Design and Performance Evaluation of a Mixed-Mode Solar Crop Dryer

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Abstract—This study is concerned with development and performance evaluation of a mixed-mode solar yam dryer. It was done to address the problems of uneven drying of product on different trays coordinate position in a typical indirect multiple trays dryer. Solar energy drying system was designed using the meteorological conditions of Zaria, Nigeria to dry yam slices in the mixed-mode natural convection. The dryer was designed to dry (7 kg) of yam slices. The dimensions of the dryer were: collector length, collector area, height of the drying chamber, chimney height, length of the drying chamber, and Width of the drying chamber were 0.65 m, 0.27 m^2, 0.9 m, 0.7 m, 0.5 m, and 0.43 m, respectively. The solar yam dryer was exposed to solar radiation from 10:00 am to 06:00 pm and tested without load and with yam chips of 5 mm average thickness. Meteorological conditions were monitored during the dehydration process. The average drying rate, collector efficiency and drying efficiency were 2.55 kg/s, 42.20% and 25.35%, respectively. The results of performance evaluation of the solar dryer showed that the drying rate decreases by 3% and 8% in the second and third trays relative to the first tray. This shows that the drying rates did not vary significantly with the coordinate positions of the trays.

Keywords— Mixed-mode solar dryer, performance evaluation, uniform drying

1. Introduction

Solar thermal technology is rapidly gaining acceptance as an energy saving measure in agriculture application. It is preferred to other alternative sources of energy because it is abundant, inexhaustible and does not pollute the environment. (Bukola and Ayoola, 2008). After agricultural produce are harvested, there is need for proper storage for future use. The products upon harvesting have high moisture content which makes it unsafe for storage because the moisture in the crops attracts microorganisms and fungi which result in deterioration of the products. Among other reasons, crops are dried to improve shelf life, retain original flavor and reduce weight for easy transport and trade (Amma, 2014).

The rationale behind drying food items is to reduce its water content to a level where it can be safely stored for future use (Bolaji, 2005). Yam is an economically useful plant belonging to the genus *Dioscorea* or Tubers/ rhizomes of the plants. Yam is a food security crop and a source of industrial starch in some sub-Saharan African countries. Besides, Yam plays a vital role in traditional culture, rituals and religion as well as source of income for African people. The production of yam in Nigeria has not been fully achieved due to insufficient processing technology obtainable in other developing countries. Its high moisture content poses a great challenge for it storage (Liberty, Odo and Ngabea, 2013).

Conservatively, yam slices, vegetables and fruits are dried by thinly spreading them on a prepared ground, flat forms, and paved ground in open sunlight. Large losses are generally incurred as a result of using this method. The losses are attributed to birds, rodents, domestic animals and wind blowing the product beyond recovery. High humidity levels associated with tropical environments has been contributing immensely to crop lost to fungal and microbial degradation (Drew, 2011). Controlled Solar drying gives quality end product, rapid drying and more hygienic product.

Many dryer types have been in used in both households and industries but simplicity of design and economic consideration make tray dryer most extensively used. A tray dryer consists of several stacks of trays placed in an insulated chamber in which hot air is distributed by fan or natural flow (Misha et al., 2013).

An investigation using natural convection solar crop dryer was carried out by Ajao and Adedeji (2008) to assess the drying rates of some crops in solar dryer. The analysis of the result revealed that an average drying efficiency of 18% was recorded at an average drying rate of 2.50 kg/s for yam drying. The objectives of this study were to develop and carry out performance evaluation of a mixed-mode natural convection solar dryer for yam drying.

2. Materials and Methods

2.1 Materials

Materials used were:

i. Solar Collector (Galvanized steel)
ii. Glazing (4mm thick glass)
iii. Insulation (Fiber glass)
iv. Connecting Duct (Galvanized steel)
v. Drying Chamber (Galvanized steel)

2.2 Design consideration

The following parameters were considered during the design of the solar dryer as given in Table 1.

