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The design, fabrication and performance evaluation of solar sustained batch type maize dryer for valuation addition

Fraz Ahmad Khan[1*] Anjum Munir[2] Abdul Ghafoor[1] Ghulam Murtaza[1]

[1]University of Agriculture, Faculty of Agricultural Engineering and Technology, Department of Farm Machinery and Power, Faisalabad-Pakistan

[2]University of Agriculture, Faculty of Agricultural Engineering and Technology, Department of Energy Systems Engineering, Faisalabad-Pakistan

*Corresponding Author: fraz465@gmail.com

Abstract

Drying is the taking away of water from agricultural product thus at the same time provide extended period of shelf life. In this study, an innovative solar sustained maize dryer along with screw conveyor for unloading the grain and central air perforated duct (throughout aeration chamber length) has been developed. High drying rate was achieved due to central air distribution model of the dryer during the drying process. Using 758-kg of freshly harvested maize at moisture content 24% (wet basis), dryer was evaluated. The average aeration rate of the solar sustained maize dryer was 3.67 kilogram per hour. 60% saving in drying time was also achieved by using the solar sustained maize dryer. From 24% to 13% moisture content for drying the whole maize, solar sustained maize dryer took 27 hours. It is economical and environment friendly drying method. Cost analysis was also done and it was found by using this drying method, at very low cost we can dehydrated better quality maize. At community level, marketable size of the solar sustained maize dryer can be better and formed for revolution of agriculture in the country-side areas.

Keywords: Moistness, aeration rate, even drying, central air perforated duct model

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Introduction

Due to ruthless global industrialization energy demand is constantly growing. For most of the world fossil fuel remains the main source of energy; however, consumption is harming the environment and reserves are diminishing. Heating process requires burning of extensive fossil fuels. Due to increasing energy demand and severe energy crises, alternate energy resources such as Solar Energy is used to minimize the load from the fossil fuels.

In Pakistan mean global solar irradiation ranges between 200-250Wm^{-2} per day. It is equal to 1,500-3,000 sunshine hours per year. Pakistan is receiving on an average 5.3 kWh m^{-2} per day. Pakistan lies between longitude 62.0 and 75.0 degree east and latitude 24.0 and 37.0 degrees north. Pakistan is located ideally to get maximum available solar radiation and possess abundant capacity to overcome its energy crises.

Solar energy is used by the solar air heaters to heat air and it can be engaged in many applications demanding moderate to low temperature lower 60°C, for example heating of spaces and drying of fruits vegetables and crop material (Kurtbas and Turgut, 2006).

Drying is the taking away of water contents from agricultural product. The drying carries out in two processes. In first process, the vaporization of moisture hooked on the atmosphere from surface of the substance at stable rate of drying. In second process, drying rate decreased because drying rate decreases with moisture content or decreases with increases in air humidity. Solar dryers are the machines that organize the drying practice and prevent the agriculture product from destroy by insect pest, rain and dust. Grains are the main food items in agriculture. Grains like maize, wheat and rice are accounted for 43% of all food calories and 87% of all grain production Worldwide. Maize is the most consumed food in the World. Over 42% of the world's population depends on maize to fulfill its food requirements. About 87% of the whole output of maize is consumed and produced in developing countries (FAO, 2002).

Hanif et al. (2012) designed and developed the solar collector for air heating and evaluated the energy requirements for the drying of grains. Blower was used to thrown the air that strike with the grains. With the bin in which grains were kept solar collector was joined. Solar collector 6m in length, 4 m in width and 0.3 m in depth. The material used for absorber plate was steel metal sheet. For glazing a single glass with 6 mm thickness was used. They used plywood as an insulating material for the body of the solar collector. They were tested the performance at seven different convective air flow rates. They found that drying efficiency of solar collector was 10% higher than all previous conventional methods. Statistical analysis was also done to check the performance of solar collector and showed that the flow rate of hot air increased the performance of solar collector (Hanif et al., 2012).

