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Drying Kinetics of Muscat Grapes in a Solar Drier with Evacuated Tube Collector

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ABSTRACT

A solar drier assisted with evacuated tube collector is designed and developed to study and examine the drying Kinetics of muscat grapes in Thanjavur, Tamilnadu, India. During the drying period, temperature at various places, relative humidity, wind velocity and mass of the sample are measured on hourly basis. The outlet temperature of the collector and temperature within the chamber varies from 74-130 ºC and 50-87 ºC respectively, while the ambient temperature ranges from 29.5-33.2 ºC. Solar insulation recorded during these days ranges from 155.6-1115 W/m^2. The designed drier takes 14 hours to reduce the moisture content of muscat grapes from 78% to 9.5% (wb) to ensure safe storage. It is found that the whole drying process exists in falling-rate period. The maximum drier efficiency for muscat grapes is found to be 29.92% during the drying period. Six thin-layer drying models have been used to fit the experimental moisture ratio obtained for muscat grapes by nonlinear regression analysis using IBM SPSS 20 statistical package. According to the results, Page model shows a good fit with highest correlation (R^2 = 0.991), lowest reduced chi-square (χ^2 = 0.001) and lowest root mean square error (RMSE = 0.0297).

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1. INTRODUCTION

To lead an active and healthy life, man needs adequate food and balanced nutritive diet. Vitamins, minerals and fiber are present abundantly in vegetables and fruits. Fruits and vegetables also provide antioxidants which prevent many chronic diseases.

Most of the fruits and vegetables are seasonal. Seasonal surplus and short shelf-life make these food crops perish [1]. About 20 - 30% of the total production is lost due to spoilage at various post harvest stages. Food spoilage is caused due to action of microbes such as yeast, bacteria, molds and enzymes [2].

Food preservation can reduce spoilage due to seasonal surplus and can yield high market value during demand [3]. Drying is one of the preservation technique used to prolong shelf-life of the food crop and make it available throughout the year [4].

Natural sun drying is the traditional method used in most of the tropical and subtropical countries [5]. But, the quality of the food crop dried is found to be poor due to contamination by dust, birds, rodents and insects [6, 7]. Uncontrolled drying, uncertainty in weather conditions such as rain, large area and long duration required for drying, and high labor cost are also reasons that limit the use of natural sun drying [8].

To overcome the disadvantages of natural sun drying, several attempts have been done to develop mechanical driers in the recent years. Most of these mechanical driers require electricity or fossil fuel for operation and the energy reserves are depleting at a rapid rate. These driers also cause pollution. Solar energy is abundantly available and is also inexhaustible. Mechanical driers which use sun as the source of energy can solve the problem [9]. Solar driers are practically attractive, as they are pollutant-free and eco-friendly.

Different types of solar driers are available to dry agricultural products [10-15]. To absorb solar radiation, solar driers require solar collectors. A Flat Plate Collector (FPC) consists of an absorber plate covered with a glass top to trap solar radiation. Literature

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survey reveals that most of the solar driers are assisted with FPC [16-18]. Evacuated Tube Collector (ETC) could be a good alternative to FPC to trap solar radiation. ETC is made of two glass tubes – an inner tube and an outer tube. The inner tube is coated using selective coating and the space between the two tubes is evacuated. As the space between the two tubes is evacuated, there is no heat loss due to convection, and conduction. This enhances the efficiency of the collector [19] and hence the performance of the drier could be relatively better than the FPC assisted solar drier. Only very few attempts have been made and reported in designing solar driers with ETC so far [20-22].

Several studies have been reported on drying behavior of various agricultural products such as rice [8], cassava [23], ginger [24], chilli pepper [25], pork strips [26], prickly pear cladode [27], tomato [28], onion [29] and grapes [30-33]. Also from the literature, it is noted that no study has been carried out on drying kinetics of grapes in solar driers with ETC.

Grape (*Vitis Vinifera*) is one of the world's largest fruit crop. The world production of grapes is presently 65.5 billion tons per year out of which India accounts for 1.2 million tons per year [34]. It contains flavonoids, which have antioxidant effect. Grape is used for preventing high blood pressure, heart attack and stroke. Drying of grapes produces raisins. It is a natural coolant that helps in easy bowel movement. It is also useful in the treatment of excessive thirst, fever, vomiting and intestinal disorders.

The present study aims in designing a novel solar drier assisted with ETC and evaluating the drying kinetics of muscat grapes experimentally in Thanjavur, Tamilnadu, India, and thus to select a suitable model of solar drying curve.

