditions (*viz.*, open sun, Layer 1 and Layer 2) the rate of drying was highest within the first 2.5 hours of drying. The drying rate reduced significantly for the subsequent hours of drying. Further, the results show that amaranth grains with initial moisture content ranging from 61.3–66.7% d.b dried to an equilibrium moisture content of 7% d.b. It took 3.5, 4.5 and 6 hours to attain the equilibrium moisture content for Layer 2, Layer 1 and open sun, respectively. It is also shown by the drying curves that the entire thin layer drying process of amaranth grains obeyed the falling rate period (Diamente and Munro, 1993).

When Layers 1 and 2 are compared, it is noticed that the drying rate was higher for the latter than the former at any given time (Figure 7). This is because Layer 2 attained high drying temperatures as compared to Layer 1. Similarly, comparison of the solar dryer and the open sun shows that the drying rate was high for the dryer. The temperatures recorded in the dryer were higher than those in the open sun. In addition, the relative humidity values were lower in the dryer than in the open sun. The higher the temperature and the lower the relative humidity, the faster the drying (Ronoh *et al.*, 2009; Sacilik *et al.*, 2006).

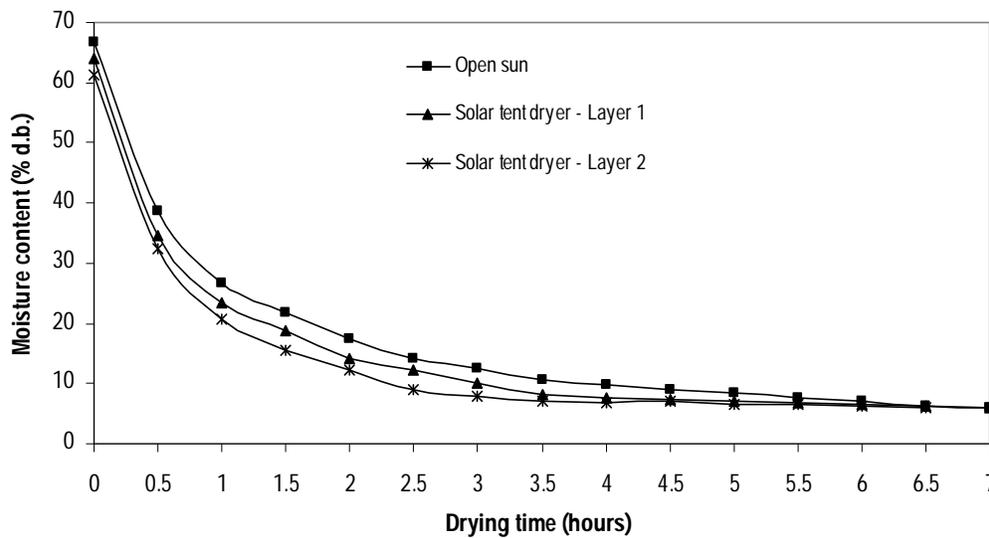


Figure 7: Drying curves for amaranth grains dried under open sun and in the solar tent dryer

An ANOVA conducted on the drying data at 5% level of significance shows that for the first 2.5 hours of drying the drying rates were not significantly different under the solar dryer and the open sun (*p*-value, 0.881; $F_{critical}$, 3.682; $F_{computed}$, 0.127). During this drying period there is sufficient energy and relative humidity to dry the grains under both conditions, a characteristic of the first falling rate drying period (Omid *et al.*, 2006). Conversely, the drying rates for the solar dryer and the open sun were slightly different between 2.5–8 hours of drying since the $F_{critical}$ obtained was lower than the $F_{computed}$ (*p*-value, 0.033; $F_{critical}$, 3.403; $F_{computed}$, 3.934). The slight difference can be attributed to the difference in energy and humidity levels recorded under both drying conditions. When the drying rates for Layer 1, Layer 2 and the open sun are compared for the entire drying period, the results show that there was no significant difference among them (*p*-value, 0.837; $F_{critical}$, 3.220; $F_{computed}$, 0.179). Although the preceding findings imply that there is no need for employing a solar tent dryer vis-a-vis the open sun for drying amaranth grains, extra energy and favourable relative humidity conditions are required to dry the grains to equilibrium moisture content. This extra energy and conducive relative humidity can sufficiently be provided by the solar tent dryer as opposed to the open sun. Similar observations have been noted by Basunia and Abe (2001) during thin

layer drying of rough rice under natural convection.

