Original Research Article

Development of mini solar tunnel dryer and validation of thin layer drying modelsfor pomegranate seeds

ABSTRACT

A portable mini solar tunnel dryer was developed and evaluated in terms of drying rate, moisture ratio and drying efficiencyfor drying of pomegranate seeds. The drying characteristic curves were also determined for drying in mini solar tunnel dryer and open sun drying. In order to study the drying behaviour of pomegranate seeds in open sun drying and mini solar tunnel dryer, seven different models were fitted. The best prediction model was determined to estimate drying kinetics as criteria for evaluating the goodness-of-fit based on R^2, SSE and RMSE. The Approximation of Diffusion model was adequate to describe the drying kinetics of pomegranate seeds in open sun drying and mini solar tunnel dryer with R^2 value of 0.99189 and 0.9943, respectively. The mini solar tunnel dryer was 7% more efficient in drying of pomegranate seeds compared to open sun drying without affecting the quality of seeds. The dryer can used by the farmersas an alternative to sun drying for on field drying of their product without compromising the quality.

Keywords: Solar tunnel drying, thin layer drying models, pomegranate seed drying, drying characteristics

Introduction

Pomegranate (*Punicagranatum L.*) is an important fruit of tropical and subtropical regions. The edible parts of pomegranate fruit represented 52% of total fruit weight, comprising 78% juice and 22% seeds. The fresh juice contained 85.4% moisture, 10.6% total sugars, 1.4% pectin, 0.1g/100 ml total acidity (as citric acid)(Schubert et al., 1999). Dried pomegranate seeds (anardana) find its utility as a condiment ayurvedic medicines in the treatment of dysentery, diarrhoea, stomach-ache, inflammations, hymenoletidosis, dyspepsia, bronchitis and cardiac problem (Anonymous, 2018; Viuda-Martos et al., 2010).

Drying is the most common and fundamental method for post-harvest preservation of medicinal plants as it is a simple and quick method for conservation of the medicinal qualities of the plant material(Mori-Okamoto et al.,2004). Drying represents 30 to 50% of the total costs of the product (Lee et al., 2010). Currently, energy demand of drying represents a significant cost factor, especially with the increased price of fossil fuels. This is largely due to the high moisture content of the product is to be removed. Drying temperature should be chosen as high as possible without reducing the quality of the product to achieve increased dryer capacity.

In the open sun drying pomegranate seeds are exposed to the sun light directly. Due to direct solar radiation colour of the dried product becomes lighter and thus the market value of the product decreases. Whereas, drying in dryer may retain the colour of the dried product thus the market value of the product may increase.

Large sizes of the solar dryers are fixed type and could not change their location. Therefore,it is difficult to change the orientation of these dryers. So, the small house hold size mini solar tunnel dryer can be used at domestic level for drying of fruits & vegetables. Further, the price of the mini solar tunnel dryer may also low as compared to large sizes solar dryers. Thus, this can be easily owned by small farmers.

Therefore, a mini solar tunnel dryer was developed and evaluated for drying of pomegranate seeds. Further, the results were validated with different thin layer drying models.

Material and methods

The mini solar tunnel dryer consisted of A hemispherical cylinder-shapedtunnel (drying chamber)**,**UV protected Plastic Sheet (Solar heat collector) and drying trays (Garget al., 2000; Raju et al., 2013).

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Table 1. Design considerations

Sr. no.	Particular	Assumptions
1	Loading capacity	10 kg per batch
2	Initial moisture content (%wb & %db)	80 & 400
3	Final moisture content (%wb & %db)	10.7 & 12
4	Sunshine hour, h	8
5	Drying period required, h	18
6	Global solar radiation (I), ($W.m^{-2}$)	520
7	Dryer efficiency (%)	27
8	Collector material (cover)	UV polythene 200µm sheet
9	Density of air at ambient ($kg.m^{-3}$)	1.252
10	Height of chimney (H), m	0.35
11	Percentage area of mini solar tunnel dryer receiving solar radiation	65

In order to design a dryer, moisture removal is the prominent factor which needs to be determined. The moisture removed was calculated using Eq. (1).

$$M_w = M_d \frac{(m_i - m_f)}{100} \quad \text{.................. (1)}$$

Where, M_d = Mass of dry matter (kg), m_i = Initial moisture present (db%), M_w = Mass of water to be removed (kg) and m_f = Final moisture to be remained (db%).

