

Effect of operational parameters on drying rate and moisture content of maize by using hybrid solar dryer

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Solar dryers are not so efficient due to improper control of air flow rate and its temperature. The issue is resolved by developing the hybrid solar dryer which was opted in this study. The experiments were conducted on maize at different drying air temperature (40°C, 45°C and 50°C), air flow rate (300 m³h⁻¹, 400 m³h⁻¹ and 500 m³h⁻¹) and drying time (8 h, 12 h and 16 h). The change in moisture content and drying rate were analyzed under different experimental conditions. The reduction in moisture content of maize was better when drying time was increased from 8 h to 12 h, air flow rate from 300 m³h⁻¹ to 400 m³h⁻¹ and drying temperature from 40°C to 45°C as compared to further increase in the values of experimental parameters. The similar trend was observed for drying rate. Moreover, the quadratic model developed showed good relationship between predicted and actual response by which hybrid solar dryer can be set at operational conditions for desired drying rate and moisture content of maize. The optimum conditions were observed at 45°C temperature of drying air with air flow rate of 400 m³h⁻¹ for 12 hour while drying maize.

Keywords: hybrid solar dryer, moisture content, air flow rate, drying time, air flow rate.

INTRODUCTION

Pakistan is one of agro-based countries of South Asia. The role of agriculture in Pakistan's GDP is 24% with a workforce of 48% and also contributes 75% to foreign exchange (Nadeem *et al.*, 2018; Economic Survey of Pakistan, 2013). About 67% of Pakistan's population living in villages are directly or indirectly attached with agriculture (Economic Survey of Pakistan, 2013; FAO, 2004). Maize (*Zea-Mays*) is an important cereal crop, used as food for both human being and animal. At harvest, maize usually contains too much moisture (20-25%) which creates an environment which is favorable for the growth of moulds (fungi) and insects that normally cause grain damage (Folaranmi, 2008). The deterioration of high moisty maize starts after harvest due to low temperature and high relative humidity of the atmospheric air. Postharvest losses are the major threats to the farmers of developing countries. According to Chelkowski, 1991, about 10-30% of world grain production is lost due inefficient handling and inadequately implementing the post-harvest technologies. Post-harvest losses in Pakistan are reported to be 17.01 % for rice, 15.31 % wheat and 12.64% in corn. These losses occurred due to improper crop handling

during threshing, cleaning, drying and storage (Ahmad, 2009; Chaudhary, 1980). To avoid these losses farmers of Pakistan sold their high moisture crop at lower price in the market that not only decreased the income of farmers but could develop the food security problem. In order to avoid from these losses, drying of maize must be done to reduce the moisture content in range 11.8-13% for safe storage (Folaranmi, 2008).

Drying is one of oldest technique for food preservation. It is defined as the removal of moisture from food stuff to moisture content in equilibrium with the surrounding air so-that the chance of mould's enzymic action and insect's infestation could be reduced. The basic purpose of food drying is to improve their texture, storability and transportability. Most farmers of developing countries still use the direct sun drying for food preservation (Bola *et al.*, 2013). This traditional method is although cheap but susceptible to dirt, foreign materials, animals and require large open space (Chan *et al.*, 2015). According to Ruyter, 2007, the food losses during open sun drying are accounted to be 10%. This method of drying is discouraged by different researchers due to more drying period, low drying rate and aflatoxin contamination because air temperature, relative humidity and wind speed remains as independent factors during open sun drying (De



Groote et., 2021; Kaaya and Kyamuhangire, 2010; Meas, 2008, Purohit et al., 2006).

One of the possible solution to above problem is to dry the crop in a closed vessel (mechanical dryer) that can eliminate the threats of open sun drying as well as to preserve product quality for a longer time. One practical form of such vessels are solar and biomass type batch dryers that are comparatively low in cost and simple in design as compared to electrical dryers (Jain and Tiwari, 2004). In such type of dryers, heated air is forced into the drying chamber containing a static grain bulk to be dried. The wet grains can easily be dried if inlet air conditions are drier than wet sample. This means that the moisture carrying capacity of air can be enhanced by raising its temperature. Thus, drying period can be reduced considerably as compared to traditional sun drying (Sreekuma et al., 2008). Moreover, the physical properties of grain like color, nutritional value, texture and flavor can also preserved (Beigi, 2016). These batch type dryer are widely used due to simple design but the problem of uneven air distribution encounters in these dryer which causes low drying efficiency and lack of homogeneity of products being dried (Amjad et al., 2015; Misha et al., 2013; Mirade, 2003).

Tzempelikos et al., 2012 suggested that geometry of drying chamber determine the uniformity of drying and thus the quality of final product. Non-uniform drying in typical batch type dryers occurs due to creation of different regions i.e. dried, drying, undried along the length of dryer as the heated air is injected and deducted from the drying chamber (Abur et al., 2014). Such regions not only caused heterogeneity in drying but also effect the drying time and drying rate. A lot of work has been done to overcome such issues by improving the shape, type, heat generation and transfer mechanism (Mahesh and Sindho, 2015). It is observed that the uniformity in drying can be attained by proper controlling the dryer processes especially the hot air circulation and heat utilization inside the dryer (Zare and Chen, 2009). Keeping in view, the above problems, a central duct dryer was design and developed to reduce postharvest losses faced by farmers thereby increasing their economic status.

