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# Modelling the thin-layer drying of horse chestnut (*Aesculus indica*)

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**Abstract**
The impact of temperature and relative humidity during hot-air drying on the drying kinetics and some quality attributes of Horse chestnut seed slices was studied. Experiments were conducted at 50, 60 and 70ºC. Experimental drying curves showed that drying process took place in the falling rate period. The moisture transfer from slices was described using various mathematical models. In all the cases, models were evaluated for goodness of fit by comparing their respective $R^2$, $\chi^2$, and RMSE parameters. Comparison of statistical parameters led to conclusion that Diffusion model showed a better quality of fit and presents dehydration characteristics in a better way to obtain drying curves than any other model. Slices dried at 60°C had better color and efficient drying and thus 60°C temperature has been adjudged as the best condition of drying for good quality Horse Chestnut flour.

**Keywords:** horse chestnut slices, tray dryer, temperature, drying, moisture

## Introduction

Indian Horse Chestnut (*Aesculus indica*.) is a large deciduous tree locally known as '*Handun*', usually growing in hilly areas and is a fast growing tree species most often used for reforestation (Rafiq *et al.*, 2016) [18]. The seeds, fruits and roots have been traditionally used against rheumatism, skin diseases and vein complications (Majeed *et al.*, 2010) [15] and thus play a significant role for medicinal purposes. The plant contains saponins, flavonoids, glycosides and fatty oils (Zhang *et al.*, 2010) [31]. Seeds are edible, like in Himachal Pradesh, are consumed in the form of porridge (*Halwa*) and *chapattis* (Rajasekaran and Singh, 2009) [19]. As food, these have also been consumed by various tribes of North and North Eastern India during famine times. These are also used for gruel purposes (Singh *et al.*, 1976) [22].

Drying is probably the oldest, favoured and the most important preservation method for fruits and vegetables practiced by human. It improves the food stability by reducing the water and microbial activity and minimizing physical and chemical changes during storage (Doymaz, 2012) [10].

Nowadays, dehydration is regarded not only as a preservation process, but also as a method for increasing value-added foods and it is one of the important unit operations used in formulating a functional food product. Selecting appropriate control parameters can lead to higher yield from the point of view of operational and capital investment and produce a high quality final product (Di Scala *et al.*, 2011 and Lopez *et al.*, 2013) [8, 14]. The drying kinetics of food is a complex phenomenon and its mathematical modelling is crucial for optimizing the process parameters and predicting the drying behavior. Many empirical and semi-empirical models have been used to describe the drying process of which thin-layer drying models have been widely used (Singh and Pandey, 2012) [25]. The drying process being one of the vital industrial operations utilizes nearly 10–25% energy used during process manufacturing (Mujumdar and Passos, 2000) [17]. During drying process, drying kinetics is greatly influenced by material dimensions and air temperature (Kiranoudis *et al.*, 1997) [12]. Besides this, drying may also affect color, taste and lead to loss of nutrients due to high temperature exposure.

Different mathematical drying models described the drying behaviour, process optimization and efficient drier design (Singh *et al.*, 2008) [24]. Drying of Horse Chestnut is important for the development of flour and to achieve longer shelf stable products. Thus, the objective of this study was to investigate the effect of air-drying temperature (50, 60 and 70ºC) on drying kinetics and surface color attributes of Horse Chestnut slices during convective dehydration.

## Material and methods

### Materials

The Horse Chestnut seeds were harvested during October, 2015 (15-20ºC temperature and 35-40% relative humidity) from trees located in Anantnag area of Jammu & Kashmir, India and then washed with water to remove impurities.

### Preparation of sample

The outer shell of seeds was removed manually while the inner cotyledons were sliced and the diameter of the fresh slices was measured using a digital caliper (Mitutoyo Corp., Japan) and an average value of 30 measurements was recorded (4 ± 0.4 mm). The moisture content of the fresh slices was immediately determined according to the AOAC (1990) method and found to be 55 ± 0.5 g water per 100 g sample on wet basis.

## Methods
### Drying experiments
The Horse Chestnut slices were spread uniformly in a thin layer within stainless steel trays of size 40cm x 40cm with a load of 100 g (approximately, 0.625 Kg/ $m^2$). The drying process was carried out in a convective dryer (M/s. Balaji Enterprises, Saharanpur, India) at the mentioned air temperatures and constant air velocity 1.5 m/s and ambient relative humidity (40%).

