# Evaluation of Solar-Energy Dryer Systems on Drying Behaviour and Quality Attributes of Amaranth Grains

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*Abstract-* **This work aimed at evaluating the thin layer drying behaviour of amaranth grains (*Amaranthus cruentus*) and comparing the quality of the grains dried under solar-energy tent dryer systems and the open sun. The dryers were covered with clear, yellow and nectarine diffused polyvinyl chloride (PVC) materials of 200 micron thickness whose transmissivities were 90%, 85% and 82%, respectively. The ambient temperature and relative humidity ranged from 23.3～33.5°C and from 24% ～ 46%, respectively, while the inside temperature and relative humidity in the solar dryers ranged from 30.4～50.7°C and from 15%～44%, respectively. Fresh amaranth grains with an initial moisture content ranging from 66.7% ～ 68.8% dry basis (d.b) were dried under both conditions for 8 hours to an equilibrium moisture content of about 7% d.b. The quality attributes assessed were colour, hardness and crude protein content. The findings showed no significant effect of colour of cover material on the grain quality. The study demonstrates that natural convection solar tent dryers covered with PVC materials enhance the thin layer drying rate of amaranth grains without significantly affecting their quality.**

***Keywords- Thin Layer; Amaranth Grains; Solar-energy Tent Dryers; Open Sun; Quality***

## I. INTRODUCTION

The need for diversified food production in semi-arid areas of Kenya calls for the promotion of indigenous crops such as amaranths. Amaranth grows vigorously, tolerates drought, heat, and pests, and adapts readily to a wide range of environments [1], [2]. In addition, amaranth's great nutritional qualities are the driving force facilitating its promotion. It is high in protein (16%～18%), particularly in the amino acid, lysine, which is low in the cereal grains [1], [3]. The high productivity (1000 ～ 3000 kg/ha) of amaranth fosters food security and high economic returns [2]. Amaranths are susceptible to partial shatter losses during harvest, especially, when their moisture content in the field is less than 30% dry basis (d.b) [2]. Storage of this grain at a moisture content that is higher than the equilibrium moisture level of about 10% d.b leads to mould growth and become unfit for human consumption [1]. To ensure safe preservation of amaranth grains, they must be dried to equilibrium moisture content which requires good drying techniques [4]. These grains are mostly dried in the rural areas in thin layers either in the open sun or in a solar dryer [1]. 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 [5]. Open sun drying, however, has disadvantages such as lack of temperature control, labour intensive and contamination from dust, foreign materials, rodents and bird droppings [6]. 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 [7].

The analyses of quality attributes of cereals grains as affected by the drying process are scarce and the grains are sourced from different varieties and geographical locations [8]. In real on-farm processing much higher temperatures are used in order to increase the output of the dryer although this can have an adverse effect on the quality aspects. The study was therefore undertaken to describe the thin layer drying behaviour of amaranth grains under different natural convection solar tent dryers, and also to investigate the effect of drying on product quality (hardness, colour and crude protein content).

## II. MATERIALS AND METHODS

### A. Experimental Solar Tent Dryers

The schematic of the natural convection solar tent dryers, used in this study, is shown in Fig. 1. The dryers consisted of a chimney, the main structure with a door and a concrete base. The main structure of the dryer measured 0.4 m wide, 0.5 m long and 0.5 m high. The top part of this structure was semi-circular in shape with a radius of 0.1 m and was entirely covered with a polyvinyl chloride (PVC) material.

The cover materials used to seal the dryers were clear, yellow and nectarine diffused PVC of 200 micron thickness whose transmissivities were 90%, 85% and 82%, respectively. For air circulation purposes, a protruding chimney was provided at the top center of this structure.

