



Development of Mini Solar Tunnel Dryer and Validation of Thin Layer Drying Models for Pomegranate Seeds

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A portable MSTD (mini solar tunnel dryer) was developed and evaluated in terms of drying rate, MR (moisture ratio) and drying efficiency for drying of pomegranate seeds. The drying characteristic curves were also determined for drying in MSTD and OSD (open sun drying). In order to study the drying behaviour of pomegranate seeds in OSD and MSTD, 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 OSD and MSTD with R^2 value of 0.99189 and 0.9943, respectively. The MSTD was 7% more efficient in drying of pomegranate seeds compared to OSD without affecting the quality of seeds. The dryer can be used by the farmers as an alternative to sun drying for on field drying of their product without compromising the quality.

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1. INTRODUCTION

Pomegranate (*Punica granatum L.*) is an important fruit of tropical and subtropical regions. The edible parts of pomegranate fruit represent 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) [1]. Dried pomegranate seeds (anardana) find its utility as a condiment ayurvedic medicines in the treatment of dysentery, diarrhoea, stomach-ache, inflammations, hymenoleitidosis, dyspepsia, bronchitis and cardiac problem [2,3].

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 [4]. Drying represents 30 to 50% of the total costs of the product [5]. 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 that needs 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 OSD 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 MSTD can be used at domestic level for drying of fruits and vegetables. Further, the price of the MSTD may also be lower as compared to larger sizes of solar dryers. Thus, this can be easily owned by small farmers.

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

2. MATERIALS AND METHODS

The MSTD consisted of a hemispherical cylinder-shaped tunnel (drying chamber), UV protected Plastic Sheet (Solar heat collector) and drying trays [6,7]. The design considerations for the development of MSTD are given in Table 1 [8,9].

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).

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

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%).

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 200 μm sheet
9	Density of air at ambient ($kg.m^{-3}$)	1.252
10	Height of chimney (H), m	0.35
11	Percentage area of MSTD receiving solar radiation	65

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

$$Q = M_d \times C_d \times (T_2 - T_1) + M \times C_p \times (T_2 - T_1) + M_w \times \lambda \quad (2)$$

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

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

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

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).

$$A_c = \frac{q}{I \times \eta \times 0.65} \quad (5)$$

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 MSTD was developed (Fig. 1). The major dimensions of the system are presented in Table 2.

2.1 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 MSTD and the weight loss corresponding to time, solar intensity, ambient temperature, wind velocity and relative humidity inside and outside of the system were recorded.

2.2 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 [10]. The MR of the sample was also computed based on the methodology suggested by Chakraverty [11]. The obtained values of MR were plotted against the drying time and its fitting for different thin layer drying models was validated [12] (Table 3). Various statistical parameters such as coefficient of correlation (R^2), Error sum of square (SSE), and root mean square of error (RMSE) values were found with the help of same tool to decide the quality of fit.



Fig. 1. Developed MSTD

Table 2. Specifications of MSTD

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

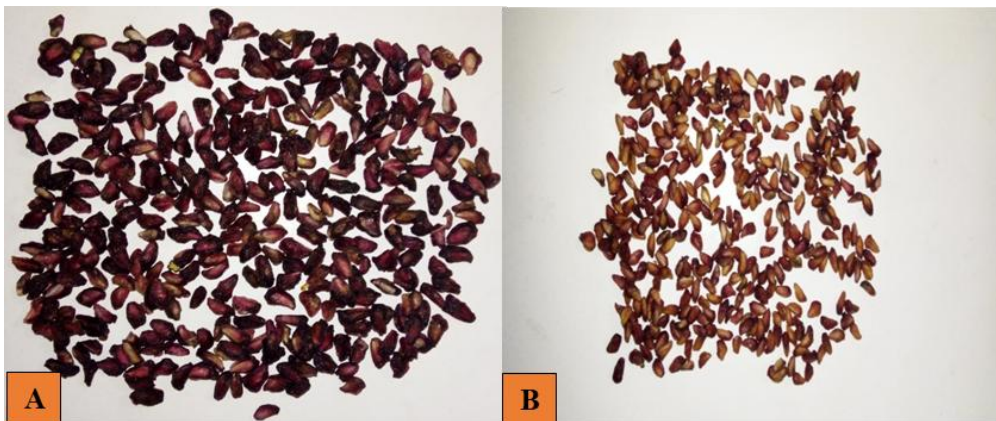


Fig. 2. Dried pomegranate seeds (A) drying of seeds in MSTD, (B) drying of seeds in sun drying

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

Model	Equation	References
Newton	M.R = exp(-kt)	Agarwal <i>et al.</i> 1977
Henderson and Pabis	M.R = a exp(-kt)	Chinnman 1984
Page	M.R = exp(-kt ⁿ)	Onwude <i>et al.</i> 2016
Modified page	M.R = exp(-kt) ⁿ	Wang <i>et al.</i> 1978
Wang and Singh	M.R = M ₀ + at + bt ²	Henderson & Perry 1976
Two terms	M.R = a exp(-K ₁ t) + b exp(-K ₂ t)	Kaseem 1998
Approximation of diffusion	M.R = a exp(-Kt) + (1-a) exp(-Kbt)	Basunia & Abe 2001