2. MATERIAL AND METHOD

2. 1. Experimental Set-up The four essential parts of the designed solar drier are evacuated tube collector, drying chamber, chimney and blower. The schematic view and photograph of the novel solar drier are presented in Figures 1 and 2 respectively.

The size of the drying chamber is chosen such that the design parameter (ratio of surface area to volume) is greater than 3. The drying chamber is made of stainless steel and is insulated with rock wool on all the sides to prevent heat loss. The drying chamber consists of three aluminum perforated trays to load the sample.

The novel idea in the design of the solar drier is that it is assisted with evacuated tube collectors. Six evacuated tube collectors are used in this drier. Based on the latitude of Thanjavur district (10º 45" N) the collector is placed at an angle of 25º 45" (latitude + 15º) facing south in order to trap optimum solar radiation the whole day. As the space between the inner and outer tube is evacuated, heat loss is minimized to a greater extent. Ethylene Propylene Diene Monomer (EPDM) rubber hose is used to connect the drying chamber to ETC.

Air is blown into the collector with the help of a centrifugal blower. The flow of air can be adjusted and controlled with the help of the regulator attached in the blower. On the top of the drying chamber, a 100 cm height chimney is fitted for the moist air to escape from the chamber. It also increases the flow of air inside the chamber under the convective principle of hot air rising up [35].

2. 2. Measuring Instruments and Devices A digital anemometer MASTECH MS 6252B is used to measure relative humidity, ambient temperature and wind velocity. A solar power meter TES 1333 is used to measure the solar insulation of the location. Six RTD (Resistance Temperature Detector) PT100 sensors connected to a temperature controller and display unit is used to measure temperature of the evacuated tube collector (inlet and outlet), temperature of the trays placed in the chamber and the temperature of the moist air escaping through the chimney. Samples are weighed using a D-sonic digital electronic balance (±0.1g accuracy) [35].

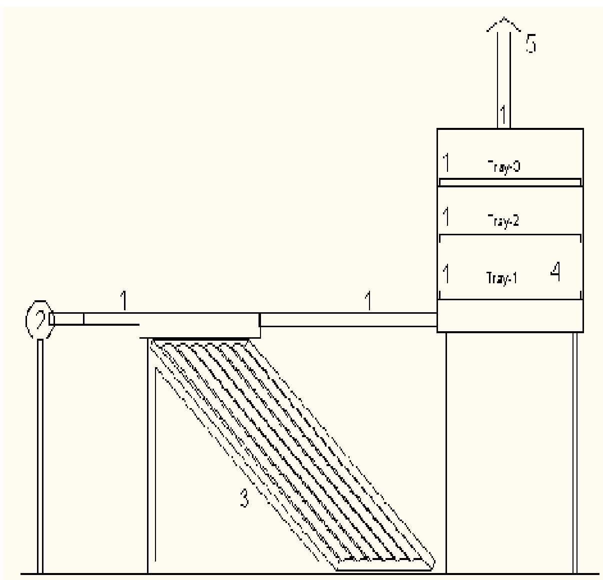

Figure 1. Design of the solar drier with ETC (1, temperature sensor; 2, blower; 3, evacuated tube collector; 4, drying chamber; 5, chimney)

Figure 2. Photograph of the solar drier consisting of drying chamber, evacuated tube collector, blower motor and chimney

TABLE 1. Various Mathematical Models for solar drying of high moisture content crops

Model Name	Model Equation	Reference
Newton	MR = exp (-kt)	[11], [20], [25-30]
Page	MR = exp ($-kt^n$)	[11], [20], [25-30]
Henderson & Pabis	MR = a exp (-kt)	[11], [20], [25-30]
Logarithmic	MR = a exp (-kt) + c	[11], [20], [25-28]
Two term exponential	MR = a e^{-kt} + (1–a) e^{-kat}	[11], [25-28], [30]
Wang & Singh	MR = 1 +at + bt^2	[19], [25-28], [30]

2. 3. Experimental Procedure The initial moisture content of muscat grapes is determined by placing 200 g of fresh sample in hot air oven at a temperature of 105ºC for 24 hours. For solar drying, fresh grapes are taken and uniformly spread on all the three trays in the drying chamber. The air is carried into the collector as soon as the blower is switched on and gets heated up rapidly and is made to pass into the drying chamber where the samples are placed. The hot air helps in the removal of moisture present in the sample and the sample starts to lose its mass. The wind velocity, relative humidity, ambient temperature, temperature of the evacuated tube collector at inlet and outlet, temperature of the three trays, temperature of the chimney and the mass of the sample are measured on hourly basis from 9.00 a.m. to 5.00 p.m. until the sample acquires constant mass which is its equilibrium moisture content [35].