MATERIALS AND METHODS

Location: Research work on a hybrid solar dryer (HSD) was carried out at the solar park situated in the Engineering workshop, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad, (Latitude 31.4504° N and Longitude 73.1350° E), Pakistan.

Dryer Description: The main component of the hybrid solar dryer are solar modules, blower, heating unit, drying chamber, air duct, and a conveyor. A photovoltaic (PV) system with three number of modules (0.75 kW), two number of batteries (100 amperes each) and an inverter (750 W) was used to operate the electrical appliances of the dryer i.e., blower and conveyor. A centrifugal blower (0.37 kW, 220V)

was used to send a required pressurized air in the drying chamber. To maintain the required airflow, a flap/variatic was connected with blower. A heating unit (solar collector plus LPG heater) was used to add heat into the drying air up to required limit (46°C). For the purpose of uniform airflow, an air duct (0.203 m diameter and 1.247 m height) was fixed in the center of the chamber. A batch of 500 kg maize grains was dried easily in the dryer (diameter 0.94 m and 1.244 m height). The connecting pipes between heating unit and the dryer were raped with wool for insulation purpose. The dried product was easily unloaded with an auger type conveyor of 50 W.

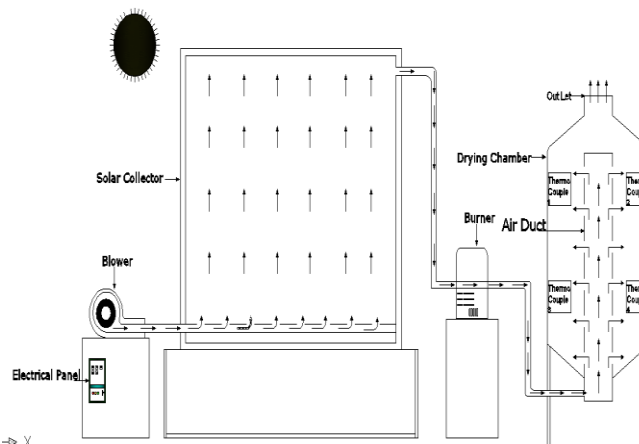


Figure 1. Schematic view of the hybrid solar dryer

RSM design: Response surface methodology (RSM) was used to investigate the effects of independent variables on dependent variables. The effects of drying temperature (40-50°C), drying time (8-16 h) and airflow rate (300-500 m³h⁻¹) on moisture variation (%) and drying rate (kg h⁻¹) were investigated. Equations used in RSM described the single and combined effect of operating parameters on response variables. For performance evaluation, the software used was Design Expert software 7.0.0. The purpose was to check the effects of single and interaction of operating parameters and for each response a 3D response surface was made to see results in better form. The input variables (independent) were fed into software in different ranges. As an output of this software, optimum values were predicted.

Regression coefficients: The Central Composite Rotatable Design (CCRD) was used to design 20 experiments (Table 1 & 2). For dependent variables, regression coefficients were determined by fitting experimental data in second-order multi regression mode. The model for each predicted response (MC and DR) is as follows:

$$Y = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i=1}^3 \beta_{ii} X_i^2 + \sum_{i < j=1}^3 \sum_{j=1}^3 \beta_{ij} X_i X_j + e$$

Where β_0 , β_i , β_{ii} , and β_{ij} are intercept, linear, quadratic and interaction regression coefficient terms, respectively. X_i ,

Table 1. ANOVA table for moisture content.

Source	Sum of squares	df	Mean square	F-value	P-value	Remarks
Model	73.190	9	8.13	2667.73	< 0.0001	Significant
A-Air flow rate	22.660	1	22.66	7431.87	< 0.0001	
B-Temperature	25.510	1	25.51	8369.23	< 0.0001	
C-Time	19.710	1	19.71	6467.12	< 0.0001	
AB	0.015	1	0.02	5.02	0.0489	
AC	0.390	1	0.39	128.46	< 0.0001	
BC	1.320	1	1.32	433.11	< 0.0001	
A ²	1.430	1	1.43	470.36	< 0.0001	
B ²	1.310	1	1.31	429.13	< 0.0001	
C ²	1.550	1	1.55	507.99	< 0.0001	
Residual	0.030	10	0.003048			
Lack of Fit	0.008	5	0.001680	0.38	0.8438	Non-significant
Pure Error	0.022	5	0.004417			
Total	73.220	19				

X_j are independent variables and e is the random error. Model was judged by R^2 , R^2_{adj} and R^2_{pred} , C.V. (lack of fit > 0.1; $R^2 > 0.95$) (Myers and Montgomery, 2002). The model was considered acceptable if the p -value that defines significance of coefficients was less than 0.05 (confidence interval at 95%).