2.3 Drying Efficiency (η)

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

$$\eta = \frac{m_w \times \lambda}{I_t \times A_c \times t} \times 100 \quad (6)$$

Where, m_w = Weight 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 (m²) and t = Drying time (s)

3. RESULTS AND DISCUSSION

The initial moisture content of pomegranate seeds was 406.33% (db). The drying readings were recorded between 9 AM to 5 PM at 30 min intervals [13]. The ambient temperature, cabinet temperature, intensity of solar radiation, relative humidity and wind velocity varied from 20 to

33°C, 45 to 55°C 362.8 to 697.8 W.m⁻², 31 to 52% and 0.2 to 2.4 m.s⁻¹, respectively.

3.1 Drying Characteristics of Pomegranate Seeds in MSTD (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 MSTD and OSD respectively. It was also observed that the moisture characteristics curve followed an exponential trend with coefficient of determination values (R²) of 0.97 and 0.98 for MSTD and OSD, respectively (Fig. 3).

The drying rate of the pomegranate seeds varied from 0.583 to 0.037 and 0.709 to 0.014 g.min⁻¹ per 100 g of bone-dry matter in MSTD and OSD, 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).

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 (R²), error sum of square (SSE) and root mean square error (RMSE) (Table 4 and 5).

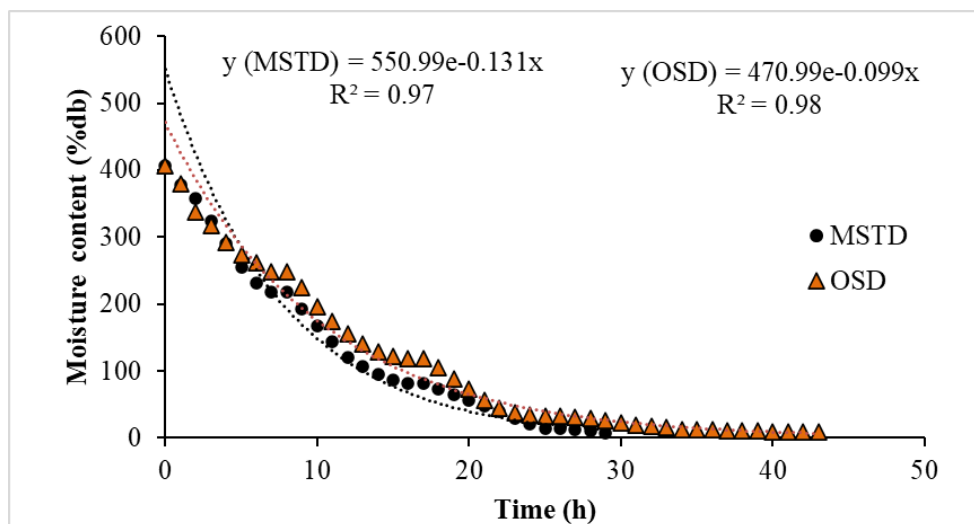


Fig. 3. Variation in moisture content (db%) with drying time in OSD and MSTD for pomegranate seeds

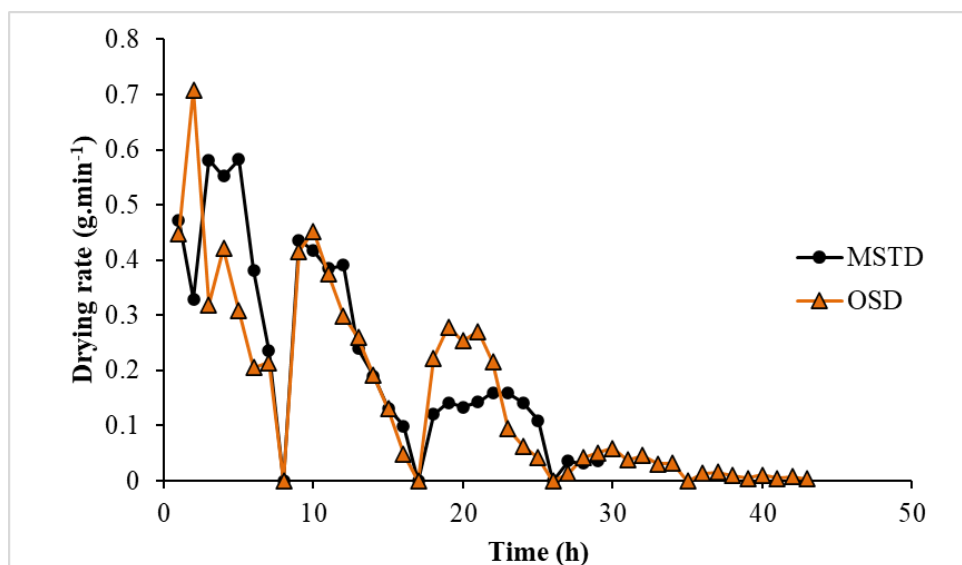


Fig. 4. Variation in the drying rate of pomegranate seeds in MSTD and OSD with drying time

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	

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	

The approximation of diffusion model had highest R² 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 R² 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 as the approximation of diffusion model had highest R² 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 [14].