2. 4. Drying Kinetics Thin layer drying model is generally used to understand the drying characteristics of agricultural products. The amount of moisture content by wet basis (M_{wb}) is determined using the formula [25]

$$M_{wb} = \frac{m_i - m_f}{m_i} \qquad (1)$$

where, m_i and m_f are the initial and final mass of the sample, respectively.
The moisture ratio (MR) is defined as follows [11, 20, 25-28]:

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad (2)$$

where, M, M_0 and M_e are moisture content at any time, initial moisture content and equilibrium moisture content, respectively. But M_e is found to be negligible. So, the moisture ratio is simplified as follows [11, 20]:

$$MR = \frac{M}{M_0} \qquad (3)$$

Mathematical models that are extensively suitable for high moisture content crops such as grapes are listed in Table 1. Here, t is the drying time and k, n, a, b and c are drying constants. The experimental moisture ratio (MR) obtained using Equation (3) is fitted to these six mathematical models. The coefficients and the constants of the model are predicted by non-linear regression analysis using IBM SPSS 20 statistical package. The formula used to predict correlation coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) are as follows [11, 25-28]:

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i}-\overline{MR}_{\exp})(MR_{pre,i}-\overline{MR}_{pre})}{\sqrt{\sum_{i=1}^{N}(MR_{exp,i}-\overline{MR}_{\exp})^2\sum_{i=1}^{N}(MR_{pre,i}-\overline{MR}_{pre})^2}} \qquad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i}-MR_{pre,i})^2}{N-n} \qquad (5)$$

$$RMSE = \left[\frac{1}{N}\left(\Sigma_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right)\right]^{\frac{1}{2}} \qquad (6)$$

where, $MR_{exp,i}$ and $MR_{pre,i}$ are the ith experimental and predicted moisture ratio respectively, $\overline{MR}_{\exp}$ and $\overline{MR}_{pre}$ the mean of sum of $MR_{exp,i}$ and $MR_{pre,i}$ respectively, N and n the number of observations and number of constants in the equation, respectively. The model that has highest correlation coefficient (R^2), lowest reduced chi-square (χ^2) and lowest root mean square error (RMSE) value is considered as the most relevant model for drying [11, 20, 25-30]. The efficiency of the drier which determines the performance of the drying method is given by

$$\text{Efficiency of the drier} = \frac{\Delta W\, L}{I\, A\, t} \qquad (7)$$

where ΔW is the mass of water evaporated in time 't' hours, L latent heat of vaporization of water, I the total hourly solar insolation on the collector, A the effective area of the collector and t the time required for drying.

3. RESULTS AND DISCUSSION

Solar drying experiments were carried out in the designed solar drier assisted with ETC in Thanjavur, Tamilnadu, India during the months of March and April 2013. Each day, the experiments were performed from 9.00 a.m. to 5.00 p.m.

Hourly variation of solar insulation recorded during day 1 of the experiment with respect to time of the day is shown in Figure 3. It is noticed that solar insulation is maximum between 12.00 noon to 2.00 p.m. due to clear sky, and the performance of the drier is also observed to be more during this period. Solar insulation is found to vary from 155.6 W/m^2 to 1115 W/m^2 during the entire experimental study. The ambient temperature varied from 29.5ºC to 33.2ºC, while the temperature of the drying chamber varied from 50ºC to 87ºC and outlet temperature of ETC varied from 74ºC to 130ºC. As the outlet temperature of ETC and temperature inside the drying chamber are very high compared to ambient temperature, it is evident that the performance of the collector increases the drying rate.

The initial moisture content is measured using hot air oven and is found to be 78% (wb). The designed drier takes 14 hours to reach a final moisture content of 9.5% (wb) considered as safe moisture content whereas it has taken 5.5 days to dry Sultana grapes from initial moisture content of 78% to a final moisture content of 15% in the indirect and mixed mode solar drier designed by Zomorodian [30]. The photograph of the muscat grapes before and after drying in the designed drier is shown in Figures 4a and 4b, respectively.

The relative humidity of the drying chamber when compared to the ambient relative humidity is found to be less during the experimental study. This is attributed to the rise in temperature and continuous air flow inside the chamber. Similar results were observed by Fadhel et al. [31].

It is observed that rate of drying decreases with increase in drying time and decrease in moisture content. During the whole drying process, constant-rate drying period is not observed. Hence, it is apparent that falling-rate period alone exists.

The moisture ratio obtained through the experiment is applied to six different mathematical models. Using IBM SPSS 20 statistical package the model constants and coefficients are predicted. The results of the thin layer model fitted for muscat grape is listed in Table 2.

