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THIN LAYER DRYING OF SLICED SQUASH BY FORCED CONVECTION

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ABSTRACT In this study, a laboratory dryer was used for thin layer drying of sliced squash at different drying conditions. The effect of slice thickness, drying air temperature and velocity were investigated. The head and the end parts were removed and then the squash was sliced. The moisture ratio changes during the drying time were calculated with initial moisture content and weight changes during the process. The moisture ratio values were applied to the 12 different thin layer drying models, namely Newton, Page, Henderson and Pabis, logarithmic, two-term, two-term exponential, Wang and Singh, Thompson, diffusion approximation, Verma et al., modified Henderson and Pabis and Midilli et al. These moisture ratio models were evaluated according to the statistical criteria of root mean square error, reduced chi-square and modeling efficiency. According to the results, sliced pumpkin was dried in about 1.5 hours at slice thickness of 6.4 mm and 5.5 hours at slice thickness of 25.4 mm for constant drying air temperature of 80°C and velocity of 2.0 m/s. The drying time was 1.5 hours at drying air temperature of 80°C and more then 8.0 hours at temperature of 40°C at slice thickness of 6.4 mm and drying air velocity of 2.0 m/s. While the drying time was about 4.0 hours at drying air velocity of 1.0 m/s, it was decreased to 1.5 hours at the velocity of 2.0 m/s at constant slice thickness of 6.4 mm and drying air temperature of 80°C. The Page model was chosen to explain thin layer drying behaviour of sliced squash satisfactorily.

Keywords: drying, squash, thin layer drying models.

INTRODUCTION Many different types of vegetables have been produced in Turkey because of its suitable climate. Squashes generally refer to four species of the genus *Cucurbita* native to Mexico and Central America. The zucchini or courgette is a small summer squash. Along with some other squashes, it belongs to the species *Cucurbita pepo*. This squash can be yellow, green or light green, and generally have a similar shape to a ridged cucumber. When used for food, they are usually picked when under 20 cm in length and the seeds are soft and immature. Unlike cucumber, squash are usually served cooked. It can be prepared using a variety of cooking techniques, including steamed, boiled, grilled, stuffed and baked, barbecued, fried, or incorporated in other recipes such as *soufflés*. The squash is low in calories (approximately 15 food calories per 100 g fresh squash) and contains useful amounts of folate (24 mcg/100 g), potassium (280 mg/100 g) and vitamin A (115 mcg/100 g). 1/2 cup of squash also contains 19% of the recommended amount of manganese (Annoymous, 2010). The squash production in Turkey is 279 451 tons in 2008 (TUIK, 2010).

Drying of agricultural products has always been of great importance to the preservation of food by human beings. Although sun-drying is still the most common method in most tropical and subtropical countries, being unprotected from rain, windborne dirt and dust, and infestation by insects, rodents and other animals, the quality of food is seriously degraded such that it sometimes becomes inedible. The resulting loss of food quality in the dried products may have adverse economic effects on domestic and international markets (Szulmayer, 1971; Mühlbauer, 1986; Ertekin, 2000). Improvements in product quality and process applications. Such improvements could increase the current level of acceptance of dehydrated foods in the market (Akpinar et al., 2003a).Dried products have almost unlimited shelf life in proper packages and substantially lower transportation, handling and storage costs compared to products of other preservation methos (Sharma et al., 2004).

Convection drying is considered a simultaneous heat and mass transfer process where water is transferred by diffusion from inside the food material to the air-food interface and from the interface to the air stream by convection. Mathematical models have proved to be very useful design and analysis of these transfer processes during drying. All parameters used by simulation models are directly related to the drying conditions. Furthermore the drying conditions, as directly related to the drying time, are affecting the energy demands (Babalis and Belessiotis, 2004). This process is adventageous because full scale experimentation of different products and configurations of drying system is very time consuming and also costly (Hossain and Bala, 2002).