Economic analysis of dryer: The cost of a machine is an important factor to determine its use and viability. As drying needs more energy so economic feasibility analysis of dryer was done to find out own cost of dryer and its operation cost (Khan *et al.*, 2017; Kalinci *et al.*, 2015). Cost analysis is based on ownership cost and operating cost:

1. Ownership cost: Fixed cost of a machine paid by an owner is called an ownership cost.
2. Operating cost: Variable cost to operate a machine for specific purpose is known to be operating cost.

Fixed cost: Fixed cost consists of depreciation, interest and insurance, taxes and housing.

Depreciation

Depreciation was determined by using straight line method (Khan *et al.*, 2017). It was find out by giving an appropriate 10-15% salvage value to initial cost of dryer and then difference of initial cost and depreciated cost was divided with the years (Lee *et al.*, 2014; Weygandt *et al.*, 2008).

$$D = \frac{C_c - V_s}{L}$$

Where, D is depreciation cost per year, C_c is capital cost of dryer, V_s is salvage values (10% of C_c) and L is expected useful life in years.

Interest: The cost of owning a machine includes a fee for annual interest. Interest is considered as an opportunity cost i.e., by investing in machines, we have lost the opportunity for interest on a savings account or other interest earning investment. The amount of interest on a machine is determined by half of sum of the capital and salvage value times interest rate (Nadeem *et al.*, 2018).

$$I = i * \left(\frac{C_c + V_s}{2} \right)$$

Where I is interest per year, i is interest rate (10%), C_c is the capital cost of machine and S is salvage value of machine.

Insurance, taxes and housing (ITH): Machine is considered as a personal property and is taxed according to state and local laws. The need of machine housing depends on the climatic condition. It is generally considered that machine protected against the effect of the weather would require fewer repairs. Insurance must be added for unforeseen situation in future. ITH is usually taken as 1-2% of capital cost of a machine (Edwards, 2015; Lazarus, 2009; Jacobs and William, 1987).

$$ITH = 0.02 * \text{Capital cost}$$

Variable cost: Variable cost is the cost that is used to operate a machine. This cost changes with amount of annual use. In general accountings, variable cost includes labor cost to operate the machine, fuel cost, repair and maintenance (Edwards, 2015).

Labor cost: There is some hesitation to include the labor cost in the operating cost when the owner is doing his or her work. Labor is an important operational cost. The cost of labor is an important to decide the size of a machine to be purchased. The hours saved by using a large machine often prove an important decision factor. When used a hired labor then actual hourly rate is used to find out labor cost (Nadeem *et al.*, 2018).

Fuel cost: A gas burner was used to add heat in the drying air when drying temperature of air is less than required temperature. The gas consumption varies with the climatic condition. The burner was adjusted between drying chamber and solar collector so that in case of less temperature at outlet of collector, more heat can be added to drying air by burner.

Repair and maintenance cost: A proper periodic repair and maintenance of a machine should be carried out to enhance its useful life. Irregular maintenance schedule will decrease the life of machine resulting in damage of machine parts and enhance repair cost. The knowledge of repair and maintenance cost is important for making decisions for

replacement of a machine (Khan *et al.*, 2017). Normally, this is considered to be 15% of capital cost (Edward, 2015).

Breakeven analysis: Breakeven analysis was performed by determining fixed and variable cost of dryer to find out the breakeven point of the machine.

RESULTS

The following quadratic equation for percentage moisture content (MC) was developed through regression analysis on the basis of outcomes of designed experiments.

$$MC = +15.99 - 1.29A - 1.37B - 1.20C + 0.044AB - 0.22AC - 0.41BC - 0.32A^2 - 0.30B^2 + 0.33C^2$$

Where A, B and C represents flow rate, drying temperature and process time respectively. It can be observed that the drying temperature has more effect as compared to other factors alone. On the other end, flow rate and drying temperature has the least effect as compared to combine effect of drying temperature and drying time. An F-value test is used for comparison of model and residual variances, which are calculated by dividing model mean sum of squares with residual mean squares. The ANOVA table clearly shows the significant effect of all parameters and their interactions in Table 1, whereas the graph between fitted and modeled values for moisture content is shown in Fig. 2.

While performing the regression analysis, following quadratic equation is achieved for drying rate.

$$DR = +3.40 + 0.62A + 0.75B - 0.50C - 0.045AB - 0.12AC - 0.47BC - 0.19A^2 - 0.20B^2 - 3.685E^{(-003)} C^2$$

Where A, B and C represents flow rate, drying temperature and process time, respectively. It can be observed that air flow rate has more effect on drying rate as compare to drying temperature whereas the time has negative effect over drying rate as observed in Fig. 8 to 10. It can also be observed that when time (C) combines with other two parameters (A&B) the cumulative is negative effect over drying rate. The

ANOVA of the model is shown in Table 2, represented the significant effect of all parameters and their interactions. It is depicted from Table 2 that the model is statistically significant with “Model F-value” of 63.49. A p-value less than 0.05 shows the statistical significance of the model terms and it is clear that flow rate, temperature, process time, AB, AC, BC, A2, B2 and C2 were the significant model terms. The F-value for lack of fit (0.57) implies that the lack of fit is not significant relative to the pure error, which indicates that the model is well fitted with the experimental data. Coefficient of variation value (5.85%) was found to be have reliability of the model results with the experimental data, because generally, a model with less than 10% CV is considered reasonably reproducible. The graph between the modeled value against the observed values of moisture content and drying rate is shown in Fig. 3.