Thereafter, the energy required to remove this water was calculated by the Eq. (2).

$$Q = M_d \times C_d \times (T_2 - T_1) + M \times C_p \times (T_2 - T_1) + M_w \times \lambda \text{.............. (2)}$$

Where, Q = Total energy required to dry the product (kJ), M_d = Mass of dry matter (kg), C_d = Specific heat of dry matter ($kJ.kg^{-1}K^{-1}$), T_1 = Ambient air temperature (°C), T_2 = Temperature inside the solar tunnel dryer (°C), M = Total initial mass of water (kg), C_p = Specific heat of water ($kJ.kg^{-1}K^{-1}$), λ = Latent heat of vaporization of water ($kJ.kg^{-1}$).

Further, energy required per hour for drying and drying rate were calculated using Eq. (3) and Eq. (4).

$$q = \frac{Q}{Drying\ Time} \quad \text{........................(3)}$$

$$k = \frac{M_w}{Drying\ Time} \quad \text{........................(4)}$$

Where, q = energy required per hour for drying and k = drying rate.

Collector area of solar tunnel dryer required for drying was calculated using Eq. (5).

$$A_C = \frac{q}{I \times \eta \times 0.65} \quad \text{...................... (5)}$$

Where,A_c = Area of the collector (m^2) and q = Power required to dry the product (kW)

Thus, based on the above design calculation the mini solar tunnel dryer (MSTD) was developed (Fig. 1).

Figure1. Developed mini solar tunnel dryer

Table 2. Specifications of Mini solar tunnel dryer

Sr. no	Dimensions	Value
1.	**Overall Dimensions**	
	Length	1.30 m
	Width	1.06 m
	Height of the Dryer	0.91 m (Straight 0.38 m & Radial 0.53 m)
2.	**Top Tray Size**	
	Length	1.6 m
	Width	0.6 m
3.	**Bottom Tray Size**	
	Length	1.3 m
	Width	0.81 m
4.	Height Of the Chimney	0.35 m
5.	Area of the Collector	3.9 m^2

Sample preparation

Fresh and clean mature pomegranates were selected. Peeling and separation of pomegranate seeds had been done to prepare the sample (Fig. 2). The samples were kept in the mini solar tunnel dryer and the weight loss corresponding to time, solar intensity, ambient temperature, wind velocity and relative humidity inside and outside of the system were recorded.

Figure 2. Dried pomegranate seeds (A) Drying of seeds in mini solar tunnel dryer, (B) Drying of seeds in sun drying

Drying characteristics

The drying mechanism depends on simultaneous heat and mass transfer phenomena and factors dominating each process determine the drying behavior of the product. The drying rates were computed from the experimental data and drying characteristics curves (moisture content (db) vs drying time, drying rate vs drying time) were plotted (Dubey et al., 2021). The moisture ratio (MR) of the sample were also computed based on the methodology suggested by Chakraverty(1988). The obtained values of MR were plotted against the drying time and its fitting for different thin layer drying models was validated(Yaldyz and Ertekyn, 2001).Various statistical parameters such as coefficient ofcorrelation (R^2), Error sum of square (SSE), and root meansquare of error (RMSE) values were found with the helpof same tool to decide the quality of fit.

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Table 3. Drying models (Thin layer) considered in the study for validation

Model	Equation	References
Newton	M.R = exp(-kt)	Agarwal *et al.* 1977
Henderson and Pabis	M.R = a exp(-kt)	Chinnman 1984
Page	M.R = $\exp(-kt^n)$	Onwude *et al.* 2016
Modified page	M.R = $\exp(-kt)^n$	Wang *et al.* 1978
Wang and Singh	M.R = $M_0 + at + bt^2$	Henderson & Perry 1976
Two terms	M.R = $a \exp(-K_1t) + b \exp(-K_2t)$	Kaseem 1998
Approximation of diffusion	M.R = a exp(-Kt) + (1-a) exp(-Kbt)	Basunia& Abe 2001

Drying efficiency (ŋ)

The drying efficiency of MSTD and OSD for pomegranate seeds was calculated by the Eq. (6).

$$\eta = \frac{m_w \times \lambda}{I_t \times A_c \times t} \times 100 \qquad \text{……………………..} (6)$$

Where,m_w = Wight of water evaporated (kg), λ= Latent heat of water vaporization ($J.kg^{-1}$), I_t = Insolation on collector surface ($W.m^{-2}$), A_c= Area of collector (m^2) and t= Drying time (s)

Results and discussion

The initial moisture content of pomegranate seeds was 406.33% (db). The drying readings were recorded during 9 AM to 5 PM at 30 min intervals. The ambient temperature, intensity of solar radiation, relative humidity and wind velocity varied from 20 to 33°C, 362.8 to 697.8 $W.m^{-2}$, 31 to 52% and 0.2 to 2.4 $m.s^{-1}$, respectively.