Table 1. Design specifications and assumptions

Items	Condition and assumptions
Location and Latitude	Zaria (Lat 11.2°)
Crop	Yam
Design Capacity	7.0 kg
Bulk density (ρ_b)	660 kg/m3
Max. allowable temperature for drying	65 °C
Initial moisture content (M_i)	60-80 %

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Final moisture content (M_f)	17 %
Average Yam thickness (Y_l)	5 mm
Drying time per day (sunshine hours) (t_d)	5 hours
Drying Period	August
Wind speed (V_a)	1.52 m/s
Ambient temperature (T_a)	28.6 °C
Incident Solar Radiation (H)	18.0 MJ/m²/day
Collector type	Flat Plate
Collector tilt angle	21°
Collector Efficiency (η_c)	30-50%
Absorber thickness	0.8-1.0mm
Collector Channel Depth	70 mm
Glazing thickness	4 mm
Thickness of Insulation	25 mm
Vertical Distance between adjacent trays	300 mm

2.3 Design Procedure of the dryer

According to (Bukola and Ayoola, 2008) the useful energy gained by the collector is given by:

$$Q_u = A_c[\alpha\tau I_T - U_L(T_c - T_a)] \quad (1)$$

Q_u = useful energy gained by the collector,
I_T = incident solar radiation, kW/m²
T_c = temperature of the collector's absorber, K
T_a = ambient air temperature, K
C_p = specific heat capacity of air, kJkg⁻¹K⁻¹
U_L = overall heat loss coefficient, Wm⁻²K⁻¹

If the heated air leaving the collector is at collector temperature heat gained by the air is given by:

$$Q_a = \dot{m}_a C_p(T_o - T_a) \quad (2)$$

Q_a = heat gained by the air
$\dot{m}_a$ = mass flow rate leaving the collector per unit area, kg/s
T_o = temperature of air at the collector outlet, K
The collector heat removal factor FR is the quantity that relates the actual useful energy gained by the collector.

$$F_R = \frac{\dot{m}_a C_p(T_o - T_a)}{A_c[(\alpha\tau)I_T - U_L(T_c - T_a)]} \quad (3)$$

$$Q_a = A_c F_R[\alpha\tau I_T - U_L(T_C - T_a)] \quad (4)$$

Amount of moisture to be removed from the yam slices is the mass of water Mw to be evaporated, it is estimated from the initial moisture content and the final desired moisture content (Bolaji, 2005).

$$M_w = M_{we}\left[\frac{M_i - M_f}{1 - M_f}\right] \quad (5)$$

M_{we} = mass of the wet yam slices, kg
M_i, M_f = initial & final moisture contents on wet basis, %

Drying heat load was determined by the amount of crop to be dried, its initial and final moisture contents (Kamble et al., 2013).

$$Q_{load} = M_w L_v \quad (6)$$

Mw= amount of moisture to be removed, kg
L_v= latent heat of vaporization of water from the yam slices, kJ/kg

Total solar radiation on the collector (tilted) surface is given by (Alamu, Nwaokocha and Adumola. 2010) with the assumption that effective ratio of solar energy on tilted surface to that on the horizontal surface R

$$I_T = H \times R \quad (7)$$

H= horizontal radiation, W/m²
R= ratio of solar radiation on tilted surface to that on the horizontal, (dimensionless)

Solar Collector Area is the required surface area of the transparent cover for crop drying, depends primarily on the heat load of the drying system given by (Kamble et al., 2013).

$$A_c = \frac{Q_{load}}{\eta I_T t_d} \quad (8)$$

t_d= drying time, h
I_T= total solar radiation incident on the collector surface, kW/m²
η = collector efficiency, %
The absorber surface area is approximately equal to the surface area of collector receiving solar insolation.

$$A_c = L_c \times W \quad (9)$$

Therefore, the absorber surface area becomes;

$$A_{ab} = A_c = L_c \times W \quad (10)$$

L_c, W = length and width of the solar collector respectively,

The total volume of air required for removing the moisture from the yam slices is evaluated from the equation given by Forson et al., (2007).

$$V_A = \frac{M_w h_{fg} R_a T_a}{C_p P_a(T_o - T_f)} \quad (11)$$

where, T_f= temperature of air leaving the drying bed obtained from the following relationship.

$$T_f = T_a + 0.25(T_o - T_a) \quad (12)$$

R_a = gas constant, kJ/kgK
T_o= temperature of air at the collector outlet, ℃
P_a= partial pressure of dry air in the atmosphere, N/m2
C_p= specific heat capacity of air, kJ/kgK