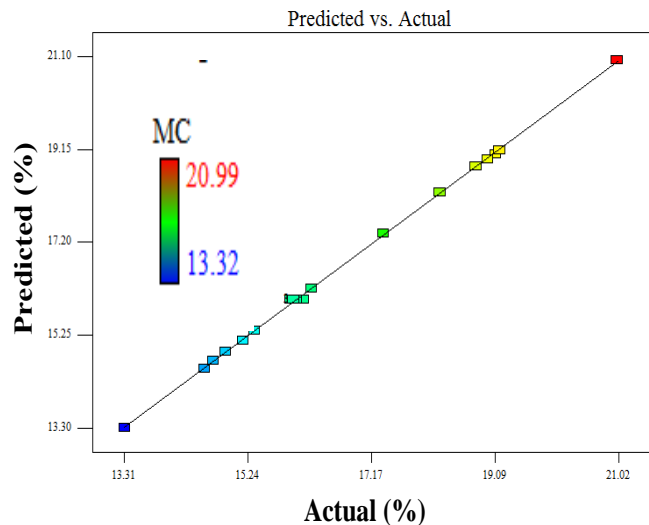


Figure 2. Relationship between predicted and observed values of moisture content (%wb)

Table 2. ANOVA of drying rate

Source	Sum of squares	df	Mean square	F-value	P-value	Remarks
Model	19.22	9	2.14	63.49	< 0.0001	Significant
A-Air flow rate	5.32	1	5.32	158.29	< 0.0001	
B-Temperature	7.60	1	7.60	226.03	< 0.0001	
C- Process time	3.36	1	3.36	99.83	< 0.0001	
AB	0.016	1	0.016	0.48	0.5035	
AC	0.12	1	0.12	3.72	0.0828	
BC	1.80	1	1.80	53.65	< 0.0001	
A ²	0.51	1	0.51	15.07	0.0031	
B ²	0.57	1	0.57	16.82	0.0021	
C ²	1.957E-004	1	1.957E-004	5.817E-003	0.9407	
Residual	0.34	10	0.034			
Lack of Fit	0.12	5	0.024	0.57	0.7250	Non-significant
Pure Error	0.21	5	0.045			
Total	19.56	19				

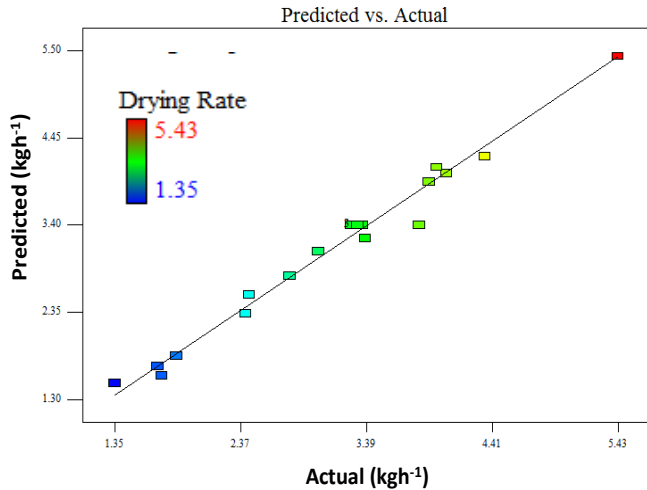


Figure 3. Relationship between predicted and observed values of drying rate

DISCUSSION

Effect of airflow, time and temperature on maize grain's moisture: The effect of keeping air flow constant at various drying time and air temperature within experimental range is shown in Fig. 4. It can be observed that the increasing the time from 8 h to 16 hours decrease the moisture content from an average initial moisture content of 23% to 18.35% at air flow rate of 300 m³h⁻¹ and drying air temperature of 40°C (Fig. 4a).

When the air temperature was increased to 45°C at the same air flow, the moisture content decreased to 16.55% whereas when the drying air temperature was increased to 50°C the final moisture content were 15.85%. The increase in drying temperature at same air flow rate increases the moisture content removal efficiency by 20.22% at 40°C, 28.04% at 45°C and 31.09% at 50°C (Fig. 7). It is clear that increasing the air temperature from 40°C to 45°C is better in term of reducing moisture content as compared to increasing the air temperature from 45°C to 50°C at airflow rate of 300 m³h⁻¹ with 16 h drying time. Observing the moisture content at 300 m³h⁻¹ and 45°C, increasing the drying time from 8 h to 12 h decreases the moisture content from 18.85% to 17.25% but further increase in time to 16 h decrease the moisture content level at 16.55%, which indicated that 12 h drying time is more effective than 16 h drying time.