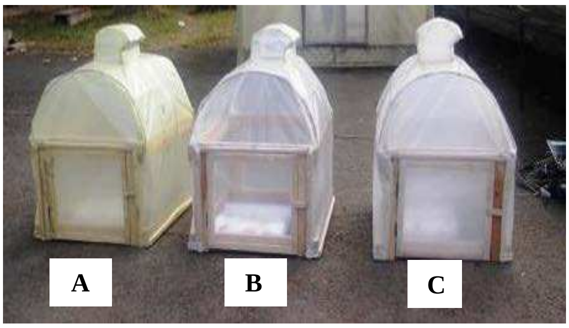


Fig. 1 Plates showing the experimental set-up of the model solar tent dryers

In the figure: A, yellow cover; B, clear cover; C, nectarine diffused cover

*B. Sample Preparation and Drying Procedure*

Freshly harvested amaranth grains were obtained from the Horticultural farm, Jomo Kenyatta University of Agriculture and Technology (JKUAT). The grain samples were detached from the seed heads of amaranth plant and hand cleaned to remove any foreign material before being dried. The thin layer drying experiment was conducted in an open area near the Agricultural Processing Laboratory of Biomechanical and Environmental Engineering Department (BEED) under the climatic condition of Juja, Kenya (latitude 1.19$^o$S; longitude 37.05$^o$E).

Data acquisition involved recording temperature and relative humidity values in the open sun and inside the dryers. The moisture content of the grains during drying was also monitored. The data were recorded at 30 minutes intervals from 8:00 a.m to 5:00 p.m for three consecutive days. Thermocouples were used to relay temperature data from the dryers to the data-logger while a digital thermo-hygrometer (HC-520, Hong Kong), with ±5% accuracy within 20 and 99%, was used to obtain relative humidity values. Amaranth grain sample of approximately 50 g was evenly spread on a drying tray (0.25 m × 0.25 m) to form a single layer. The control involved drying the grains in the open sun. 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$^o$C for about 24 hours. The dried grains were removed from the oven and the dry weight, $W_d$, recorded. The percent d.b moisture content M was then evaluated from the Expression [9] given by (1).

$$M = \frac{W_t - W_d}{W_d} * 100 \tag{1}$$

The data collected were used to plot graphs relating temperature, relative humidity and moisture content with drying time for the different cover materials in order to compare the performance of the different materials with the open sun. An ANOVA was also conducted to determine whether there existed significance difference within the performance of the different cover materials, and between the materials and the open sun.

*C. Effective Moisture Diffusivity*

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 [10]. 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 [11]. Assuming that amaranth grains can be approximated to spheres, the diffusion is expressed by (2) [12], where $D_e$ is the effective moisture diffusivity ($m^2s^{-1}$) and $r_a$ is the radius (m) of amaranth grain.

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

For the transient diffusion in a sphere, assuming uniform initial moisture content and a constant effective moisture diffusivity throughout the sample, the analytical solution of (2) yields (3). The effective moisture diffusivity is determined by applying logarithms to (3) to obtain a linear relation of the form shown in (4). Therefore, a plot of ln(MR) versus time yields a straight line, and the diffusivity is determined from the slope (slope $= -D_e\pi^2/{r_a}^2$).

$$MR = \frac{M - M_e}{M_o - M_e} = \left(\frac{6}{\pi^2}\right) \exp\left[ -D_e t \left( \frac{\pi^2}{{r_a}^2} \right) \right] \tag{3}$$

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \left( D_e \frac{\pi^2}{{r_a}^2} \right) t \tag{4}$$

*D. Physical and Chemical Analyses*

Amaranth grains dried under different cover materials and in the open sun were sampled and their properties (viz., physical, optical and nutritive) determined. Hardness, which is important during milling process of amaranth, was selected to represent the physical property while colour and crude protein content represented the optical and nutritive properties, respectively.

*1) Hardness Test:*

The hardness of dried amaranth grains was determined using the hardness tester (Kiya Seisakusho Ltd, Tokyo, Japan) with a capacity of 20 kg. The test involved holding the grain sample between the two faces of the tester while increasing the force until the grain crushed. Hardness values were recorded at the crushing point. The tests were done in six replicas to achieve accurate and reliable results.

*2) Colour Tests:*

For colour tests, dried amaranth grains (approximately 10 g) were placed into a clear polythene paper which was subjected to a spectrophotometer sensor (NF333, Nippon Denshoku, Japan). The sensor was pointed directly at the grains to record the colour values and care was taken to avoid any interference from ambient light sources. The tests were conducted in a clean and air-conditioned room to avoid any deposits on the instrumental components. The colour of the grains was measured, in six replicas, for *L** (light-dark spectrum), *a** (green-red spectrum) and *b** (blue-yellow spectrum) values. Hue angles (*h**) were calculated using (5) [13].