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Pakdaman et al. (2011) designed and develop the natural convection air solar heater and evaluated the performance of this system. On absorber plate, rectangular fins were mounted. The objective of this study was to achieve an empirical model for natural convection solar air heaters which forecasts several important features. In this study Nusselt number correlations for such devices were also obtained. Maximum efficiency for the system were also determined through exergy analysis. Solar collector frame 2000 mm in length, 1000 mm in width and 150mm in depth. The material used for absorber plate was black tinted galvanized-iron with a thickness of 1 mm. A total of 46 rectangular fins was 20 mm apart from each other which were attached to the absorber plate. The dimensions of attached fins were 2000x10mm with a thickness of 1 mm. For glazing a single glass cover with a thickness of 4 mm was used. It was concluded that heat transfer rate enhanced by longitudinal rectangular fin arrangement of air solar heaters. In this study, the heat transfer was increased by 20% approximately whereas heat transfer area was increased by 66%.

Soysal et al. (2009) compared the drying methods of microwave by air and commercial drying. The main purpose was to establish favorable drying conditions for good quality products. The main quality parameters were color and stiffness as well as sensory analysis for overall acceptance. They used to microwave dryers for drying actions. The output power for both microwave dryers was 597.20W and 697.87W. Two different modes like continuous and intermittent were used for actions in microwave dryers. The continuous mode showed power result of drying time as compared to commercial drying. Whereas the intermittent type showed good result of drying as compared to commercial dryer. So, they concluded that convective microwave uses 35^0 C - 38^0 C temperature and use 597.20W of energy of drying method was gentle also. They also resulted that products were good in quality like in color and teste.

Zomorodian et al. (2007) designed, fabricated and evaluated solar drier of semi-continuous type for cereals (Maize, etc.). Active mode type maize dryer was efficient timer assisted semi-continuous discharging system. The dryer consisted of: an inlet bin, an outlet bin and a plenum chamber and a drying chamber ended with a discharging valve. Mass flow rate and discharge interval time was the two parameters on which they conducted an experiment. They evaluated the drier capacity, efficiency of collector and overall efficiency of the drying. They found that 21.24% maximum overall efficiency of drying with 55^0 C of temperature. The dryer drying capacity was about, maize of 132 kg with MC 27% (d.b) dried to 13% (d.b) final MC in 3 h of drying time. Keeping in view the above stated problems of energy crisis and the opportunity of utilizing solar energy potential in Pakistan, this research was focused on design and fabrication of the solar sustained batch type maize dryer.

Methodology

To develop a solar sustained maize dryer for farm practices on farm, the subsequent possessions and parameter were calculated.

Design Process and Scheming

For the development of solar sustained batch type maize dryer, the dimensions of the dryer were calculated with the bulk density of the maize grain. The drying temperature was established by using ambient temperature. For the better aeration without evolving the stresses inside the maize the maximum temperature calculated. Relative humidity and mean average temperature is 70% and 29 ^{0}C respectively. The maximum drying temperature was maintained up to 45 ^{0}C for the drying of maize. With the assistance of grain moisture meter initial and final moisture content for the harmless storing of maize was measured that was 24% (w.b) and 13% (w.b) respectively. From the psychometric chart others intended values like moistness, enthalpy and air movement rate was resolute. The subsequent possessions and parameters were resolute for the designing purpose.

Initial Moisture Content of Maize

Initial moisture content of the maize was resolute to find the total of water required to take away from maize. Sample grains was dried in an electric oven for 16 hours at 130 ^{0}C (Ratti, 2001). When sample achieved the constant weight then the sample was taken out from oven and permitted to air quiet. By using the electric balance, the weight of sample was measured. By using Eq.1 moisture content was determined.

$$M.C = \frac{w_1 - w_2}{w_1} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.1)$$

Bulk Density

Bulk density of a material is the mass per total volume of the material. The bulk density of maize was about 824 kg/m^3.

Design of Aeration Compartment

Bola et al. (2013) designed the aeration compartment with the expectations that; formation is cylinder-shaped and mass of maize is 758 kg. Maize bulk density was about 824 kilograms per m^3. So, 1 kilogram's maize inhabits 0.00123 m^3 and 758 kilograms will inhabit 0.92 m^3.

The volume of drying chamber was 0.92 m^3. Since the extents of cylinder-shaped aeration compartment was calculated using equation given as above and were found to be 1.240 m in height and 0.94 m in diameter. At the bottom of the cylinder cone was also mounted which is 0.23 m in height and 0.94 m in diameter.