On the other end, increasing the air flow rate to 400 m³h⁻¹ for 16 h results in moisture level of 17.45%, 15.65% and 14.95% at 40°C, 45°C and 50°C, respectively (Fig. 4b). The decrease in moisture content at 45°C was much better as compared to 50°C and further increasing the drying time from 8 h to 12 h increased the moisture removal efficiency from 21.95% to 28.91% whereas further increase in time to 16 h increased the efficiency to 31.95%, which represent that 12 hour incubation is more effective (Fig. 7).

The similar trends can be observed at 500 m³/h air flow rate by increasing the drying time from 8 h to 12 h when moisture content removal efficiency increased from 17.82% to 31.74%

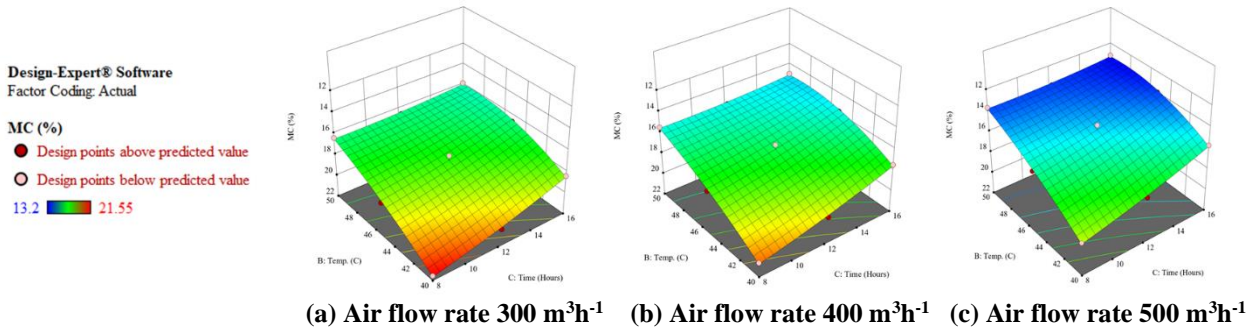


Figure 4. Effect of time and temperature at different air flow rate on moisture content

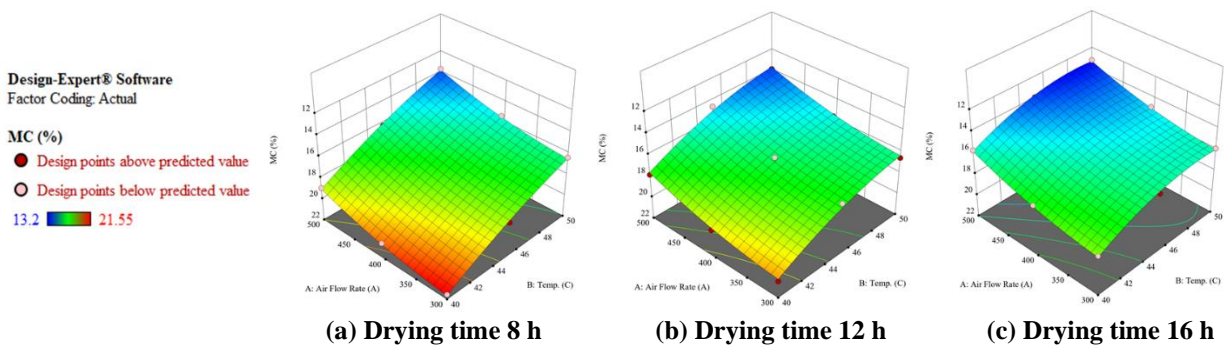


Figure 5. Effect of air flow rate and temperature at different time on moisture content

at 40°C, 29.57% to 39.59% at 45°C and from 40.43% to 42.61% at 50°C (Fig. 7). Again 45°C is more efficient in moisture removal and the final moisture content were 14.6% at 8 h against 13.9% at 12 h. Keeping in view the variation of moisture content with air flow rate, the 45°C with 12 h time is optimum for drying using HSD.

For better understanding the results were drawn in Fig. 5 to compare the effect of drying time at various experimental levels. It was observed that at 8 h drying time increasing the air flow rate from 300 m³h⁻¹ to 500 m³h⁻¹, the moisture content decreased from 21.55 % to 16.35 % at 40°C, 18.85% to 17.95 % at 45°C and from 16.35% to 13.7% at 50°C (Fig. 5a). At the same time, increasing the drying time to 12 h decreased the moisture content in better way for 45°C when air flow rate was increased from 300 m³h⁻¹ to 500 m³h⁻¹ results in an increase in the moisture content removal efficiency from 25% to 36.5% (Fig. 7). The highest moisture content removal efficiency of 39.52% at 12 h drying time was reached at 50°C

and 500 m³h⁻¹ which was closed to 42.61% moisture content removal efficiency at 16 h drying time under same temperature and flow rate (Fig. 5c). Keeping in view the efficiency analysis it is observed that the 12 h drying has effect close to 16 h drying.

The variation in moisture content at different experimental temperature is shown in Fig. 6. The final moisture content level varied from 21.55% to 15.7% at 40°C whereas it varied from 18.85% to 13.9 % at 45°C and 16.35% to 13.2% at 50°C as observed in Fig. 5. It is clear that the 45°C is better as compared to other two tested temperatures as also reported by Hao *et al.* (2020) which can also be observe in in Fig. 7.