Drying characteristics of Pomegranate seeds in Mini Solar Tunnel Dryer (MSTD) and OSD

The average moisture content (%db) of Pomegranate seeds was reduced from 406.33 to 7.92% and 406.33 to 9.06% (db) in 26 h and 39 h in case of mini solar tunnel dryer (MSTD) and open sun drying (OSD) respectively. It was also observed that the moisture characteristics curve followed an exponential trend with coefficient of determination values (R^2) of 0.97 and 0.98 for MSTD and OSD, respectively (Fig. 3).

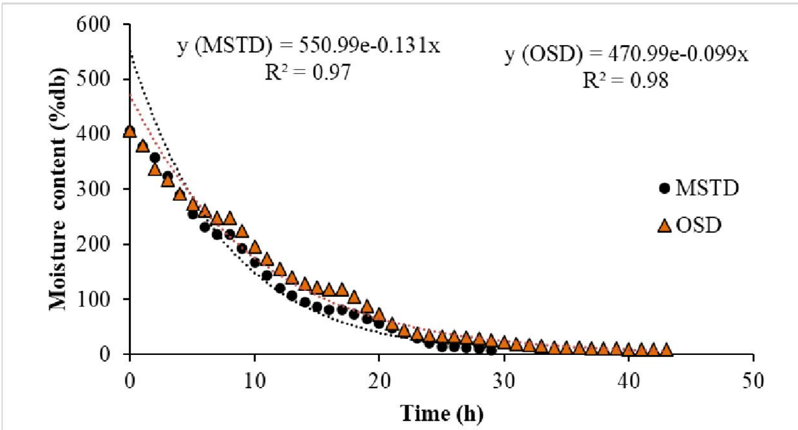

Figure3. Variation in moisture content (db%) with drying time in OSD and MSTD for pomegranate seeds

The drying rate of the pomegranate seeds varied from 0.583 to 0.037 and 0.709 to 0.014 g.min^{-1} per100 g of bone-dry matter in MSTD andOSD, respectively. The average drying rates were found to be 0.229 and 0.154 gm/100gm bone dry matter per min for MSTD and OSD, respectively (Fig. 4).

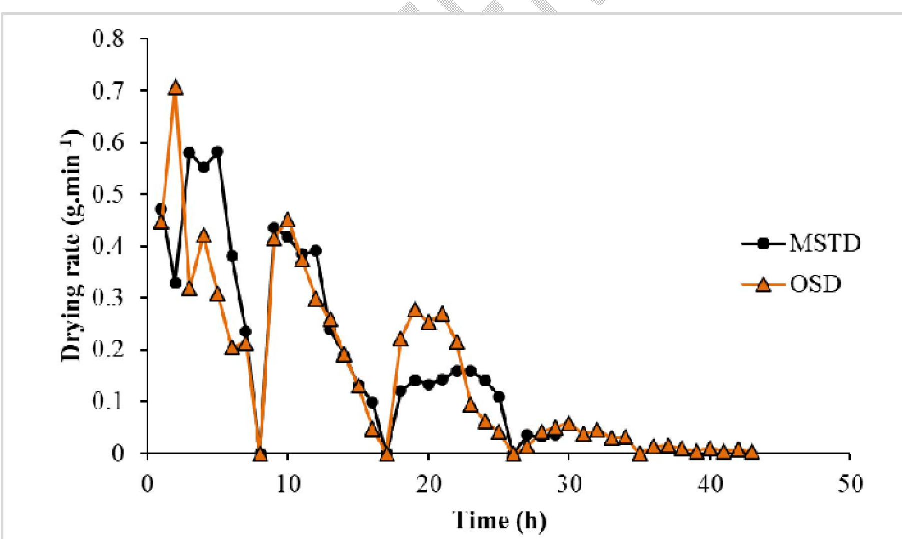

Figure4.Variation in the drying rate of pomegranate seeds in MSTD and OSD with drying time

Various coefficients of different models were determined using Origin pro software. The MR were validated for MSTD and OSD with these models and adequate models were selected based on coefficient of determination (R^2), error sum of square (SSE) and root mean square error (RMSE) (Table 4 and 5).