The mass flow rate of Air needed to effect the drying is given by (Tonui et al., 2014)

$$\dot{m}_a = \dot{V}_a \rho_a \quad (13)$$

Where, $\dot{V}_a = \frac{V_a}{t_d}$ (14)
t_d = drying time per day, hrs
$\dot{V}_a$= volume flow rate of the drying air, m3/s

The width of the collector (W) was considered equal to the width of the drying chamber (B). The volume of yam slices per tray can be obtained from equations (15), (16) and (17) given by (Adzimah and Seckley, 2009);

Total volume of the yam slices on the trays in the drying chamber can be obtained as;

$$V_y = W_T L_T Y_l \quad (15)$$

Total volume of the yam slices on the trays in the drying chamber can be obtained as;

$$V_T = nV_y = nW_T L_T Y_l \quad (16)$$

Also, the total volume can be related to bulk density as:

$W_{we} = \rho_b V_T$ (17)

$Y_l =$ thickness of the yam slices in drying chamber, m

W_T= width of the tray which is equal to the width of the drying chamber, m

L_T= length of tray, m

W_{we}= total mass of yam slices, kg

ρ_b= bulk density of yam, kg/m3

The length of the drying chamber is approximately equal to the length of the tray, $L_d \cong L_T$. To determine the height of the hot air column (chimney), it's necessary to determine the pressure drop through the drying bed. The resistance of air flow through the packed bed of agricultural produce is expressed in the form giving by (Forson et al., 2007). Chimney height is given by (Forson et al., 2007);

$$u = a\left(\frac{\Delta P_B}{h_L}\right) \quad (18)$$

where,

u = superficial air velocity (m/s), which is the volumetric flow rate divided by the cross-sectional area

h_L =drying bed thickness, m

a =constant whose value determined experimentally. For natural convection of air through a thin layer of crop ($h_L \leq 0.2m$), the value of the constant is 0.465 m3s/kg.

The gross pressure drop is about six times the value of ΔP_T (Forson et al., 2007)

$$\Delta P_T = 6 \times (2 \times \Delta P_B) \quad (19)$$

$$H_{ch} = \frac{\Delta P_T R}{g\left(\frac{1}{T_{amb}} - \frac{1}{T_{dryer}}\right) P_a} \quad (20)$$

ΔP_T= the total pressure drop in the dryer, Pa

R = the gas constant, kPa m3/kgK

T_{dryer} = the temperature of air in the dryer, K

T_{amb} = the temperature of ambient air, K

g = the gravitational acceleration, m/s2

$\boldsymbol{P_a}$ = ambient pressure, Pa

2.4 Construction of the Prototype Solar Dryer

The solar dryer is shown in Fig. 1 with dimensions in Table 2. The transparent top cover is a 4mm thick clear glass with dimensions 650mm by 450mm.the distributing duct made out of 1 mm galvanized steel sheet is 450 mm by 100 mm and the drying chamber dimensions are 450 mm by 500 mm by 900 mm. The drying chamber was partitioned into three each with an independent chimney. Additional glazing and access door were also provided for additional heating and to facilitate easy loading and offloading of the yam slices respectively.

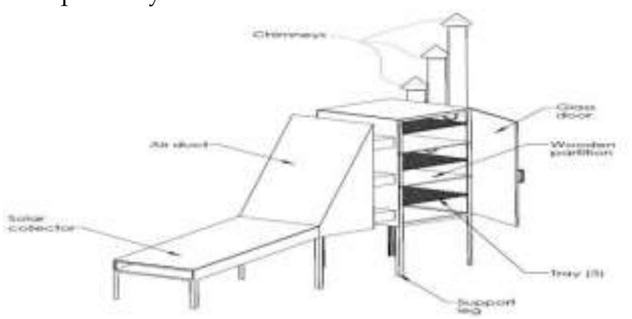

Fig. 1: Mixed mode solar crop dryer

Table 2: Summary of the Dimensions of the Prototype Fabricated

S/N	Parameter	Dimension
1	Solar Collector	
	Length(L_c)	0.65m
	Width (W)	0.43m
	Area of the Collector (A_c)	0.27m2
2	Drying chamber Length (L)	0.50m
	Width (B)	0.43m
3	Chimney Height (H_{ch})	0.70 m