Drying rate evaluation: The increase in drying time decreases the drying rate as initially the moisture removal is more but with time it decreases as it can be observed in Fig. 8. It is obvious that the drying rate is high at high 50°C and air flow rate changes the drying rate from 4.04 kgh⁻¹ to 5.43 kgh⁻¹ when air flow rate was increased from 300 m³h⁻¹ to 500 m³h⁻¹

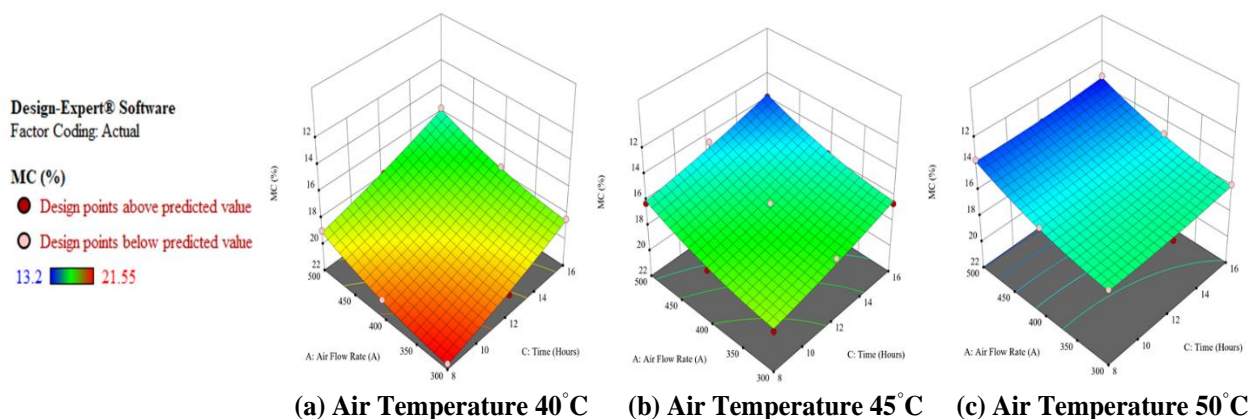


Figure 6. Effect of air flow rate and time at different air temperature on moisture content

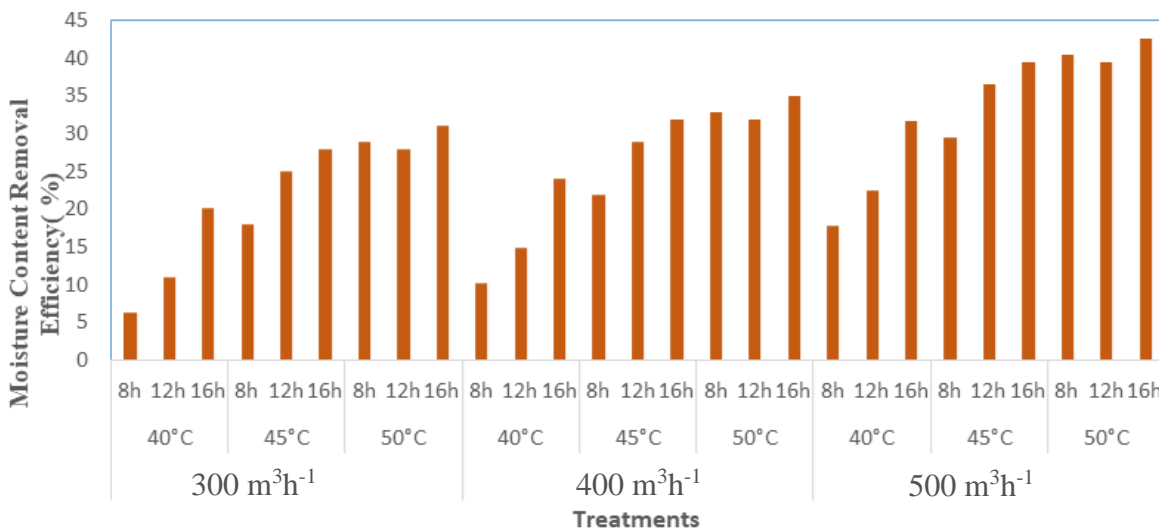


Figure 7. Moisture content removal efficiency determined by drying maize grains with flow rates at specified temperatures with respect to varying residence time.

at 8 h drying at which the final moisture content were 16.35% to 13.7%, respectively (Fig. 8a). When the drying time was increased to 12 h, the drying rate reduced and optimum drying rate of 3.32 kg h^{-1} were achieved at 45°C with flow rate of 400 m^3h^{-1} (Fig. 8b). On the other end, the drying rate has huge variation from 1.7 kg h^{-1} to 3.38 kg h^{-1} when temperature was changed from 40°C to 50°C and air flow rate from 300 m^3h^{-1} to 500 m^3h^{-1} at 16 h of drying time (Fig. 8c). The effect of drying temperature over other two experimental parameters is shown in Fig. 9. The drying rate varies between