Comparison of the drying rates on Layers 1 and 2 of the solar dryer within the first 2.5 hours of drying shows no significant difference (p -value, 0.819; $F_{critical}$, 4.965; $F_{computed}$, 0.055). Similarly, the results show no significant difference (p -value, 0.2017; $F_{critical}$, 4.494; $F_{computed}$, 1.776) in the drying rates between 2.5–8 hours of drying on Layers 1 and 2. These results, therefore, show that Layers 1 and 2 of the solar tent dryer can be used to dry amaranth grains in thin layers without significantly affecting the drying rate of the grains.

Moisture transfer in amaranth grains during the thin layer drying process can be explained by the effective moisture diffusivity (D_e). Figure 8 shows a semi-logarithmic plot of dimensionless moisture ratio versus time in the solar tent dryer and the open sun. The slope of this plot was taken for the computation of D_e using Equation 13. The D_e values of amaranth grains attained for Layers 1 and 2 were 5.88×10^{-12} and 6.20×10^{-12} m^2/s , respectively, while for the open sun the value was 5.49×10^{-12} m^2/s . The diffusivity values obtained are of the same order of magnitude as those reported for amaranth grain (Vizcarra Mendoza *et al.*, 2003). The effective moisture diffusivities calculated from the drying data represented an overall mass transport property of moisture in the grains. High temperatures developed on Layer 2 of the solar tent dryer led to highest D_e value and this clearly shows a dependence of moisture removal from amaranth grains on temperature.

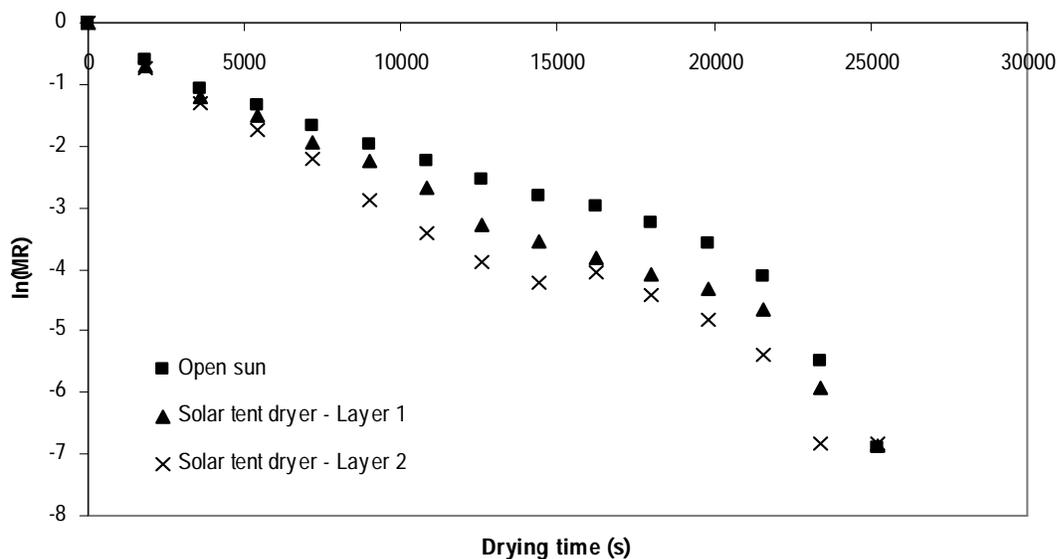


Figure 8: Variation of $\ln(MR)$ with drying time in the solar tent dryer and the open sun

5.0 Conclusions and Recommendations

The results of this study show that there was no significant difference in the distribution of temperature within and between Planes 1 and 2 that were spaced at 0.75 and 1.5 m above the ground concrete surface of the solar tent dryer, respectively. This implies that the dryer capacity can be increased by drying the grains in layers. However, high mean temperatures in the range of 38.8–39.2°C were developed at Plane 2 as compared to 38.2–38.4°C for Plane 1. In addition, the results indicate that the solar tent dryer successfully dried amaranth grains to an equilibrium moisture content of 7% d.b after 4.5 hours of drying as opposed to 7 hours for the open sun. The findings demonstrate that the dryer output can be increased by drying the grains in vertical layers without significantly affecting the drying rate. Since the vertical spacing was subjectively chosen, there is need to determine whether or not more layers can be utilized to achieve effective drying of agricultural produce in the solar tent dryer under natural convection.