Mass of moisture to be removed

By using the Eq.3 we can find quantity of moisture required to take away from the maize which is intended as (Henderson and Perry, 1980).

$$M_w = \frac{W(Mo - Mf)}{Mo} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.2)$$

Where,

M_w = Quantity of water required to remove in kilograms

W = Mass of the maize in kilograms

M_o = Initial moisture content of the maize in % w.b

M_f = Desired moisture content of the maize in % w.b

W=758 kilograms, M_o=24% (w.b), M_f = 13% (w.b) and M_w = 99.25 kilograms.

Amount of Air Required for Drying of Maize

By using Eq. 4 air quantity required for aeration the maize was intended (Ichsani and Dyah, 2002).

$$m_w = (mC_p \frac{T_b - T_a}{Lw}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.4)$$

Where,

m_w = Air quantity (kilograms)

L_w = Free water latent heat of evaporation (Joule/kilogram)

C_p = Air specific heat at constant pressure (Joule/kilogram °C)

T_a = Ambient temperature (°C)

T_b = Ultimate temperature (°C)

From psychometric chart required air quantity was intended. If the relative humidity is the 70% and ambient air at temperature Ta is the 29 ˚C is heated up to the temperature of T_b is the 45 ˚C, for maize is the safe drying temperature (Hall, 1980), then from initial relative humidity 70% will reduce to 20%. 0.0160 kilograms of water per kilograms of dry air was measured as absolute humidity. Until an equilibrium relative humidity is reached, the warmed air is used to take away water, 99.25 kilograms from maize of 758 kg. Absolute humidity was increased from 0.016 to 0.0220 kilograms of water per kilograms of dry air when the temperature of the aeration air was reduced. Transformation in humidity ratio was determined, which was equal to ΔW =0.0060 kilograms of water per kilograms of dry air. By using Eq.5 required quantity of air was determined (Ichsani and Dyah, 2002).

$$M_a = \frac{M_W}{\Delta W x\ n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.5)$$

Where,

Ma = Required quantity of dry air in kilograms

Mw = Quantity of water required to remove in kilograms

ΔW = Difference in absolute humidity

n = Pick-up factor per (Axtell, 2002).

Hence, from the psychometric chart, ΔW = 0.0060 kilograms of water per kilograms of dry air, using n = 0.250 than tapping all values in the Eq. 5 the required quantity of air is intended that was started to be 66166.68 kilograms. 27 hours per batch drying time was considered, Hence, M_a = 3676 kilograms/hour which is equivalent to 1.021 kilograms/second.

Volumetric Flow Rate

By using Eq.6 volumetric flow rate was measured (Axtell, 2002).

$$Q_v = M_a \times V_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.6)$$

Where,

Q_v = Drying air volumetric flow rate in m^3/second

V_a = Drying air specific volume in m^3/kilograms

From the psychometric chart, the value of V_a is 0.872 m^3/Kg and from the equation (5) the value of the required quantity of air is 1.021 Kg/s, hence, Q_v = 53.35 m^3/min or 1880 cfm.

Fan Selection

Fan selection was based on the depth of the product bed and the pressure drop for air flow (Brooker et al., 1992). From fan characteristics curve (Stream rate (cfm) vs Resistance of air movement), the static pressure value was measured 43 mm of water. Then pressure drop multiply with a pack factor. The value of pack factor is 1.5 for maize and other crops. 0.5 is also added to the measure total static pressure if air is delivered from duct. Then the full static pressure value was 65 mm of water (Kenneth and Hellevang, 2013).

$$\text{Fan HP} = \frac{\text{Air flow rate} \times \text{Static pressure}}{3814} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.7)$$

Thus, by using Eq. 7 the needed HP is 0.8 hp. Consequently, a one-horse power centrifugal fan is carefully chosen.

Total of Heat Required

By using Eq. 8 for removing moisture from maize, the total of heat energy required was considered as (Hall, 1980).

$$Q = ML + Mh_{fg} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.8)$$

Where,

Q = Total heat energy in Watt

M = 99.25 kilograms is the amount of water need to remove

L = From the steam tables latent heat evaporation = 2.261×10^6 Joule/kilograms

h_{fg} = From steam tables heat coefficient = 43990 kilo-Joule/Kalvin moles of water

Then for drying the total of heat required is 2.3526 kilo-Joule/second.