The dryer was switched on 30 min before drying experiments to achieve steady-state conditions. The sample under drying was weighed at regular time intervals (15 min) during the drying process using a digital balance, with an accuracy of 0.01 g. A tray with the sample was taken out from the oven, weighed and placed back into the drying chamber. The weighing process took about 10 seconds. Drying was continued until the equilibrium moisture content was reached, and a constant weight of the samples was registered (Vega-Galvez *et al.*, 2012) [10]. The drying experiments were conducted in triplicates and the average of the moisture ratio at each value was used for drawing drying curves (Doymaz, 2012) [10]. The dried samples were kept in sealed polypropylene bags and stored at 4ºC until further analysis. Experiments were performed at 50, 60 and 70°C and the drying kinetics for convective drying was determined on mass loss basis from the slices.

### Instrumental surface color measurement
The color of fresh and dried Horse Chestnut slices was measured using Color Flex Spectrocolorimeter (Hunter Lab Colorimeter D-25, Hunter Associates Laboratory, Ruston, USA). Color was expressed by CIE L*(whiteness or brightness), a*(redness or greenness), and b*(yellowness or blueness) coordinates. Measurements were replicated five times and the results were averaged. The total color difference (ΔE) was calculated by equation (Chen and Martynenko, 2013) [3] where $L_0$, $a_0$, and $b_0$ are the control values for fresh slices.

$$\Delta E = \sqrt{(L - L_o)^2 + (a - a_o)^2 + (b - b_o)^2}$$

### Mathematical modelling of drying curves
Drying process was not constant during all the experiments of this study. The main driving force for dehydration of product is considered to be diffusion (Doymaz, 2004). Drying of a material mainly occurs at falling rate period of the process during which rate of diffusion is directly proportional to the surface area and concentration gradient. The moisture content of Horse Chestnut slices at time "t" can be transformed to moisture ratio (MR) using the following Page's equation (Sharaf-Eldeen *et al.*, 1979) [20].

$$MR = \frac{M - M_e}{M_i - M_e} \quad (1)$$

Where,

M = moisture content on dry weight basis at time t,

$M_i$ = initial moisture content on dry weight basis,

$M_e$ = equilibrium moisture content (EMC) on dry weight basis.

The drying data obtained were fitted to six thin-layer drying models that are detailed in Table (1) using the nonlinear least squares regression analysis.

### Calculation of the effective moisture diffusion and activation energy
It has been accepted that the drying characteristics of biological products in the falling rate period can be described by using Fick's diffusion equation. To evaluate the dependence of the effective diffusivity on the temperature, an Arrhenius-type equation (Eq. 2) was used, from which the activation energy ($E_a$) was determined (Xiao *et al.*, 2010) [30]:

$$k = k_o \exp(-E_a / RT) \quad (2)$$

Where $E_a$ is the activation energy of the moisture diffusion (KJ/mol), ($k_o$) is the diffusivity value for an infinite moisture content ($m^2$/s), (R) is the universal gas constant (KJ/mol K), and (T) is the drying air temperature (˚K).

### Statistical Evaluation
All the drying experiments performed at different drying temperatures were replicated thrice. Regression analysis was performed using the Statistica software package version 7 (Stat Soft Inc., OK, USA). The determination of correlation coefficient ($R^2$) is one of the primary criteria for selecting the best model to describe the drying curves of the dehydrated samples. In addition to $R^2$, reduced chi-square ($\chi^2$) and Root Mean Square Error (RMSE) was used to determine the quality of the fit and calculated as below:

$$RMSE = \sum_{i=1}^{N} \sqrt{\frac{(MR_{Experimental\ Value} - MR_{Predicted\ Value})^2}{N}}$$

$$\chi^2 = \sum_{i=1}^{N} \frac{(MR_{Experimental\ Value} - MR_{Predicted\ Value})^2}{(N - n)}$$

The significant differences were obtained by a one-way analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT) ($P < 0.05$).

## Results and Discussion
### Effect of temperature on moisture ratio
Figure (1) showed the experimental drying curves of the employing air temperatures. All curves showed a clear exponential tendency with moisture content decreasing as the drying air temperature increased. An increase in drying air temperature was accompanied by a decrease in drying time from 435 min (50 ºC), 390 min (60 ºC) to 325 min at 70 ºC to achieve the equilibrium moisture content. These results well agree with those reported in previous studies for drying on sweet potato slices (Singh *et al.*, 2006) [23], jujube slices (Chen *et al.*, 2015) [4], and sour cherries (Wojdylo *et al.*, 2014) [29] drying.