Mathematical models of the drying processes are used for designing new or improving existing drying systems or even for the control of the drying process. All parameters used by these models are directly related to the drying conditions, i.e. temperature and velocity of the drying medium inside the dryer (Simal et al., 1997). Thin layer drying equations are used to estimate drying times of several products and also to generalise drying curves. Several investigators have proposed numerous mathematical models for thin layer drying of many agricultural products. For example, barberries (Aghbashlo et al., 2009), spinach (Ozkan et al., 2007), apricot (Bozkir, 2006), banana (Dandamrongrak et al., 2002), red chilli (Hossain et al., 2007), rosehip fruit (Marquez et al., 2006), tomato (Sacilik and Elicin, 2006), yam slices (Sobukola et al., 2008) and fig (Xanthopoulos et al., 2007).

The aim of this study were to study the effect of slice thickness, drying air temperature and drying air velocity on drying characteristics of squash and to investigate the applicability of several thin layer drying models and to fit drying data into most suitable model by appropriate statistical analyse procedures for squash.

MATERIALS AND METHODS

The laboratory dryer The drying experiments were carried out using the laboratory dryer in the Department of Farm Machinery, Faculty of Agriculture, University of Akdeniz, Antalya, Turkey, which could be regulated to any desired drying air temperature and velocity with high accuracy.

It consists of an airflow control unit, a heating and heating control unit, an electrical fan, measurement sensors and the drying chamber. The air flow control unit regulate the velocity of the drying air flowing through the drying chamber in diameter of 30 cm. The product were spread in thin layer to the sieve. The desired drying air temperature was attained by resistances and controlled by the heating control unit. The air passed from heating unit and heated to the desired temperature and channeled to the drying chamber. Desired drying air temperature and velocity were measured directly under the drying chamber. Weighing of samples inside the drying chamber was done manually through an electronic balance.

Drying Material The squash were obtained from the local market in Antalya, Turkey, and good quality squashes were selected and used in the experiments.

The Experiments The drying samples were cut into different slice thicknesses of 6.4, 12.7 and 25.4 mm. Thin layers of squash slices were dried between 40 and 80^{o}C with 10^{o}C intervals using the laboratory dryer. Drying air velocity was fixed 1.0 and 2.0 m/s. Experiments at slice thickness of 25.4 mm and drying air velocity of 1.0 m/s at all drying air temperatures were not applied because of very long drying times. The head and back of squash were peeled then sliced. Moisture content determination was done by drying the samples at 70^{o}C until the weight became constant (Yagcioglu, 1999)]. The air velocity was measured by hot wire digital anemometer with the accuracy of ±0.1m/s, temperature by T-type thermocouple with the accuracy of ±1^{o}C, weight by digital balance with the capacity of 2000 g and accuracy of ±0.01 g.

Mathematical modelling of drying curves In thin layer drying models, the rate of change in material moisture content in the falling rate drying period is proportional to the instantaneous difference between material moisture content and the expected material moisture content when it comes into equilibrium with the drying air. It is assumed that the material layer is thin enough or the air velocity is high so that the conditions of the drying air (humidity and temperature) are kept constant throughout the material.

The drying curves obtained were fitted with twelve different moisture ratio models (Table 1). However, the moisture ratio (MR) was simplified to M/M_o instead of the $(M-M_e)/(M_o-M_e)$ (Diamente and Munro, 1991; Menges and Ertekin, 2006; Ertekin and Yaldiz, 2004).

The reduced chi-square, root mean square error (RMSE) and modeling efficiency (EF) were used as the primary criterion to select the best equation to account for variation in the drying curves of the dried samples (Ozdemir and Devres, 1999; Sarsavadia et al., 1999; Ertekin and Yaldiz, 2004). These statistical values can be calculated as follows;

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{i,pre} - MR_{i,\exp}\right)^2}{N}} \tag{2}$$

$$EF = \frac{\sum_{i=1}^{n}\left(MR_{i,\exp} - MR_{i,\exp_{mean}}\right)^2 - \sum_{i=1}^{n}\left(MR_{i,pre} - MR_{i,\exp}\right)^2}{\sum_{i=1}^{n}\left(MR_{i,\exp} - MR_{i,\exp_{mean}}\right)^2} \qquad (3)$$

where $MR_{exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observations, n is the number of constants in the drying model and $MR_{exp\ mean}$ is the mean value of experimental moisture ratio.