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.

3.2 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 drying efficiency was associated with total drying hours and heat input by solar energy. The total drying hours, average moisture removed and average heat input for pomegranate seeds in MSTD were 26 h, 7.9 kg, 421 W.m⁻², respectively. Whereas, in case of OSD were 43 h, 7.8 kg, 421 Wm⁻², respectively. It was revealed that the overall efficiency of pomegranate seeds dried in the MSTD 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.

3.3 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.

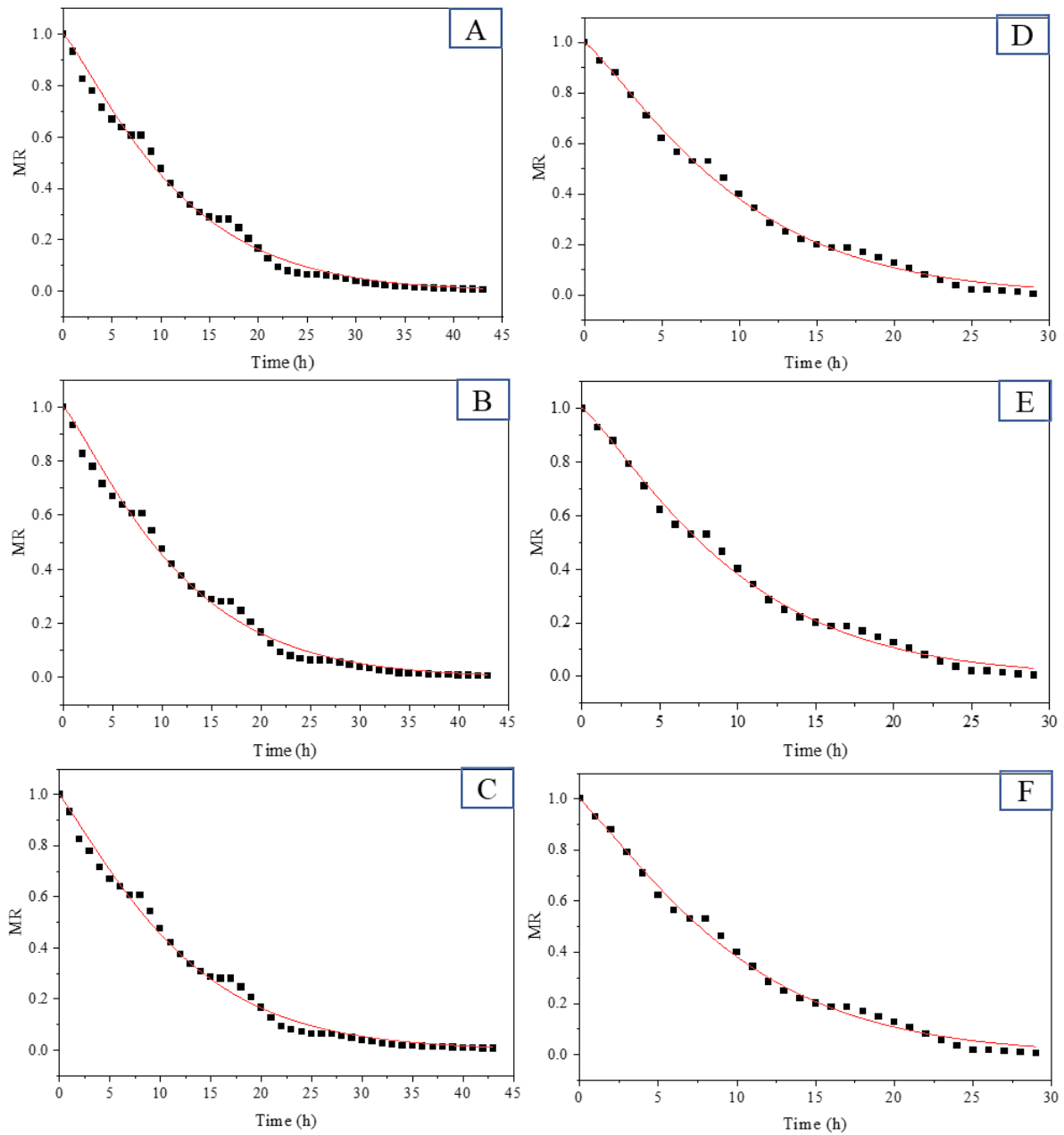


Fig. 5. Curve fitting for different models in OSD and MSTD

(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

Table 6. Economic analysis of MSTD 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

4. CONCLUSION

The developed dryer was effective in drying of pomegranate seeds compared to OSD. 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%) compared to OSD (10.7%). The dryer was economically feasible with benefit cost ratio and payback periods (year) of 1.35 and 0.5, respectively. It can be used for domestic purpose as well as by small farmers for drying of their products on field to increase their income and self-life of the product.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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