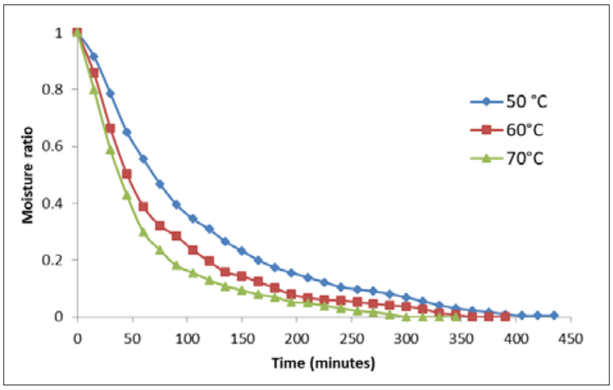


**Fig 1**: Experimental drying curves for Horse Chestnut slices samples at different air-drying temperatures.

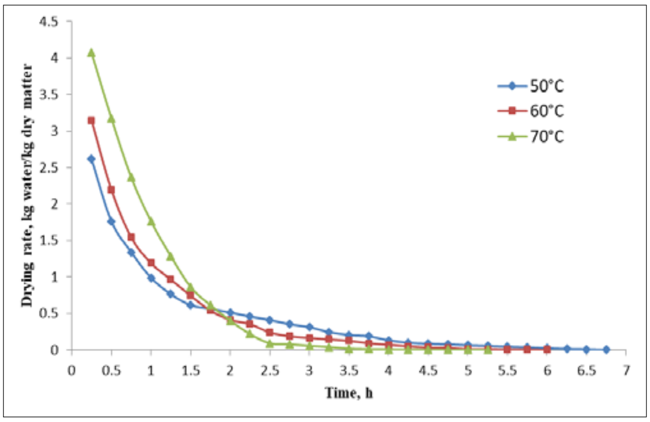


**Fig 2:** Effect of temperature on drying rate of Horse Chestnut slices

## Drying rate

The relation between the drying rate of Horse Chestnut slices and the moisture content (dry basis) is shown in Figure (2) for various drying air temperatures. It was clear that the drying rate decreased continuously with decreasing the moisture content during drying process. The drying rate was rapid during the initial period but it became very slow at the last stages of the drying process. It was mainly because the thin-layer of slices could not provide a constant supply of water during the drying process (Shi *et al.* 2008) [21]. As shown in Figure (2) there was no constant drying rate period and the drying process took only in the falling rate period. The drying rate decreased due to water linkage and falling drying rate period occurred after 30 min. It can be noticed from the curves that the drying temperature had a significant effect on the drying rate. This showed that diffusion is the dominant physical mechanism governing moisture movement in the samples and explaining the use of the empirical models presented in Table (1) (Doymaz, 2012; Lopez *et al.*, 2013 and Vega-Galvez *et al.*, 2014) [10, 14, 28].

## Drying model

The moisture content data obtained at different air temperatures were converted to dimensionless moisture ratio and then fitted to six thin-layer drying models (Table 1) and the average values (n= 3) of the kinetic and empirical parameters obtained for all proposed models are summarized in Table (2). It was found that parameter k for the proposed models increased with drying air temperature. It may be assumed that the constant would be directly proportional to temperature. Table (2) showed also the results of the statistical tests ($R^2$, $\chi^2$ and RMSE) used to analyze the goodness of fit of proposed models. The best model describing the thin-layer drying characteristics of Horse Chestnut slices was the diffusion model.