1.35 kg h^{-1} to 3 kg h^{-1} at 40°C, at boundary conditions of other two parameters (Fig. 9a). Increasing the air temperature to 45°C, the drying rate of 3.32 kg h^{-1} were achieved at 12 h of drying and 400 m^3h^{-1} air flow rate (Fig. 9b). Further increase in temperature to 50°C, the drying rate of 2.41 kg h^{-1} was observed at 16 h drying time and 300 m^3h^{-1} which was changed to 3.38 kg h^{-1} at 500 m^3h^{-1} at same drying time (Fig. 9c). The maximum experimental drying rate of 5.43 m^3h^{-1} was achieved at 500 m^3h^{-1} air flow rate and 50°C where the drying time was 8 h resulting final moisture content of

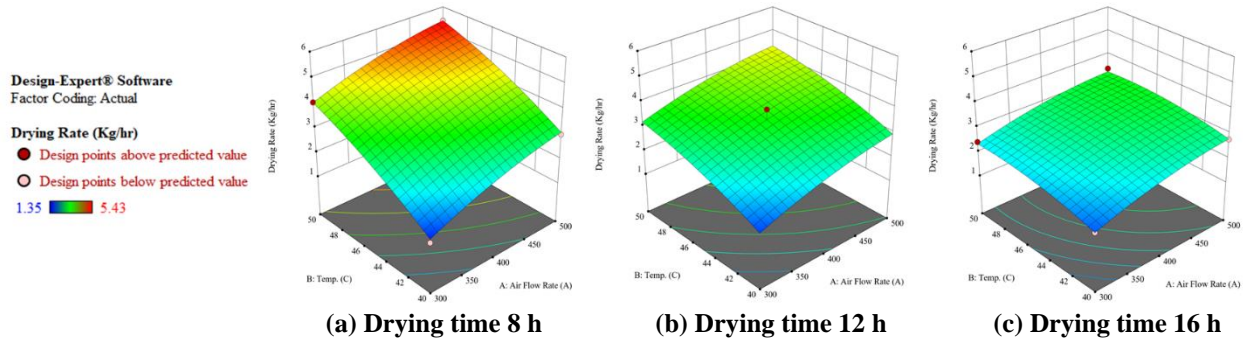


Figure 8. Effect of air flow rate and temperature at different time on drying rate

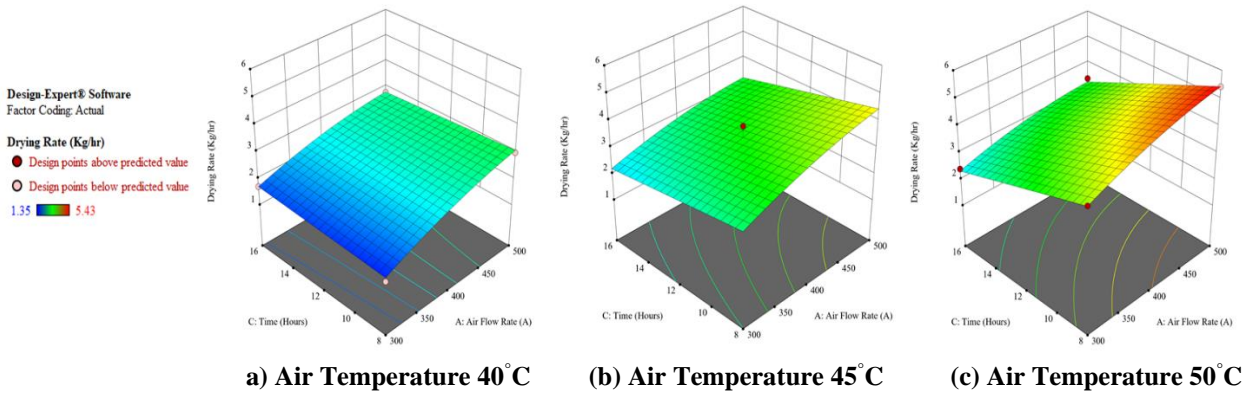


Figure 9. Effect of air flow rate and time at different air temperature on drying rate