Area of Solar Collector

For the essential heat, collector area Ac was intended by using Eq.9 (Hall, 1980).

$$Q = A_c(I_t\delta_a - U_L(T_b - T_a)F_R) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.9)$$

Where,

A_c = Collector area

I_t = Solar intensity (Pakistan) = 855 W/m^2 on normal basis

U_L = Overall heat coefficient = 7.38 W/m^2 ^{0}C

$\mathcal{E}_a$ = Transmissivity = 0.89

F_R = Heat removal factor = 0.9

T_a = Average ambient temperature = 29 ^{0}C

T_b = Average needed temperature = 45 ^{0}C

In conclusion, with equation (9), the collector area is considered as 4 m^2.

Enlightenment of Solar Sustained Maize Dryer

The concept of dryer plan is grounded on batch nature dryers. The working principal of the solar dryer is that when ambient air passing through the solar collector its temperature increase by absorbing the solar energy and then moisture from the moist grains is removed with the use of this heated air. In the workshop of Agricultural Engineering, University of Agriculture, Faisalabad solar sustained batch type maize dryer was developed and constructed. Plane platter collector, blower, aeration compartment and central air perforated duct model are some important parts of solar sustained batch type maize dryer. Plan diagram of the dissimilar parts of the machine are shown in the Figures 1and 2 respectively.

Figure 1 shows the cross-sectional understanding of aeration compartment. Drying bins were used to collect the grains. To maintain static, pressure the depths of grain in the drying bin was selected. For natural air, drying system to keep the static pressure as low as possible, larger diameter, and shallow bins were fabricated. Solid chamber, perforated drying chamber, central vertical duct and plenum chamber were the main parts of aeration compartment.

Figure 2 shows the isometric view of solar flat plate collector. A collector with flat rectangular plate was used which was helped with heat absorbing black sheet of mild steel, glazing glass, and specific amount of space was made for the wind to collect heat from sun. Solar collector intensified the solar radiations towards the heat absorbing plate as the solar radiation reached the glazing glass. Solar radiation heated the absorbing plate up to a specific temperature. By the help of blower, the wind touching absorbing plate was heated up and was forced towards the maize drying chamber. Figure 2 also shows the cross-sectional view of air duct. To remove moisture that was extracted from the maize, the air distribution system was used. It removes moisture to deliver air to the drying zone in the dryer through perforated duct. To maintain the uniform air flow rate over the material air distributors were designed and selected. Figure 3 shows the actual view of solar sustained batch type maize dryer.

Table 1. Design Specification.

Items	Units	Conditions and Assumptions
Location	_	Faisalabad, Pakistan
Crop	_	Maize
Bulk density	Kg/m^3	824
Grain mass per batch	Kg	758
Initial moisture content	% (w.b)	24
Required moisture content	% (w.b)	13
Temperature of ambient air,	^{0}C	29
Ambient relative humidity	%	70
Maximum allowable temperature [11]	^{0}C	45
Drying time	hour	27
Incident solar radiation,	W/m^2	850
Collector efficiency, ηc	%	40 - 70
Total heat required for drying of whole maize.	KJ/s	2.3526
Transmissivity	_	0.89

Table 2. Component and material used in the fabrication.

Name of Component	Parts	Fabrication Material
Solar Flat Plate Collector	Frame	Aluminum
	Absorber	Black painted steel sheet
	Insulation	Black tape
	Cover sheet	Glazing glass
	Connection pipe	Rubber
Drying Chamber	Outer chamber	Stainless Steel
	Perforated chamber	Stainless Steel
	Perforated Air duct	Stainless Steel
Centrifugal Blower	Frame, wings	Iron
Unloading Conveyor	Frame, augar	Stainless Steel

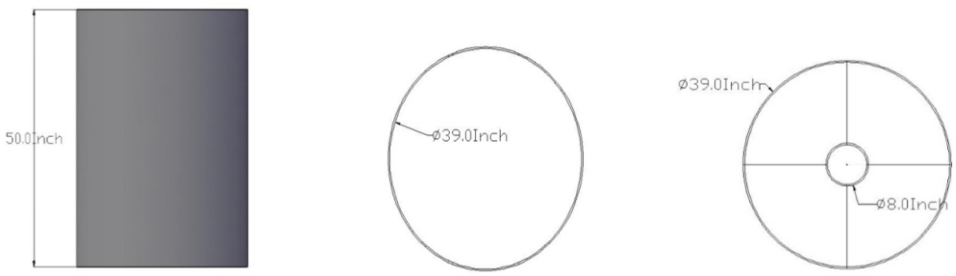

Figure 1. Cross sectional view of aeration compartment.