Acknowledgement

The authors sincerely express their appreciation to Jomo Kenyatta University of Agriculture and Technology (JKUAT) for their financial support and research facilities offered to carry out this study.

References

- Abalone, R., Cassinera, A., Gastón, A. and Lara, M. A. (2006). Thin layer drying of amaranth seeds. *Biosystems Engineering*. **93**(2), pp 179–188.
- Bala, B. K. (1997). *Drying and storage of cereal grains*. Science Publishers, Inc. Plymouth, UK.
- Basunia, M. A. and Abe, T. (2001). Thin-layer solar drying characteristics of rough rice under natural convection. *Journal of Food Engineering*, **47**(4), pp 295–301.
- Brooker, C. W., Bakker-Arkema, F. W. and Hall, C. W. (1992). *Drying and storage of grains and oilseeds*. Van Nostrand Reinhold, New York, USA.
- Crank, J. (1975). *Mathematics of diffusion* (2nd Ed.). London: Oxford University Press.
- Diamante, L. M. and Munro, P. A. (1993). Mathematical modelling of the thin layer solar drying of sweet potato slices. *Solar Energy*, pp. 271–276.
- Gupta, V. K. (1986). Grain amaranths in Kenya. In: Proc. Third Amaranth Conf. Rodale Press, Inc., Emmaus, Pennsylvania.
- Konishi, Y., Horiuchi, J. I. and Kobayashi, M. (2001). Dynamic evaluation of the dehydration response curves of food characterized by a poultice-up process using a fish-paste sausage: A new tank model for computer simulation. *Drying Technology*. **19**(7), pp 1271–1285.
- Lahsasni, S., Kouhila, M., Mahrouz, M., Idlimam, A. and Jamali, A. (2004). Thin layer convective solar drying and mathematical modeling of prickly pear peel (*Opuntia ficus indica*). *Energy*. **29**(2), pp 235–249.
- Leon, M. A., Kumar, S. and Bhattacharya, S. C. (2002). A comprehensive procedure for performance evaluation of solar food dryers. *Renewable and Sustainable Energy Reviews*, **6**(4), pp 367–393.
- Mwithiga, G. and Kigo, S. N. (2006). Performance of a solar dryer with limited sun tracking capability. *Journal of Food Engineering*, **74**, pp 247–252.
- Omid, M., Yadollahinia, A. R. and Rafiee, S. (2006). A thin-layer drying model for paddy dryer. Proceedings of the International conference on Innovations in Food and Bioprocess Technologies. 12th–14th December 2006, AIT, Pathumthani, Thailand.
- Prim, L. (2003). Growing and harvesting quinoa and amaranth. Newsletter #38: Seeds of Change, 29th November 2003.
- Ronoh, E. K., Kanali C. L., Mailutha J. T. and Shitanda D. (2009). Modeling thin layer drying of amaranth seeds under open sun and natural convection solar tent dryer. *Agricultural Engineering International: the CIGR Ejournal*. Manuscript 1420. Vol. XI. November, 2009.
- Sacilik, K., Keskin, R. and Elicin, A. K. (2006) Mathematical modeling of solar tunnel drying of thin layer organic tomato. *Journal of Food Engineering*, **73**, pp 231–238.
- Saravacos, G. D. and Kostaropoulos, A. E. (2002). *Handbook of food processing equipment*. Kluwer Academic/Plenum Publishers, New York.
- Shitanda, D. and Wanjala, N. V. (2003). Effect of different drying methods on the quality of jute (*Corchorus olitorius L.*). *Proceeding of the 3rd Asian-Pacific Drying Conference*. Asian Institute of Technology-Bangkok, Thailand. 1st–3rd September, pp. 627–636.

Sukhatme, P. K. (2003). Solar energy: principles of thermal collection and storage. 2nd Ed., Tata McGraw-Hill Publishing, New Delhi.

Uluk, H., Kanali, C. L., Mailutha, J. T. and Shitanda, D. (2006). A finite element model for the analysis of temperature and moisture distribution in a solar grain dryer. *The Kenya Journal of Mechanical Engineering*, **2**(1), pp 47–56, Fimen Publishers, Nairobi, Kenya.

Vizcarra-Mendoza, M. G., Martinez, V. C. and Caballero, D. F. (2003). Thermal and moisture diffusion properties of amaranth seeds. *Biosystems Engineering*, **86**(4), pp 441–446.

Whitfield, D. E. (2000). Solar drying. International Conference on Solar Cooking. Kimberly, South Africa, 26th–29th November 2000.