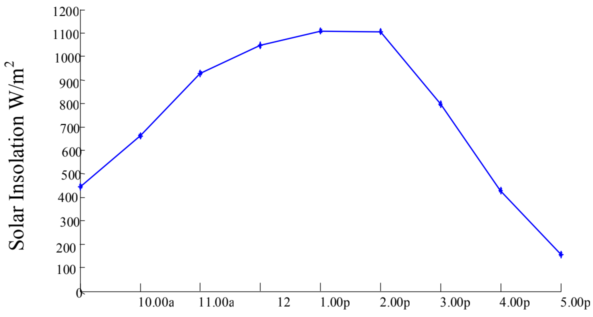

Figure 3. Hourly variation of Solar Insolation for day 1 (28/03/2013) of the experiment with time

Figure 4a. Photograph of muscat grapes before drying

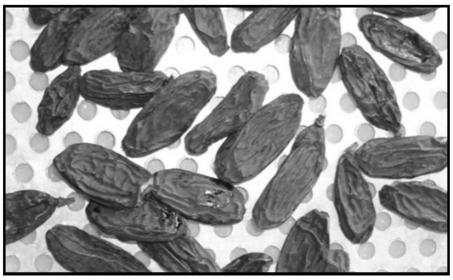

Figure 4b. Photograph of muscat grapes after drying in the designed solar drier

TABLE 2. Results of the thin layer drying models fitted for muscat grapes

Model	Constant(s)	R^2	χ^2	RMSE
Newton	k = 0.112	0.934	0.007	0.0816
Page	k = 0.031 n = 1.562	0.991	0.001	0.0297
Henderson & Pabis	k = 0.142 a = 1.281	0.984	0.002	0.0398
Logarithmic	k = 0.116 a = 1.311 c =-0.084	0.990	0.001	0.0316
Two term exponential	k =-0.005 a =-2.425	0.862	0.015	0.1178
Wang & Singh	a =-0.083 b = 0.002	0.973	0.003	0.0523

Variation of moisture ratio with respect to drying time obtained for the six mathematical models is shown in Figure 5. The model that has highest R^2, lowest reduced χ^2 and lowest RMSE is considered as best describing model. The results show that Page model could adequately illustrate the solar drying of muscat grapes with R^2 of 0.991, reduced χ^2 of 0.001 and RMSE of 0.0297. The constants of the accepted Page model for the designed drier with ETC is k = 0.031 and n = 1.562. The experimental and predicted moisture ratio value is compared for Page model and is shown in Figure 6. As the predicted value fits the experimental value at almost all the points, it is evident that Page model is the most relevant model to illustrate the drying kinetics of muscat grapes in the designed solar drier.

Zomorodian et al. have also reported that Page model is the most suitable model to illustrate the drying kinetics of Sultana grape [30]. Fadhel et al., Songehai et al. and Hany et al. have also reported that Page model is the best suitable mathematical model to illustrate the drying kinetics of chilli pepper [25], pork strips [26] and onion slices [29] respectively.