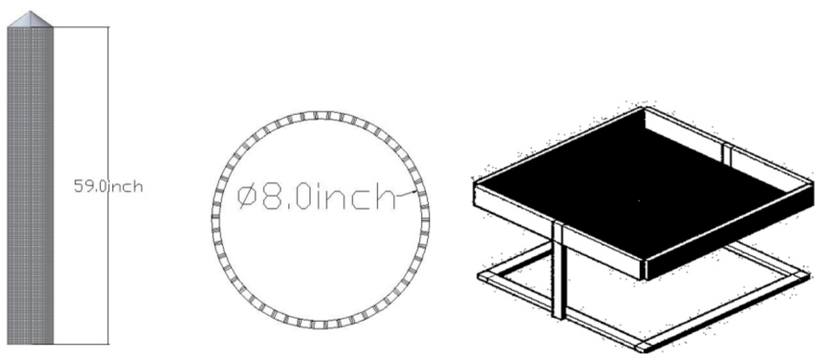

Figure 2. Isometric view of air duct and collector area.

Fabrication of Solar Dryer

All parts of solar sustained batch type maize dryer were fabricated in the workshop of Agricultural Engineering Department University of Agriculture Faisalabad, Faisalabad-Pakistan. The outer chamber was made up of Non-magnet stainless steel material and no perforations were made on this chamber. Single hole was made on this chamber which was used to support the outlet of the maize. Drying bin cover was designed to keep it safe from weathered conditions. Large perforated chamber was used, where the maize was needed to be placed. The amount of maize being dried was based on this chamber. The capacity of the maize dryer was same as the size of this chamber. It was also made with perforations on the surface. Whole surface of this chamber was contained small perforations. The size of perforations in this chamber was such that no maize should get out of the chamber. The air distributors were designed and selected to maintain the uniform air flow rate over the material. It was also fabricated from Non-magnet stainless steel material. The solar flat plate collector frame was made from Aluminum and absorber was made from black painted steel material. The choice of black painted steel material for absorber will help in absorbing all heat that come from sun in the form of radiation. The material used for conveyor construction was Non-magnet stainless. For maize unloading, the conveyor 3 inch in diameter and 24 inches in length was constructed. DC motor was used to run the conveyor with 12V/50W power.

Figure 3. Actual view of solar sustained batch type maize dryer.

Results and Discussions

Figure 4 shows that as intensity of solar radiation increases, heat added to the collector was also increases. Results shows that the average ambient temperature ranged from 24 to 32^{0}C, collector outlet temperature ranged from 38^{0}C to 65^{0}C, ambient relative humidity ranged from 70% to 29% and intensity of the solar radiation ranged from 600 to 924W/m^2.

Figure 5 shows that collector efficiency of the solar assisted maize dryer during the test day was varies from 45 to 57%, which indicating the good performance of the collector. The efficiency values obtained by (Ting and Shove, 1983) for a flat plate collector are like those obtained in this work, with a similar influence of the solar radiation and the air mass flow.

Figure 6 shows the variation in moisture content with respect to drying time of maize. Results shows that for achieving the final desired moisture content up to 13% dryer took 27 hr.

Cost Analysis

Cost analysis is the most important to check the feasibility of machine for farmer point of view to find out the drying cost. However (01 Rs = 0.01 US$), the new solar sustained maize dryer purchase price of was estimated to be US$. 1234.33/- and solar sustained maize dryer useful life is supposed to be 10 years.

The yearly static cost was considered = US$. 159.51/-
Annual drying capacity of maize dryer is assumed = 206 tons/ year
The total fixed cost of the dryer = US$. 0.77/ton
For maize labor charges = US$. 4.75/ton of maize aeration
Energy charges = US$.0.002/kg
The sum of variable charges = US$. 0.63/ton
The total cost is about = US$. 1.40/ton.
Therefore, the drying cost = US$. 0.00147/Kg.

The drying cost by using open sun drying method was 0.02 to 0.03 US$. /kg in Pakistan per literature and survey report. It is economical and environment friendly drying method.