Table 4. Thin layer drying model coefficients and statistical parameters for OSD

Model name	**R^2**	**SSE**	**RMSE**	**K (h^{-1})**	**K_1**	**K_2**	**A**	**B**	**N**
Newton	0.98239	0.06487	0.03884	0.08535					
Henderson and Pabis	0.98411	0.05851	0.03732	0.08871			-1.04213		
Page	0.9912	0.03242	0.02778	0.05078					1.19309
Modified page	0.9912	0.03241	0.02778	0.08223					1.19545
Wang and Singh	0.98911	0.0401	0.0309				-0.0592	8.70E-4	
Two terms	0.98411	0.05851	0.03825		0.08871	0.08871	0.52107	0.52107	
Approximation of diffusion	0.99189	0.02986	0.02699	0.13877			-1.7842E11	1	

The approximation of diffusion model had highest R^2 value (0.99189) with minimum RMSE (0.02699), it illustrated that the model was most adequate for drying of pomegranate seeds under OSD. However, both Page and Modified page models also showed the R^2 value of 0.9912 with RMSE of 0.02778 (Table 4). Thus, these two models can also be considered for studying the drying behaviour of pomegranate seeds under OSD. Similar finding was also observed for MSTD asthe approximation of diffusion model had highest R^2 value (0.9943) with minimum RMSE (0.02334) followed by Page and Modified Page models (Table 5). Therefore, the curve fitting of these three models had been represented in (Fig. 5, A-F) for better comparative assessment of MR with time in case of OSD and MSTD (Sacilik et al., 2006).

Table 5. Thin layer drying model coefficients and statistical parameters for MSTD

Model name	**R^2**	**SSE**	**RMSE**	**K (h^{-1})**	**K_1**	**K_2**	**A**	**B**	**N**
Newton	0.98327	0.04464	0.03924	0.09998					
Henderson and Pabis	0.98748	0.0334	0.03454	0.10595			-1.06104		
Page	0.99425	0.01534	0.02341	0.05978					1.20805
Modified page	0.99425	0.01534	0.02341	0.09711					1.20834
Wang and Singh	0.99272	0.01941	0.02633				-0.07303	0.00137	
Two terms	0.98748	0.0334	0.03584		0.10594	0.10595	0.53052	0.53052	
Approximation of diffusion	0.9943	0.01522	0.02334	0.16779			-2.0267E11	1	

It can be concluded that approximation of diffusion model was best fit for prediction of drying behaviour of pomegranate seeds under OSD and MSTD. Thus, it can be further used for elucidation of the drying trend and predicting the time required for drying of pomegranate seeds in both the conditions (OSD and MSTD). This model is beneficial for optimising operational parameters and improving the drying system's performance.