3. Testing and Performance Evaluation

3.1 Testing

The dryer was tested from 18th to 20th of June, 2016. It was tested under no load condition on the first day and thereafter with load. The solar dryer was exposed to solar radiation and loaded with yam chips of 0.67 kg on each tray at 5 mm average thickness. The hourly temperatures of air into the various trays, temperature from the collector outlet, temperature from the chimney outlet, and the ambient temperature were measured. The air temperatures were measured using thermocouple device and wire. The wind speed was measured using anemometer and solar radiation incident on the collector using solarimeter from 10:00 am to 06:00 pm. Each tray was fed with equal mass of yam slices. During sunshine hours, the air flow over the absorber plate gets heated and picks moisture from the yam slices. In the night, the yam chips were transferred to the polyethylene sheet to avoid re-absorption of moisture. The weight of the yam chips on each tray was measured at the commencement of the drying and at 2-hour intervals. The final weight was attained at the point when no further weight loss of yam chips was observed. The weight loss was used to calculate the moisture removed at the intervals.

3.2 Performance Evaluation

The basic standard procedure for evaluating solar dryer performance as recommended by Leon, Kumar and Bhattachaya, (2002) was followed. The drying system was evaluated using the solar collector efficiency, drying rate, percentage moisture loss, and drying efficiency of the dryer.

3.2.1 Percentage Moisture Loss

The quantity of moisture in percentage of the initial mass of a material can be represented on wet basis and expressed as given by Mohanraj and Chandrasekar (2009) as:

$$MC = \left[\frac{M_1 - M_2}{M_1}\right] \times 100\% \text{ wet basis} \quad (21)$$

MC = moisture loss %

M_1 = initial mass of the yam slices, kg

M_2 = final mass of the yam slices, kg

3.2.2 Average Drying Rate

The quantity of moisture removed from the food item over the drying time was given by Tonui et al. (2014).

$$m_{dr}=\frac{M_w}{t_d} \quad (22)$$

M_w= mass of water evaporated from the yam slices, kg
t_d= drying time per day, hr

3.2.3 Solar Collector Efficiency

Efficiency of a solar collector is the ratio of heat gained by the air leaving the collector to the incident solar energy over a particular time period (Bolaji, 2005). The steady state thermal efficiency of the solar collector is given by Hottel-Whillier-Bliss equation (Forson et al., 2007).

$$\eta_c = \frac{\dot{m}_a C\rho(T_o - T_a)}{A_c I_T} \quad (23)$$

I_T= total solar radiation incident on the top surface, W/m²
To = temperature of outgoing air from the collector, °C
Ta= ambient air temperature, °C
$\dot{m}_a$ =mass flow rate of air, kg/s

3.2.4 Dryer Efficiency

Thermal performance or drying rates of the products are the key factors used for the evaluation of the solar drying system efficiency (Leon, Kumar and Bhattachaya, 2002). For natural convection solar dryer, the system efficiency can be expressed as given by (Forson et. al, 2007 and Drew, 2011)

$$\eta_{dryer} = \frac{M_w L_v}{I_T A_c t} \quad (24)$$

Where;
η_{dryer} = dryer efficiency %
M_w = mass of water evaporated, kg
L_v= latent heat of vaporization of water, kJ/kg
t = drying time, hr
A_c= collector area, m2

4. Results and Discussion

Fig. 2 shows a typical day results of no load hourly variation of the collector outlet air temperature compared to the ambient temperature. The hourly variation of the collector outlet air temperature and the drying chamber temperatures were higher than the ambient air temperature during the testing hours, this shows a prospect for better performance than open air sun drying.