Table 1. Mathematical models applied to the drying curves

Model	Name of Model	References
$MR=\exp(-kt)$	Newton	Abalone et al., 2006
$MR=\exp(-kt^n)$	Page	Shi et al., 2008
$MR=a\exp(-kt)$	Henderson and Papis	Doymaz, 2009
$MR=a\exp(-kt)+c$	Logarithmic	Kirmaci et al., 2008
$MR=a\exp(-kt)+b\exp(-k_1t)$	Two Term	Sacilik and Elicin, 2006
$MR=a\exp(-kt)+(1-a)\exp(-kat)$	Two Term exponential	Akpinar et al., 2003
$MR=1+at+bt^2$	Wang and Sing	Al-Mahasneh et al., 2007
$t=a\ln(MR)+b(\ln(MR))^2$	Thompson	Mohapatra et al., 2005
$MR=a\exp(-kt)+(1-a)\exp(-kbt)$	Diffision approximation	Celma et al., 2009
$MR=a\exp(-kt)+(1-a)\exp(-gt)$	Verma et al.	Dadali et al., 2007
$MR=a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	Modified Henderson and Papis	Wang et al., 2007
$MR=a\exp(-kt^n)+bt$	Midilli et al.	Marquez et al., 2006

Results and Discussions In order to determine the effect of slice thickness on drying time, thickness of 0.635, 1.27 and 2.54 cm were compared at constant drying air temperature and velocity. While drying time was 1.5 hours at slice thickness of 6.4 mm, it was 5.5 hours at 25.4 mm at drying air temperature of 80 °C and velocity of 2.0 m/s (Figure 1). At the same slice thicknesses, drying time increased to 7.0 hours and 28.0 hours at drying air temperature of 40 °C and velocity of 2.0 m/s, respectively. So, increasing slice thickness increased the drying time (Ertekin and Yaldiz, 2004; Diamente and Munro, 1991; Heybeli and Ertekin, 2008; Bhuyan and Prasad, 1990).

When the effect of drying air temperature on drying time were examined at different drying air velocities and slice thicknesses, drying time increased by decreasing drying air temperatures (Figure 2). Drying time was 1.5 hours at drying air temperature of 80°C and increased to 8.5 hours at 40°C at slice thickness of 6.4 mm and drying air velocity of 2.0 m/s. These values were 5.5 and 30.0 hours at slice thickness of 25.4 mm and drying air velocity of 2.0 m/s, respectively. Drying rate was reached its maximum values at higher drying air temperatures at all slice thickness and drying air velocity conditions (Yagcioglu et al., 1999; Sarsavadia et al., 1999; Sun and Woods, 1994; Mohamed et al., 2004).

When we examine the effect of drying air velocity on drying time, it decreases by increasing drying air velocity at all examined drying air temperatures and slice

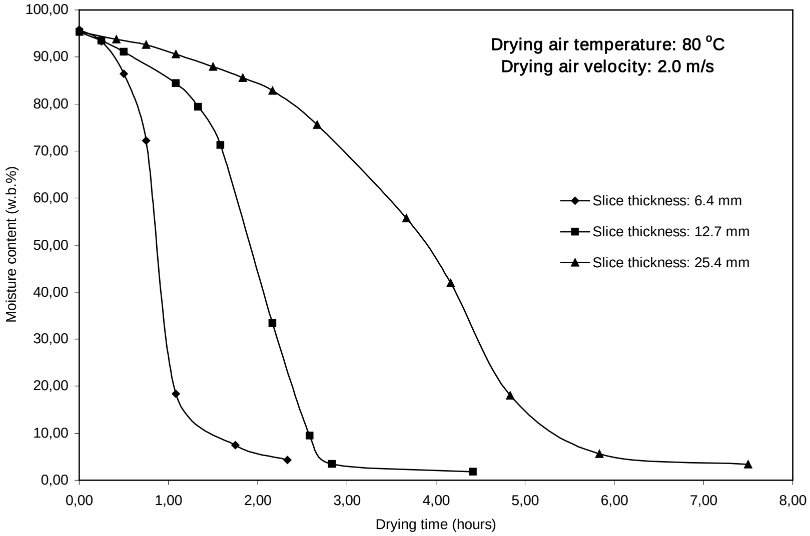

Figure 1. Effect of slice thickness on drying time.