$$MR = a\ \mathrm{exp}^{(-kt)} + (1-a)\ \mathrm{exp}^{(-kbt)} \qquad (3)$$

**Table 1:** Thin-layer models applied to the Horse Chestnut slices drying curves

| S. No. | Model Name | Model Equation | References |
|---|---|---|---|
| 1 | Newton | MR = exp(-kt) | Demir *et al.* (2004) |
| 2 | Modified page | MR = exp $(-kt)^2$ | Demir *et al.* (2007) |
| 3 | Wang and Singh | MR = $at^2 + bt + 1$ | Mohapatra *et al.* (2005) |
| 4 | Two-term | MR = a $\exp^{(-kt)}$ + b $\exp^{(-gt)}$ | Ertekin *et al.* (2004) |
| 5 | Two-term exponential | MR = a $\exp^{(-kt)}$ + (1-a) $\exp^{(-kat)}$ | Akpinar (2006) [1] |
| 6 | Diffusion | MR = a $\exp^{(-kt)}$ + (1-a) $\exp^{(-kbt)}$ | Cihan *et al.* (2007) |

a, b, k, n are empirical constants in drying models; (t) is the drying time (min); (MR) is the moisture ratio

**Table 2:** Values of the kinetic and empirical parameters and results of statistical analysis on the modelling of moisture ratio and drying time for Horse Chestnut slices at different air temperatures

| Model | Temp. (°C) | $R^2$ | $\chi^2$ | RMSE | k | a | b |
|---|---|---|---|---|---|---|---|
| Newton | 50 | 0.98738 | 0.00085 | 0.02866 | 0.009337 | - | - |
| | 60 | 0.98375 | 0.00093 | 0.03002 | 0.013646 | - | - |
| | 70 | 0.99393 | 0.00033 | 0.01784 | 0.017815 | - | - |
| Modified Page | 50 | 0.98738 | 0.00085 | 0.02866 | 0.004669 | - | - |
| | 60 | 0.98375 | 0.00093 | 0.03002 | 0.006823 | - | - |
| | 70 | 0.99393 | 0.00033 | 0.01784 | 0.008907 | - | - |
| Wang and Singh | 50 | 0.90196 | 0.00677 | 0.07989 | - | -0.005801 | 0.000008 |
| | 60 | 0.72456 | 0.01621 | 0.12362 | - | -0.006490 | 0.000010 |
| | 70 | 0.56340 | 0.02430 | 0.15137 | - | -0.006850 | 0.000010 |
| Two term exponential | 50 | 0.98738 | 0.00087 | 0.02866 | 0.0093 | -20.8025 | - |
| | 60 | 0.98375 | 0.00096 | 0.03002 | 0.01365 | 11.60968 | - |
| | 70 | 0.99393 | 0.00034 | 0.01784 | 0.01781 | -8.62951 | - |
| Two term | 50 | 0.98739 | 0.00090 | 0.02865 | 0.0094 | -14.2104 | 15.2138 |
| | 60 | 0.98380 | 0.00098 | 0.02998 | 0.0135 | -12.7309 | 13.7235 |
| | 70 | 0.99394 | 0.00035 | 0.01783 | 0.01787 | 7.38138 | -6.37866 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Diffusion | 50 | 0.99731 | 0.0001 | 0.01323 | 0.010134 | 0.986466 | -0.270998 |
| | 60 | 0.99711 | 0.00018 | 0.0126 | 0.015124 | 0.972168 | -0.055726 |
| | 70 | 0.99702 | 0.00017 | 0.01251 | 0.020338 | 0.918015 | 0.246141 |

a, b, k, n are empirical constants in drying models

**Effect of temperature variables on drying characteristics**

The drying rates were higher in the beginning of the drying process and later decreased with decrease of moisture under all the conditions of convective dehydration. The reason for reduction of drying rate might be due to reduction in porosity of the material due to shrinkage with the advancement of drying process, and this shrinkage increased the resistance to movement of water leading to further fall in drying rates. The drying rate curves for convective dehydration indicated that the drying process occurred mainly in falling rate drying period. This may be due to that, drying the samples at high temperature, increased heating energy which increases the activity of water molecules leading to higher moisture diffusion (Xiao *et al.*, 2010) [30]. The drying time was reduced significantly with increased temperature. The rate constant (k) which is a measure of the drying rate, increased (0.010134–0.020338$h^{-1}$) with the drying air temperature (T).

The activation energy (Ea) was determined by plotting the natural logarithm of K values versus the reciprocal of drying temperature (1/ T). The activation energy for the convective drying of Horse Chestnut slices is 32.117 kJ $mol^{-1}$ similar to those reported for different fruits and vegetables such as 30.46 – 35.57 KJ/ mol for strawberry (Lee and Hsieh, 2008) [13], 31.57 kJ $mol^{-1}$ for water chestnut (Singh *et al.*, 2008) [24] and 30.64 – 43.26 KJ/ mol for persimmon (Doymaz, 2012) [10]. The high value of activation energy for Horse Chestnut slices might be due to presence of high initial moisture content and thus more thermal energy would be required to remove high amount of water from the slices.