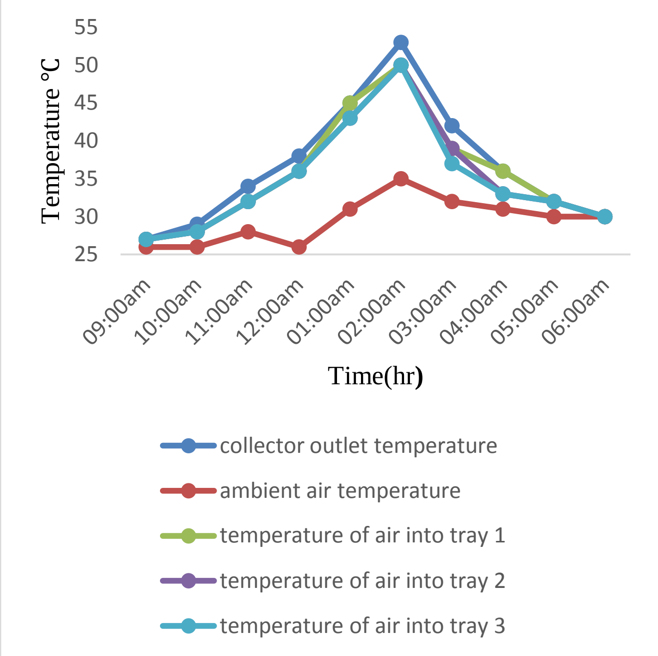

Fig. 2: Hourly variation of temperature against time on 18/06/2016

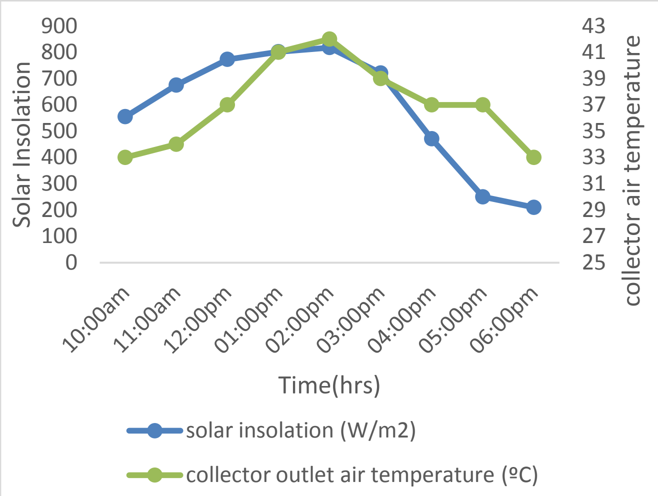

Fig 3: Variation of solar intensity and collector air temperature with time for 19/06/2016

Fig. 3 and Fig. 4 show a maximum collector outlet air temperature of about 42°C at 02:00pm and 12:00pm with corresponding solar insolation of 850W/m2 and 780 W/m2 respectively. Fig. 3 and Fig. 4 show that the temperature started increasing reasonably immediately after 11:00 am and keeps increasing with corresponding increase in insolation during afternoon hours.

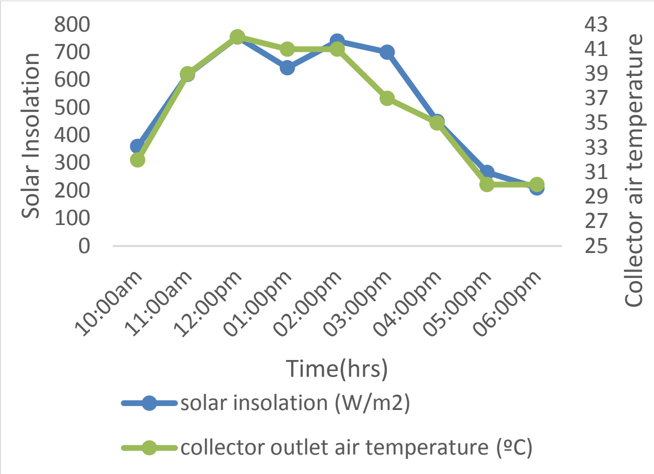

Fig. 4: Variation of solar intensity and collector air temperature with time for 20/06/2016

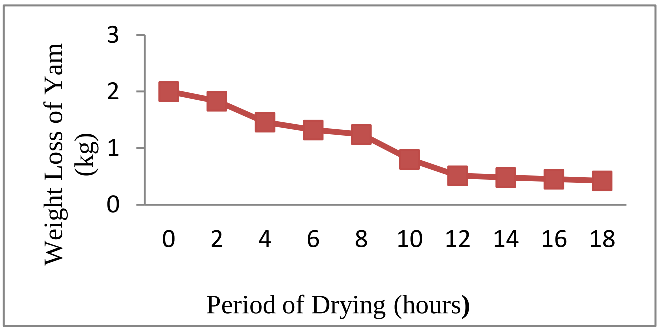

Fig. 5: Weight loss of yam against drying period

Fig. 5 shows the drying curve for the yam slices in the solar dryer. The dryer was able to remove 78% of moisture in 2-day of 8 hours drying time per day. The average drying rate of the yam slices on all trays, collector efficiency, and drying efficiency of the drying system are 2.55 kg/s, 42.20% and 25.35%, respectively. The result obtained revealed a better performance compare with that obtained by Ajao and Adedeji, (2008) who obtained a drying rate and drying efficiency of 2.50 kg/s and 18%, respectively. Moreover, the result also shows a better drying efficiency and uniform drying rate in the bottom and top trays compare with the 21% drying efficiency reported by Mohanraj and Chandrasekar (2009).