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{5}$$

*3) Crude Protein Content Determination:*

The Kjeldahl method of nitrogen analysis is the worldwide standard for calculating the protein content in a wide variety of materials [14]. It consisted of three steps, which were carefully carried out in sequence. In the first step, the sample was digested in strong sulphuric acid in the presence of a catalyst, which helped in the conversion of the amine nitrogen to ammonium ions. Next, the ammonium ions were then converted into ammonia gas, heated and distilled. The ammonia gas was directed into a trapping solution where it dissolved and became an ammonium ion once again. Finally, the amount of the ammonia that had been trapped was determined by titration with a standard solution, and the percentage nitrogen (%N) and crude protein (CP) were obtained from (6) and (7). In these equations, $V_1$ is titre for sample (ml), $V_2$ is titre for blank (ml), $N_s$ is normality of standard hydrochloric acid (HCL) solution (0.02), f is factor of standard HCL solution (approximately 1), V is volume of diluted digest taken for distillation (10 ml), S is weight of sample taken (1 g) and PF is the protein factor which is approximately 6.25.

$$\%N = (V_1 - V_2) \times N_s \times f \times 0.014 \times \frac{100}{V} \times \frac{100}{S} \quad (6)$$

$$CP = \%N \times PF \quad (7)$$

## III. RESULTS AND DISCUSSION

### A. Variation of Drying Conditions

The establishment of drying characteristics of amaranth grains involved gathering temperature, relative humidity and grain moisture content data during thin layer drying amaranth grains in the solar tent dryers. The control involved drying the grains in the open sun. A total of 17 daily data for each of the parameters (viz., temperature, relative humidity and grain moisture content) were acquired for each cover material for three consecutive days. Similar amount of data were concurrently obtained for the open sun.

The comparison of temperatures developed under the different cover materials and the open sun is shown in Fig. 2. The results indicate that the temperatures developed in the dryer with the nectarine diffused cover material were always lower (41.4±5.3°C) than those dryers with the yellow (42.3±5.8°C) and clear (44.5±5.8°C) cover materials. In addition, it is seen that the temperatures developed by the clear cover material were always highest. At any given time the temperature difference between the three cover materials seem not to have been significant. The clear cover material had highest temperatures as it allowed more heat to pass though it due to its high transmissivity ($\tau$ = 90%) compared to the rest [15]. The figure also shows that the temperatures recorded in the open sun were always significantly lower than those recorded in the dryers with different cover materials.

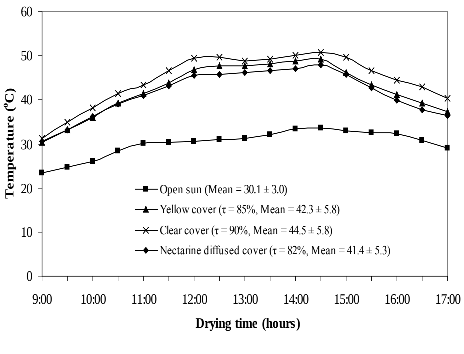


Fig. 2 Comparison of temperatures in dryers with different cover materials and the open sun

An ANOVA at 5% level of significance on the data confirmed that there were no significant differences between the temperatures developed by the different cover materials ($p$-value, 0.257; $F_{critical}$, 3.191; $F_{computed}$, 1.398). However, there was significant difference between the temperatures in the open sun and those developed in the dryers with different cover materials since the $F_{computed}$ was greater than the $F_{critical}$ ($p$-value, $1.71 \times 10^{-11}$; $F_{critical}$, 2.748; $F_{computed}$, 27.320). Similar variations of temperature in a natural convection solar dryer and the open sun have been reported by other researchers during thin layer drying [6], [16].

On the other hand, Fig. 3 compares the relative humidity values in dryers covered with different materials and the open sun. It is observed from the figure that relative humidity values in the open sun were always slightly higher (28.9±6.2%) than those in covered dryers. Comparison of the relative humidity values at any given time shows that there was no significant difference under both conditions. At any given time, there was a decreasing trend in relative humidity for dryers covered with the nectarine diffused, yellow and clear materials. When Figs. 2 and 3 are compared, it is noted that at any given time the temperatures increased from the open sun, nectarine diffused, yellow to clear cover materials. The results show that increase in temperature leads to decrease in relative humidity. This indirect relationship has also been widely reported during solar tent drying of agricultural products [6], [16].