Conclusions

From 24% to 13% moisture content for drying the 758-kg maize, solar sustained maize dryer took 27 hours and mean drying rate was 3.67 kilograms/hour. Against the outmoded open sun aeration method, 60% saving in time was achieved by using solar sustained maize dryer. Furthermore, Cost analysis was also done and it was found by using this drying method, at very low cost we can dehydrated better quality maize because in Pakistan the drying cost by using open sun drying method was 0.02 to 0.03 US$. /kg in Pakistan per literature and survey report. At community level, marketable size of the solar sustained maize dryer can be better and formed for revolution of agriculture in the country-side areas.

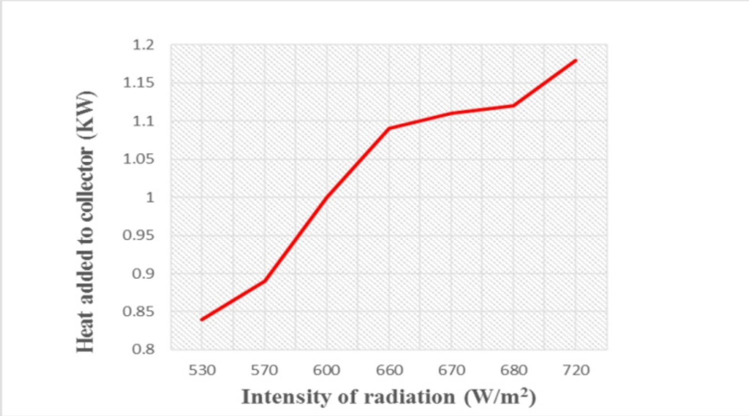

Figure 4: Efficiency of the collector for five typical days.

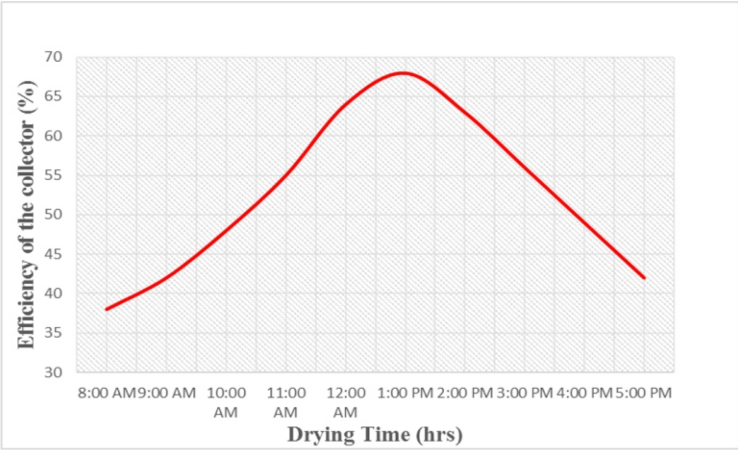

Figure 5. Efficiency of the collector for five typical days

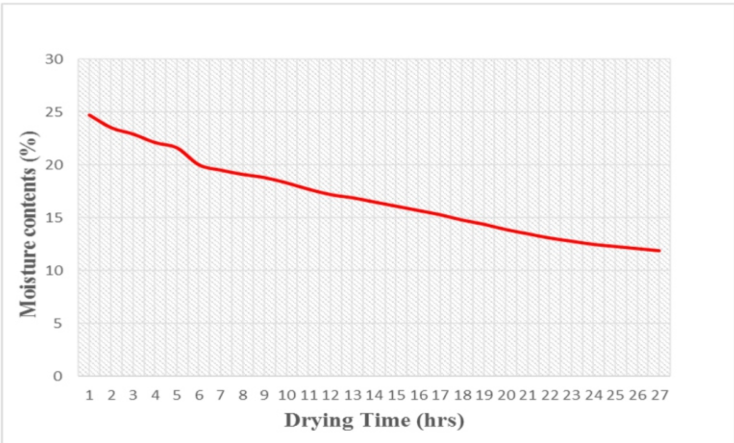

Figure 6. Variation in moisture content with time.

Fixed cost	
Depreciation (US$.)	56.97/year
Interest @ 12% (US$.)	102.54/year
Total fixed cost, (US$.)	159.51/year
Variable cost	
Repair and Maintenance @ 15% (US$.)	34.18/year
Labor @ 300 US$. / day of 9 hours	94.95/year
Total variable cost, (US$.)	129.13/year

Table 3. Drying cost worksheet.

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