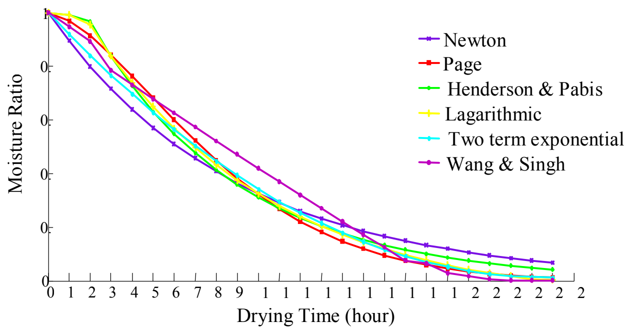

Figure 5. Predicted Moisture ratio Vs. drying time for six mathematical models

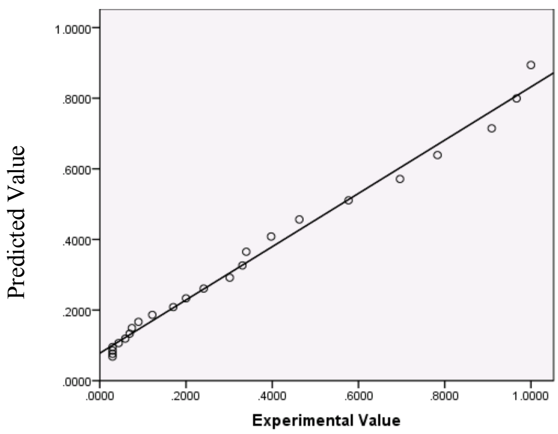

Figure 6. Experimental vs. Predicted Moisture Ratio value for Page model

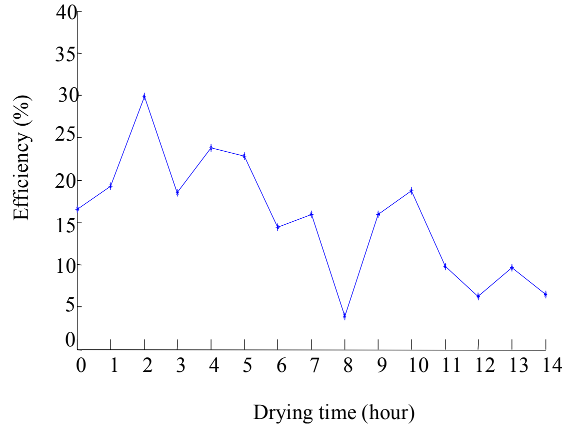

Figure 7. Hourly variation of drying efficiency with drying time

Figure 7 shows the hourly variation of efficiency of the drier with respect to drying time. The maximum efficiency observed during this period is 29.92%. Hourly value of drying efficiency is found to be more during morning hours than afternoon hours due to increase in drying air temperature inside the chamber which results in increase in moisture loss. Whereas the hourly value of drying efficiency is found to be decreasing from day to day due to the surface hardening of the sample. The surface hardening of the sample is because the moisture on the surface of the sample is removed first and later the moisture from the inner surface of the product moves to the surface of the product.

4. CONCLUSION

A novel solar drier assisted with ETC has been designed and the drying kinetics of muscat grapes is evaluated experimentally in Thanjavur, Tamilnadu, India. This drier can be used to dry various agricultural products. The designed drier is pollutant-free and eco-friendly as it utilizes energy from the sun. The other advantage of the drier is that it makes use of ETC which can perform better even in poor weather conditions. The drying process can be controlled in the designed drier. Quality of the solar dried muscat grapes is high in terms of colour, appearance and texture. It is found to be better for export which helps the farmers to yield high market value. The drier can be used to dry samples on large scale. Also, the drying period of the sample is reduced considerably. The drying time is found to be much shorter than the other solar driers introduced in literature. The whole drying process exists in falling-rate period. Based on the results, the Page model is the most relevant model that could illustrate the drying behavior of muscat grapes compared to other six mathematical models due to highest R^2 value and lowest reduced χ^2 and RMSE value. The results of the drying kinetics of muscat grapes in the designed drier are in good agreement with the results already available in literature.

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Moisture Ratio

چکیده

یک خشک کن خورشیدی به کمک کلکتور لوله‌ای تخلیه طراحی و ساخته شد تا سینتیک خشک کردن انگور مسقط در شهر تان‌ژاوور در ایالت تامیل‌نادو،هندوستان مطالعه و بررسی شود. در طول مدت خشک کردن، دما، رطوبت نسبی، سرعت باد و حجم نمونه در مکان‌های مختلف در هر ساعت روز اندازه گیری شد. در حالی که دمای محیط در محدوده‌ی ۲۹/۵ و ^{o}C ۳۳/۲ است، دمای خروجی کلکتور و دمای داخل محفظه به ترتیب بین ^{o}C۱۳۰-۷٤ و ^{o}C ۸۷-۵۰ تغییر می‌کند. شدت تابش خورشیدی ثبت شده در این روزها در محدوده‌ی ۱۵۵/٦–۱۱۱۵ W/m^2 بوده است. با این خشک کن ١٤ ساعت طول می کشد تا رطوبت انگور مسقط به منظور اطمینان از ذخیره سازی امن، از ٪۷۸ به ٪۹/۵ (بر مبنای انگور تر) کاهش یابد. نشان داده شد که کل فرایند خشک کردن با آهنگ نزولی صورت می‌گیرد. نتایج نشان دادند که حداکثر بازده خشک‌کن برای انگور مسقط در طول دوره خشک کردن، ۲۹/۹۲ ٪ است. از شش مدل خشک کردن تجربی لایه نازک برای انگور مسقط توسط تجزیه و تحلیل رگرسیون غیرخطی با استفاده از بسته‌ی آماری IBM SPSS 20 استفاده شده است. با توجه به نتایج، صفحه مدل مناسب‌ترین انطباق با بالاترین همبستگی ($R^2 = 0.991$) ، پایین‌ترین مجذور کای کاهش‌یافته (χ^2=0.001) و کمترین ریشه میانگین مربع خطاها. (RMSE = 0.0297) را نشان می دهد.

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