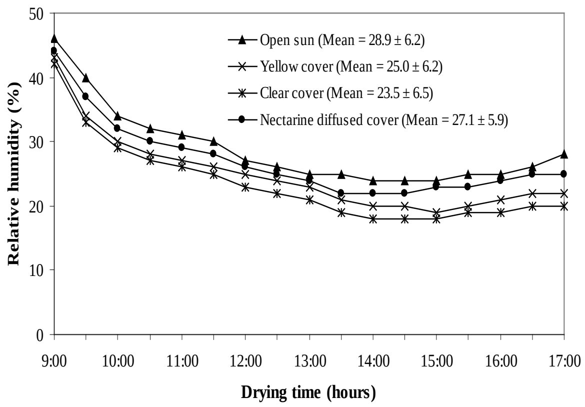


Fig. 3 Comparison of relative humidity in dryers with different cover materials and the open sun

Based on a 5% level of significance, ANOVA on the relative humidity values in the open sun and in the covered dryers showed no significant difference ($p$-value, 0.090; $F_{critical}$, 2.748; $F_{computed}$, 2.263). Similarly, there was no significant difference ($p$-value, 0.839; $F_{critical}$, 2.748; $F_{computed}$, 0.282) in relative humidity when the different cover materials were compared.

### B. Drying Behaviour of Amaranth Grains

The drying curves of amaranth grains dried under dryers with different cover materials and in the open sun are presented in Fig. 4. The results show that under all the four drying conditions (viz., open sun, nectarine diffused cover, yellow cover and clear cover) the rate of drying was highest within the first 2.5 hours of drying. Thereafter, the drying rate reduced significantly.

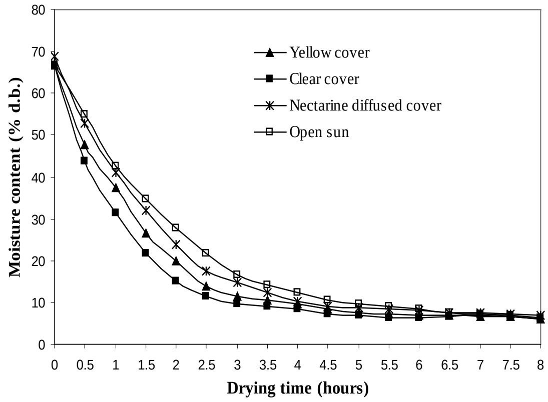


Fig. 4 Drying curves for amaranth grains under dryers with different cover materials and the open sun

The moisture loss in amaranth grains decreased exponentially with increase in drying time. This observation is common with most cereal grains as reported by Abalone *et al*. [1] and Basunia and Abe [6]. 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 grains. It is also worth noting that the grains dried from an initial moisture content ranging from 66.7%～68.8% d.b to an equilibrium moisture content of 7% d.b. The equilibrium moisture content was obtained after 4.5, 6, 7, and 7.5 hours of drying for the clear cover, yellow cover, nectarine diffused cover and the open sun, respectively.

The drying rate increased from open sun, nectarine diffused cover, yellow cover and clear cover at any given time. However, the difference in drying rate was slight from the lowest to the highest. 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 [17]. As expected, the decrease of relative humidity in the solar drying system increases the drying rate of the material because a higher driving force is developed. The drying rate decreases continuously with decreasing moisture content or increasing drying time. These results are in agreement with the observations of earlier researchers [1], [10].

An ANOVA conducted at a 5% level of significance noted that for the first 2.5 hours of drying, the drying rates were not significantly different under all the four drying conditions (viz., clear cover, yellow cover, nectarine diffused cover and the open sun) ($p$-value, 0.823; $F_{critical}$, 3.098; $F_{computed}$, 0.303). Further, the drying rates between 2.5～8 hours of drying were slightly different ($p$-value, 0.049; $F_{critical}$, 2.839; $F_{computed}$, 2.848). This can be explained by the difference in the energy and relative humidity levels required by the covered dryers and the open sun to attain the equilibrium moisture content. General comparison, however, showed that the drying rates for the entire drying period were not significantly different under all the four drying conditions ($p$-value, 0.839; $F_{critical}$, 2.748; $F_{computed}$, 0.282). Similar observations have been noted for most cereal grains and other agricultural products [6], [18], where the solar dryer proves to dry products faster than the open sun.