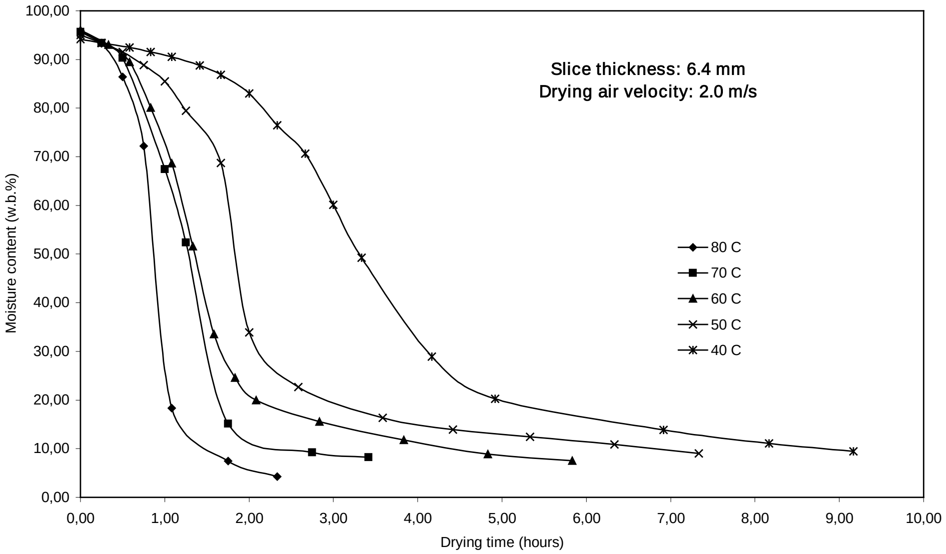

Figure 2. Effect of drying air temperature on drying time.

thicknesses (Figure 3). The drying time at drying air temperature of 80 °C and slice thickness of 6.4 mm was 4.0 hours at slice thickness of 1.0 m/s and 1.5 hours at 2.0 m/s, respectively. These values were 2.5 and 7.0 hours at same drying air temperature and slice thickness of 12.7 mm. While it was 7.0 hours at velocity of 1.0 m/s, it decreased to 5.5 hours at velocity of 2.0 m/s, respectively, at drying air temperature of 60 °C and slice thickness of 6.4 mm (Ertekin et al., 2001; Sarsavadia et al., 1999; Guarte, 1996).

The thin layer drying models were compared according to their statistical results such as RMSE, chi-square and EF. As can be seen from the statistical analysis results, generally low RMSE and chi-square and high EF values are found for the drying models. Nevertheless, the results have shown that the lowest values of RMSE and chi-square and the highest values of EF could be obtained with Page model. This model was used for sliced squash and could be shown as; $MR= \exp(-k\, t^{n})$

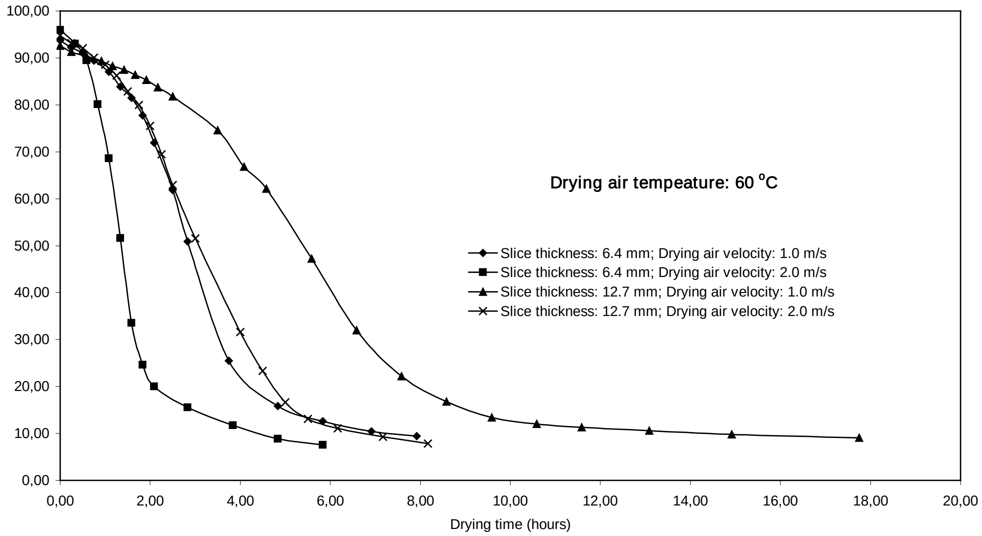

Figure 3. Effect of drying air velocity on drying time.