The dependence of the rate constant on drying air temperatures were verified from the graph plotted between drying rate constant against drying temperature that showed a linear relationship (Fig. 3).

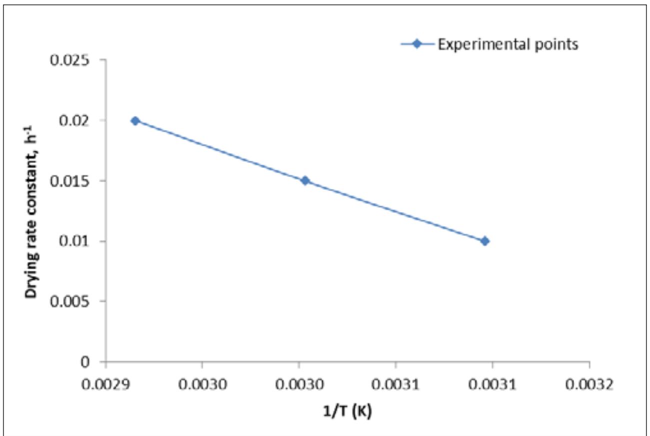


**Fig 3:** Temperature dependence of drying rate constant of Horse Chestnut slices

**Effect of temperature on Surface color attributes**

The effect of drying air temperature and time on the mean color attributes of Horse Chestnut slices are shown in Table (3). The measured values of lightness ($L_0$), redness ($a_0$) and yellowness ($b_0$) at different drying temperatures of slices were ranged 94.12 to 87.15, 3.2 to 4.83 and 11.97 to 15.23, respectively. Drying temperature and drying time affect significantly the color characteristics of Horse Chestnut slices. The increase in a* value indicated of the enzymatic or/ and non-enzymatic reactions (Vega-Galvez *et al*., 2009) [26]. Fruits dried at higher temperature (70 ºC) tended to have higher values of yellowness (b*) that those dried at lower temperature (60 ºC). The effect of drying air temperature and time on total color difference (ΔE) of Horse Chestnut slices are also shown in Table (3). The highest ΔE value was observed at 70 ºC compared with the rest of the treatments ($p< 0.05$). This may be due to the effect of the high temperature and presence of air on some heat-sensitive components such as proteins and carbohydrates led to non-enzymatic browning reactions, destruction of pigments (β-carotene) and auto-oxidation reactions involving phenolic compounds and the formation of iron-phenol complexes (Vega-Galvez *et al.*, 2009) [26]. Drying of slices at 60ºC could be considered optimum for obtaining a high quality product with less required drying time and color change. Singh *et al.* (2008) [24] has reported 70ºC as the best temperature for drying of water chestnut slices while 50ºC was the most suitable drying temperature for good quality of sweet potato slices (Singh *et al*., 2006) [23].

**Table 3:** Color parameters of Horse Chestnut slices at different temperatures

| Color | 50°C | 60°C | 70°C |
|---|---|---|---|
| L | 94.12±2.34$^{a}$ | 92.07±2.15$^{b}$ | 87.15±1.98$^{c}$ |
| a | 3.20±0.62$^{b}$ | 3.47±0.72$^{b}$ | 4.83±0.57$^{a}$ |
| b | 11.97±1.01$^{b}$ | 13.7±0.85$^{b}$ | 15.23±0.59$^{a}$ |
| ΔE | 1.43 | 4.13 | 9.25 |

Results are expressed as Mean ± Standard deviation with different superscripts in a row differ significantly ($p<0.05$).

## Conclusion

In this study, drying kinetics of Horse Chestnut slices was studied. Changes in moisture content levels during drying at different temperatures of 50, 60 and 70°C were plotted against time in the form of moisture ratio and were fitted to Newton, Modified Page, Wang and Singh, Two term, Two term exponential and Diffusion model expressions. Among these different models, Diffusion model was found to be fit for drying behaviour of Horse Chestnut slices. The drying rate constant (k) was related to temperature using Arrhenius relationship. The study concluded that dehydration of slices at 60°C provided better color quality product. Thus, the 60°C was selected as the best temperature for the drying of Horse Chestnut slices.

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