### C. Calculation of Effective Moisture Diffusivity

Effective moisture diffusivity ($D_e$) was calculated using slopes derived from the linear regression of ln(MR) versus time data as in (4). The $D_e$ values of amaranth grains dried under the model dryers with nectarine diffused, yellow and clear cover materials were found to be $3.45\times10^{-12}$, $4.29\times10^{-12}$ and $4.60\times10^{-12}$ $m^2s^{-1}$, respectively. The corresponding value for the open sun was $4.04\times10^{-12}$ $m^2s^{-1}$. The effective moisture diffusivity was highest for the model dryer with the clear cover in which high temperatures were developed. Previous studies show that increase in temperature leads to increase in moisture removal from cereal grains [18]. The effective moisture diffusivities calculated from the drying data represented an overall mass transport property of moisture in the material, which includes liquid diffusion, vapour diffusion or any other possible mass transfer mechanism. The continuous decrease in moisture ratio with increase in drying time showed that the results can be interpreted using Fick's diffusion model [12].

### D. Effect of Drying on Hardness of Amaranth Grains

The hardness of amaranth grains was based on the force required to break the grains. Table I shows the hardness values for amaranth grains dried under the different cover materials and the open sun. The types of cover materials for the dryers were clear, yellow and nectarine diffused, all of which had the same thickness. The hardness values ranged from 2.15～2.23 kg for the model dryers while an average value of 2.23 kg was achieved for the open sun. The yellow cover achieved slightly low mean hardness values (2.15±0.14) as compared with the other materials. The standard deviations for the mean hardness values obtained for all the cover materials were low and they ranged from 0.12～0.16 kg. This shows that there was uniformity in hardness values obtained for amaranth grains.

TABLE I HARDNESS AND COLOUR PARAMETERS FOR AMARANTH GRAINS DRIED UNDER DIFFERENT COVER MATERIALS AND THE OPEN SUN

| Type of Cover Material | Hardness (kg) | Colour parameters | | | |
|---|---|---|---|---|---|
| | | *L** | *a** | *b** | *h** |
| Yellow | 2.15 ±0.14 | 52.83 ±0.83 | 7.68 ±0.18 | 39.31 ±1.07 | 78.94 ±0.43 |
| Nectarine diffused | 2.23 ±0.12 | 53.35 ±0.90 | 7.32 ±0.44 | 37.41 ±1.00 | 78.93 ±0.74 |
| Clear | 2.20 ±0.13 | 54.15 ±0.61 | 7.24 ±0.37 | 37.71 ±1.78 | 79.15 ±0.19 |
| No cover (open sun) | 2.23 ±0.16 | 54.20 ±0.33 | 7.25 ±0.16 | 36.57 ±0.43 | 78.78 ±0.37 |

Mean value ± standard deviation

An ANOVA conducted on the data at 5% level of significance showed that there was no significant difference ($p$-value, 0.542; $F_{critical}$, 3.682; $F_{computed}$, 0.638) in the hardness for amaranth grains dried under the different cover materials. Similarly, there was no significant difference ($p$-value, 0.695; $F_{critical}$, 3.098; $F_{computed}$, 0.488) between the hardness values for grains dried under the different cover materials and the open sun.

### *E. Effect of Drying on Colour of Amaranth Grains*

The determination of the effect of colour of cover material on colour of amaranth grains involved recording *L**, *a** and *b** parameters from the spectrophotometer and computing the hue angle (*h**). The parameters *L**, *a** and *b** values represent light-dark spectrum with a range from 0 (black) to 100 (white), the green-red spectrum with a range from -60 (green) to +60 (red), and the blue-yellow spectrum with a range from -60 (blue) to +60 (yellow), respectively. Table I shows that *L**, *a** and *b** for amaranth grains dried under the different cover materials ranged from 52.83～54.20, 7.24～7.68 and 36.57～39.31, respectively. Amaranth grains dried in the open sun achieved slightly high *L** value (54.20±0.33) and low values of *a** (7.25±0.16) and *b** (36.57±0.43) parameters as compared to those for the different cover materials.