While the RMSE changed between 0.017489 and 0.084738, the chi-square between 0.000326 and 0.004734 and the EF between 0.948606 and 0.997177 for all drying conditions of sliced squash (Table 2). This model could be used satisfactorily to predict the experimental moisture ratio values such as used for amaranth seed (Abalone et al., 2006), apple pomace (Sun et al., 2007), apricot (Bozkir, 2006), tomato (Doymaz, 2007) and chestnut (Singh et al., 2008).

It can be seen from Figure 4 and 5 that, this model was in good agreement with the experimental results at different drying conditions. This means that, Page model is valid for sliced squash at slice thicknesses of 6.4, 2.7 and 25.4 mm, drying air temperatures of 30 to 80 ^{o}C and velocities of 1.0 and 2.0 m/s.

CONCLUSIONS Thin layer drying experiments were conducted under controlled conditions of drying air temperature and velocity. Thus, the drying behaviour of squash were investigated at different slice thicknesses. In order to explain the drying behaviour of squash at these conditions, 12 different thin layer drying model were compared according to their RMSE, chi-square and EF values. According to the results, increasing slice thickness raised the drying time. Drying time decreased by increasing drying air temperature and velocity. The drying process of sliced squash took place in the falling rate drying period. Among twelve thin layer drying models, the Page model could be used to predict the moisture ratio values during the drying process with high capability.

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Table 2. Statistical analyses of slice squash.

Slice thickness (mm)	Drying air temperature (^oC)	Drying air velocity (m/s)	k (min^{-1})	n	EF	Reduced chi-square	RMSE
6.4	80	2.0	1.126903	4.450314	0.989996	0.002306	0.040584
12.7	80	2.0	0.055660	3.846423	0.996398	0.000701	0.023683
25.4	80	2.0	0.011625	3.052556	0.992513	0.001098	0.030485
6.4	80	1.0	0.230767	2.407016	0.978079	0.003873	0.056293
12.7	80	1.0	0.032574	2.450167	0.986072	0.002022	0.041859
6.4	70	2.0	0.334867	2.935582	0.984195	0.002993	0.047377
12.7	70	2.0	0.088851	2.146289	0.982697	0.002896	0.048673
25.4	70	2.0	0.008041	2.284121	0.983168	0.002031	0.043426
6.4	70	1.0	0.067358	2.652494	0.995637	0.000792	0.026206
12.7	70	1.0	0.037133	2.169226	0.994037	0.000814	0.026794
6.4	60	2.0	0.327285	2.169641	0.967013	0.004734	0.063291
12.7	60	2.0	0.064605	2.000011	0.994228	0.000788	0.026545
25.4	60	2.0	0.012444	1.900928	0.986668	0.001552	0.038101
6.4	60	1.0	0.066452	2.060593	0.983848	0.002197	0.043841
12.7	60	1.0	0.024401	1.921892	0.986185	0.002003	0.042766
6.4	50	2.0	0.157244	2.110920	0.948606	0.008377	0.084738
12.7	50	2.0	0.008212	2.134254	0.993758	0.000786	0.026728
25.4	50	2.0	0.004365	2.017432	0.989348	0.001489	0.037282
6.4	50	1.0	0.051399	1.788540	0.995364	0.000619	0.023269
12.7	50	1.0	0.017904	2.331683	0.992262	0.001054	0.030602
6.4	40	2.0	0.029054	2.486987	0.977124	0.002985	0.051319
12.7	40	2.0	0.021008	2.085475	0.995690	0.000565	0.022492
25.4	40	2.0	0.004686	1.876374	0.997177	0.000326	0.017489
6.4	40	1.0	0.024223	1.867159	0.991712	0.001113	0.030682
12.7	40	1.0	0.008290	2.223166	0.979728	0.002758	0.049950