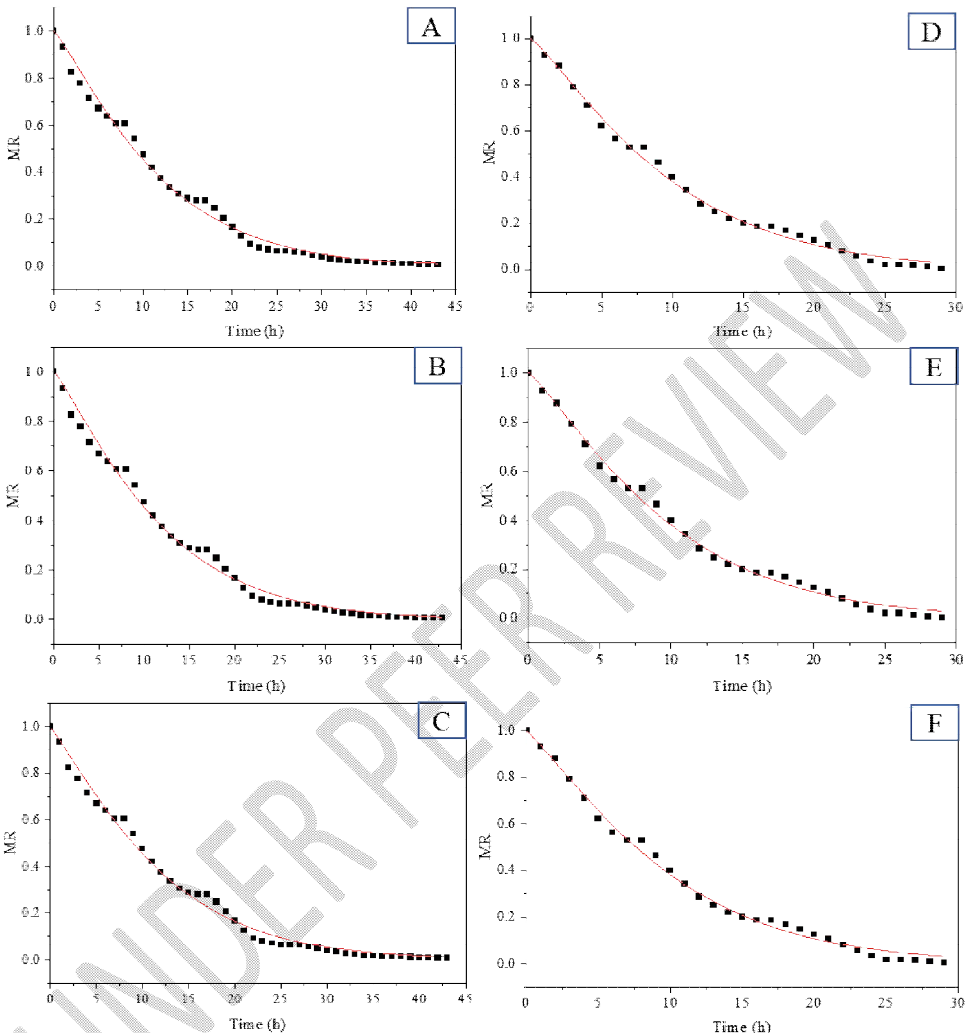

Figure 5.Curve fitting for different models inOSD and MSTD,
(A) OSD, Approximation of diffusion model (B) OSD, Page model (C)OSD,Modified Page model (D) MSTD, Approximation of diffusion model (E) MSTD, Page model (F) MSTD Modified Page model

Drying efficiency

Drying efficiency of MSTD and OSD based on experimental data was calculated by considering the total moisture evaporated associated with heat input and heat gain by product. The dryingefficiency was associated with total drying hours and heat input by solar energy.

The total drying hours, average moisture removed & average heat input for pomegranate seeds in MSTD were 26 h, 7.9 kg, 421 $W.m^{-2}$, respectively. Whereas, in case of OSDwere 43 h, 7.8 kg, 421 Wm^{-2}, respectively. It was revealed that the overall efficiency of pomegranate seeds dried in the mini solar tunnel dryer and OSD were 17.9 and 10.7 %, respectively. It was obvious that MSTD was significantly effective in drying of pomegranate seeds compared to OSD.

Economics of solar tunnel dryer for drying of Pomegranate Seeds

The economic feasibility of MSTD for the drying of pomegranate seeds was computed by considering the initial investment of the dryer, average repair and maintenance cost, cost of raw material and selling price of the material after drying (Table 6). The capacity of the dryer was 10 kg per batch.

Table 6.Economic analysis of solar tunnel dryer for different agricultural produce

S.N.	Description	Solar tunnel dryer
1	Initial investment (Rs)	6000
2	Cost of labour for drying (@120 $Rs.day^{-1}$) ($Rs.year^{-1}$)	7200
3	Operation and maintenance cost (Rs)	600
4	Cost of raw material (50 $Rs.kg^{-1}$)	500
5	Total cost of finished product (1500 $Rs.kg^{-1}$)	3000
6	B:C ratio	1.35
7	Payback period (year)	0.5

Conclusion

The developed dryer was effective in drying of pomegranate seeds compared to open sun drying. Seven different models were fitted in MR vs time curve to predict the drying behaviour of pomegranate seeds. The Approximation of Diffusion model was the best fit with R^2 value of 0.99189 and 0.9943 for MSTD and OSD, respectively. The dryer was significantly effective ($p<0.0001$) in terms of drying efficiency (17.9%) compare to OSD (10.7%). The dryer was economically feasible with benefit cost ratio and payback periods (year) of 1.35 and 0.5, respectively.Itcan be used for domestic purpose as well as bysmall farmers for drying of their products on field to increase their income and self-life of the product.

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