5. Conclusion

Solar energy drying systems was designed using the meteorological conditions of Zaria, Nigeria to dry yam slices in the mixed-mode natural convection mode with 0.27 m2 flat plate collector area with three (3) in dependent drying trays for drying of seven (7) kg of yam slices. However, a prototype was developed to dry two (2) kg of yam slices. The performance evaluation of the natural convection mixed mode solar crop dryer was successfully carried out. The temperature of air obtained from the collector outlet is always higher than the ambient temperature throughout the day time. The drying rate, collector efficiency and drying efficiency were 2.55 kg/s, 42.20% and 25.35%, respectively. The drying rate of the yam slices on each tray in the bottom, middle, and top trays inside the dryer shows that uniform drying has been achieved with this configuration of the solar dryer.

References

Adzimah, K.S., and Seckley, E., (2009). Improvement on the Design of a Solar Cabinet Drier. American Journal of Engineering and Applied Science, 2(1): 217-288.

Ajao, K. R., and Adedeji, A.A., (2008). Assessing the Drying Rates of Some Crops in Solar Dryer. Journal of Research Information in Civil Engineering, 5(1):1-12.

Alamu, O.J.,Nwaokocha, C.N, and Adumola, O.,(2010). Design and Construction of a Domestic Passive Solar Food Dryer. Leornado Journal of Sciences, 9(16):71-82.

Amma, A. S. (2014). Effect of Different Drying Methods on the Functional and Physicochemical Properties of the Flour of Selected Yam Cultivators in Ghana. (Unpublished) Msc. Thesis Department of Food Science and Technology. Kwame Nkrumah University of Science and Technology, Kumasi Ghana.

Bolaji, B.O., (2005). Performance Evaluation of a Simple Solar Dryer.6th Annual Engineering Conference Proceedings, FUT Minna. pp. 8-13

Bukola, O. B., and Ayoola P. O., (2008). Performance Evaluation of a Mixed-mode solar dryer. Technical Report, AU J.T, 11(4):225-231.

Drew, F. S., (2011). Development and Evaluation of a Natural Convection Solar Dryer for Mango in Rural Haitian Communities. (Unpublished) M.S.c.Thesis, Agricultural and Biological Engineering, University of Florida.

Forson, F.K., Nazha, M.A.A., Akuffo, F.O., and Rajakaruna, H., (2007). Design of Mixed-mode Natural Convection Solar Crop Dryers: Application of Principles and rule of thumb. Renewable Energy, 32, 1-14.

Kamble, A.K., Pardeshi, I.L., Singh,P.L., and Ade, G.S.(2013). Drying of Chilli Using Solar Cabinet Dryer Coupled with Gravel Bed Heat Storage System. Journal of Food research and technology. 1 (2):87-94.

Leon, A. M., Kumar, S., and Bhattachaya, S.C., (2002). A Comprehensive Procedure for Performance Evaluation of Solar Food Dryers, Renewable and Sustainable Energy Reviews. 6:367-393.

Liberty, J.T., Odo, C.E., and Ngabea, S.A., (2013). Performance Evaluation of a Small-Medium Scale Yam Chips Dryer, International Journal of Inventive Engineering and Sciences.1 (7):1-4

Misha, S., Mat, S., Ruslan, M.H., Sopian, K., and Salleh, E., (2013). Review on the Application of Tray Dryer System for Agricultural Products. World Applied Science Journal, 22 (3): 424-433

Mohanraj, M., and Chandrasekar, P., (2009). Performance of Forced Convection Solar Drier Integrated with Gravel as Heat Storage material for Chilli Drying. Journal of Engineering Science and technology, 4 (3):305-314

Tonui, K.S, Mutai, E.B.K., Mutuli, D.A, Mbuge, O.O., and Too K.V., (2014).Design and Evaluation of Solar Grain Dryer with a Back-up Heater. Research Journal of Applied Science, Engineering and Technology. 7 (15): 3036-3043