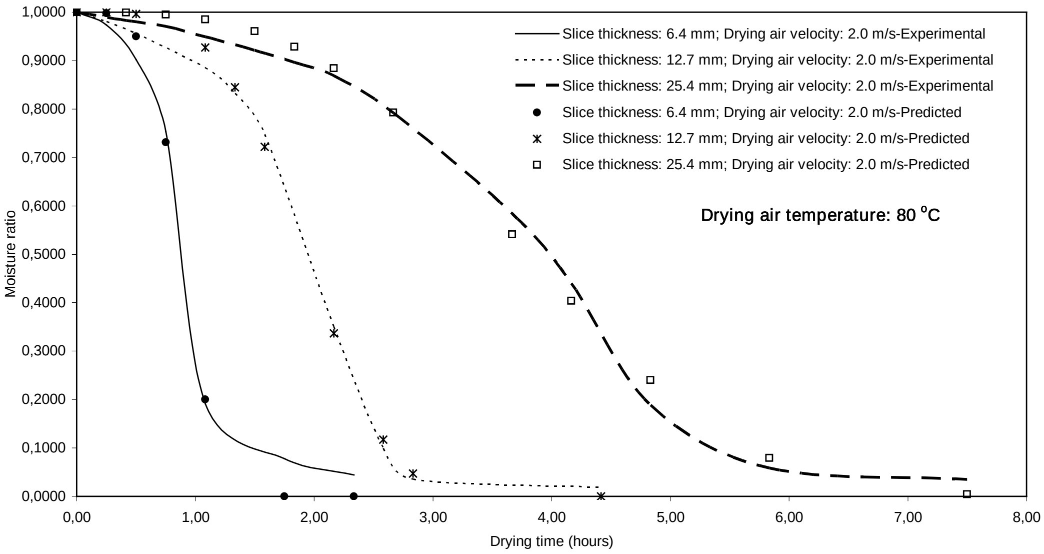

Figure 4. Experimental and predicted moisture ratio changes versus drying time.

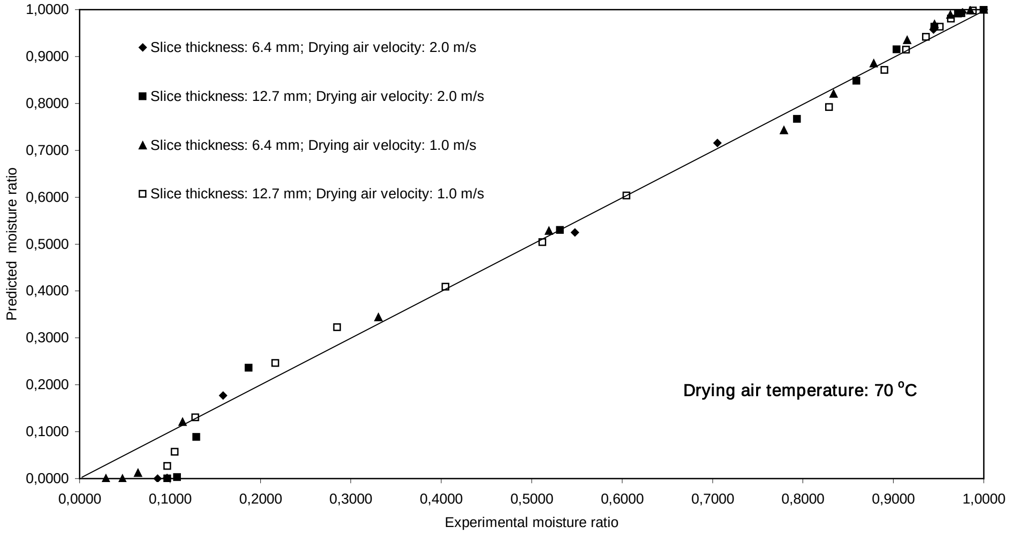

Figure 5. Experimental versus predicted moisture ratio values.

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