The *L**, *a** and *b** parameters were utilized in computing the *h** values based on (5) and the results are also presented in Table I. The results indicate that the computed *h** values of amaranth grains were in the range of 78.78～79.15$^{o}$ for all the drying conditions (viz., the three cover materials and the open sun). The clear cover achieved the highest *h** value while the open sun registered the lowest. The colour parameters are related to the browning reaction where a decrease in *L** values, an increase in *a** values and a decrease in *h** values indicate more browning [19]. Hence, the preceding results imply that the clear cover material had less browning effect on the grains during drying as compared with the other materials and the open sun.

At 5% level of significance, ANOVA showed no significant difference (*p*-value, 0.702; $F_{critical}$, 3.682; $F_{computed}$, 0.362) in hue angles for grains dried under different cover materials. Further comparison of the hue angles of grains dried under different cover materials and the open also showed no significant difference (*p*-value, 0.616; $F_{critical}$, 3.098; $F_{computed}$, 0.610). Generally an increase in temperature led to increase in hue angle, as also noted by Hii *et al*. [8].

### *F. Effect of Drying on Crude Protein Content of Amaranth Grains*

The crude protein contents of amaranth grains dried in the open sun and under different cover materials of varying transmissivities were determined using the standard Micro Kjeldhal method [14]. The results presented in Table II show the percentage crude protein content of dried amaranth grains which is a function of the percentage of nitrogen found in the grains.

TABLE II COMPARISON OF CRUDE PROTEIN CONTENT OF AMARANTH GRAINS DRIED UNDER DIFFERENT COVER MATERIALS AND THE OPEN SUN

| Type of Cover Material | Crude Protein Content (%) |
|---|---|
| Yellow cover | 17.08±0.17 |
| Nectarine diffused cover | 17.21±0.20 |
| Clear cover | 17.07±0.09 |
| No cover (open sun) | 17.54±0.31 |

Mean value ± standard deviation

The mean values of crude protein content ranged from 17.07%～17.21% for the grains dried under different cover materials while a mean value of 17.54% was obtained for the open sun. The corresponding standard deviations ranging from 0.09%～0.31% were low, which confirmed uniformity in the percentage crude protein contents of amaranth grains. An ANOVA conducted at 5% level of significance showed no significant difference (*p*-value, 0.299; $F_{critical}$, 3.682; $F_{computed}$, 1.310) in crude protein content for the different cover materials. Similarly, comparison of crude protein content for grains dried under the different cover materials and the open sun showed no significant difference (*p*-value, 0.067; $F_{critical}$, 3.098; $F_{computed}$, 2.783).

Although higher temperatures prevailed in the dryer with the clear cover, the nutritive value of amaranth grain in terms of crude protein content was not significantly affected. The results for crude protein content of amaranth grains were satisfactory as they ranged between 16% and 18% [1]. The crude protein content in grains dried in the open sun was slightly higher than those dried under the different cover materials. This is an indication that high temperatures may denature proteins in the grains [8].

## IV. CONCLUSION

The thin layer drying behaviour and quality assessment of amaranth grains were investigated in the solar-energy tent dryers under natural convection and the open sun. The dryer can be used to successfully dry amaranth grains faster than the open sun to an equilibrium moisture content of 7% d.b. Drying time was the longest in open sun drying (7.5 hours) due to the lower drying temperature compared to solar tent drying (4.5～7 hours). The entire thin layer drying of the grains occurred in the falling rate period. The effective moisture diffusivities increased with temperature and ranged from $3.45\times10^{-12}$ ～ $4.60\times10^{-12}$ $m^2s^{-1}$. Statistical analyses showed that the hardness, colour and crude protein content of the grains were not significantly different ($p$>0.05) when the samples dried in the open sun were compared with those dried in the dryers with clear, yellow and nectarine diffused PVC cover materials. However, the clear cover material recorded the highest hue angle (*h**) and the lowest crude protein content (17.07%) due to the high temperatures developed in the dryer. Generally, the results demonstrate that solar tent dryers can be utilized by small-scale farmers in Kenya to enhance drying of amaranth grains in thin layers without significantly affecting their physical, optical and nutritive properties.

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