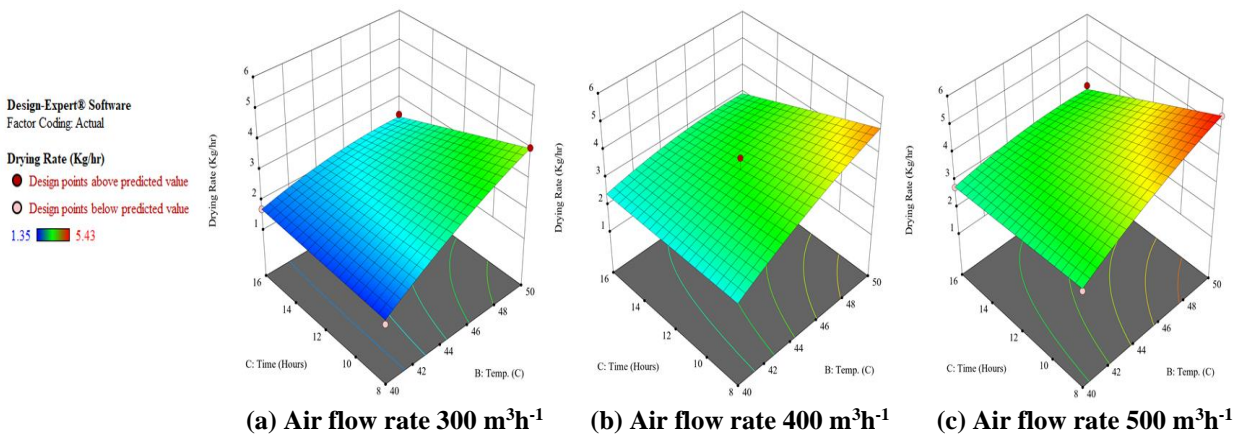


Figure 10. Effect of time and temperature at different air flow rate on drying rate

15.34%. Similar trend of drying rate with change in temperature were reported by Bosomtwe *et al.* (2019). The effect of air flow rate over drying rate in combination of other to experimental parameters is shown in Fig. 10. It is obvious that the increase in air flow rate increases the drying rate and combining the effect of air temperature caused major variation in drying rate as observed in Fig. 10a where increasing the temperature from 40°C to 50°C at 8 h time increased the drying rate 3 times when air flow rate was 300 m³h⁻¹. The variation is comparatively is more uniform at 400 m³h⁻¹ as shown in Fig. 10b where the optimum conditions of 12 h time and 45°C results drying rate of 3.32 kg h⁻¹. Further increase in air flow rate has variation of drying rate from 2.77 kg h⁻¹ to 5.43 kg h⁻¹ as observed in Fig. 10c.

Breakeven analysis of dryer: The breakeven analysis of dryer was performed to find out payback period. This is an applied technique that is used to find out a common point at which total cost becomes equal to total revenue where actual profit starts (Khan *et al.*, 2017). The breakeven point of newly fabricated hybrid solar dryer at 8 hours working per day is shown in below graph. The breakeven point of this dryer was found to be 1300 hours (Fig. 11). According to this analysis, a farmer can easily earn maximum profit beyond 1300 hours by selling 40 kg bag of maize at a cost 200-400 rupees price more as compared to undried product.

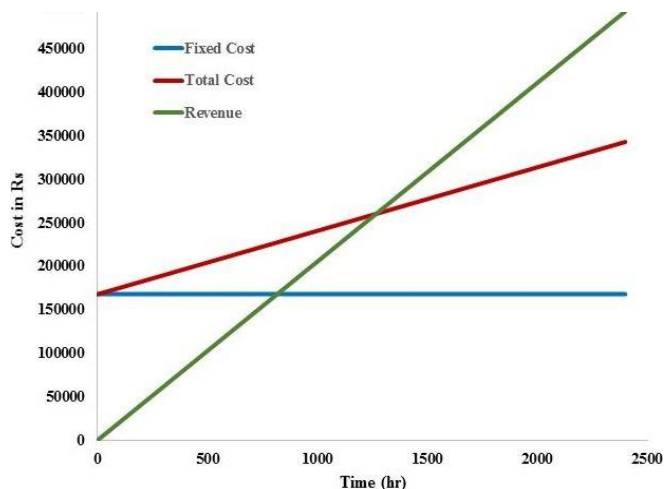


Figure 11. Break even analysis of the developed hybrid solar dryer determined by the intersection of the Revenue and Total cost trend lines

Uncertainty analysis: Instruments and measurements have general specific characteristics. An accurate measurement can be made by consideration these properties. Errors and uncertainties are inherent in both data acquisition instruments and recorded measurements (Amjad *et al.*, 2016). These errors mostly occurs due to selection and calibration of instruments and reading of measurements (Akpinar *et al.*, 2015 a,b). Therefore, the uncertainty analysis of the

measurements of different parameters was performed in detail as given in Table 3. The process of error estimation was done using the following equation considering the relative errors in the individual factors denoted by x_n (Holman, 1994).

$$U = [(x_1)^2 + (x_2)^2 \dots \dots + (x_n)^2]^{1/2}$$

Table 3. Uncertainties values of different parameters during experiment.

Parameters	Unit	Comment
Blower inlet temperature	°C	±0.296
Collector inlet temperature	°C	±0.267
Collector outlet temperature	°C	±0.275
Drying chamber inlet temperature	°C	±0.256
Drying chamber outlet temperature	°C	±0.310
Ambient temperature	°C	±0.294
Relative humidity of air	%	±0.200

Conclusion: A quadratic model was developed for drying rate and final moisture content of maize by using hybrid solar dryer using drying time, drying air temperature and air flow rate. The developed model showed good relationship between experimental and predicted outcomes by which desired final moisture content and drying rate can be achieved by using the modeled values for hybrid solar dryer. It was also concluded that 45°C air with flow rate of 400 m³h⁻¹ for 12 h drying time are optimum conditions for hybrid solar dryer when it is used for maize crop. The result of breakeven analysis showed that farmers could reach the breakeven point of this dryer just after 1300 hours of operation. This machine can also be used for the drying of other agricultural products like paddy, corn cobs etc.

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