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# Experimental analyses of drying characteristics of selected food samples

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**Abstract:** The objective of this work was to separately study the various aspects of drying. Agricultural produces were selected across various categories and their drying curves, prediction of the drying rates during constant rate periods of drying, the critical moisture contents and finally whether drying in the falling rate was capillary controlled or diffusion controlled were studied. Palm candy solution was included in the study to analyze the diffusivity values for a solution. Drying experiments were conducted with convective hot air flow in cabinet tray dryer. In case of palm candy solution and potato slices, drying was mainly capillary controlled in the falling rate period. The constant drying rate  $R_c$  in case of palm candy solution and potato slices were  $2.986 \times 10^{-4}$  and  $2.5 \times 10^{-4}$  kg H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>, respectively. In case of mango pulp and banana slices, the drying was diffusion controlled in the falling rate periods and the constant drying rates  $R_c$  for the mango pulp and banana slices were  $2.44 \times 10^{-4}$  and  $2.00 \times 10^{-4}$  kg H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>, respectively. The diffusion coefficients  $D_{eff}$  for mango pulp and banana slices were  $3.655 \times 10^{-10}$  and  $3.428 \times 10^{-10}$  m<sup>2</sup> s<sup>-1</sup>, respectively. Paddy drying properties were studied at different temperatures and it was observed that with elevation of temperature both constant drying rate  $R_c$  and diffusion coefficient  $D_{eff}$  increased.

**Keywords:** drying rates, capillary controlled, diffusion controlled, moisture diffusivity

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## 1 Introduction

Drying is the most common way to preserve agricultural commodities. It usually refers to the removal of water from a substance using some energy source. Many technologies have been developed to achieve the best products at the lowest cost such as hot air drying, vacuum drying, freeze drying and microwave drying etc. It is well known that the quality of dried product is strongly affected by drying method and drying process. In general, two major portions of the drying rate curves are constant rate and falling rate periods.

In constant rate drying period the surface of the solids is initially very wet and a continuous film of water exists on the drying surface. The water is entirely unbound and

acts as if the solids were not present. The rate of evaporation is independent of the solid and is essentially the same as the rate from a free liquid surface. Water evaporated in this rate period is supplied from the interior of the solid.

$X_c$  is the critical free moisture content, corresponding to point C, as described in Figure 1. Below this point there is insufficient moisture on the surface to maintain a continuous film of water. The entire surface is no longer wet and the wetted surface area continuously decrease in the first falling rate period until the surface is dry completely.

The second falling rate period begins at the point D, when the surface is completely dry and the plane of evaporation slowly recedes from the surface. Latent heat for the evaporation is transferred through the solid to the zone of vaporization. Vaporized water moves through the solid into the exterior. The amount of moisture removed in the falling rate period may be relatively small but the duration of moisture removal is much larger.

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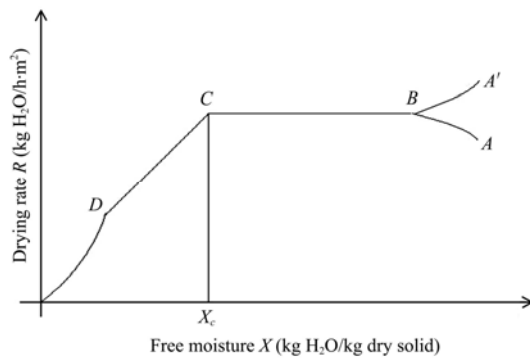


Figure 1 Typical drying rate curve for constant drying condition

To properly simulate the drying process using Fick's equation, the values of the moisture diffusion coefficient must be known. Fick's equation can be solved analytically only under a number of simplifying assumptions, including that of constant diffusivity (Islam et al., 2003). This simplification does not always apply because the diffusion coefficient frequently depends on temperature and moisture content. As moisture is removed during drying, the temperature in the interior of the product approaches drying air temperature. Moreover, in heterogeneous and non-isotropic media, the diffusion coefficient may depend on mass transfer direction, and its value may vary along the diffusion path. Several methods enabling determination of moisture diffusivity profiles in porous materials have been developed, e.g. those described by Drchalova and Cerny (1998), Perl et al. (1996). However, in many drying applications the problem of unsteady moisture diffusion is conveniently circumvented by replacing the intrinsic diffusion coefficient with the effective (also termed the equivalent, or apparent) coefficient (Maroulis et al., 2001).

Based on the work carried out at Indian Institute of Technology Kharagpur the objectives of this undertaking were:

- a. To dry palm candy solution, potato slices, mango pulp paste, paddy and banana slices in cabinet tray dryer.
- b. To analyze the drying curves of the above items for identification of critical moisture content.
- c. To analyze the falling rate drying periods for identification of capillary or diffusion controlled drying.
- d. To determine moisture diffusivity as function of moisture ratio.

The broad perspective of this study centered around the concept of constant and falling rates of drying, their

analyses and determination of drying rates and moisture diffusivity, especially during falling rate periods of drying of various products.

## 2 Materials and methods

### 2.1 Sample preparation

1. Palm Candy solution - Crystals of palm candy and water were taken in the ratio of 1:10 by weight. Palm candy crystals were dissolved in water to obtain a pure solution. Initially excess water was added to the crystals in a beaker and then the beaker was heated to dissolve all the crystal quickly. Heating was continued till the excess water added was removed completely by vaporization. Finally, calculated amount of water was added to maintain the proper ratio of water and the palm candy crystals. The solution was allowed to flow into an aluminum tray for drying.

2. Potato Slices - Potatoes were properly cleaned and the peels were removed. Thin slices were cut out. The slices were 3 mm in thickness. Upon drying in presence of hot air browning reaction is activated. So blanching of the slices before drying was absolutely necessary. Separately 2% potassium metabisulphite solution was prepared by dissolving 4 g of potassium metabisulphite powder in 200 mL distilled water. Potato slices were immediately dipped into the solution and kept for a few minutes. Potato slices were strained with suitable gauze. Finally, the slices were carefully distributed over the tray for the experiment. Care was taken that the drying layer thickness did not exceed 3 mm.

3. Mango Pulp - Each mango was washed properly and then peeled with a sharp knife. The pulp was separated from the seed and blended in a mixer. The blended pulp was collected and removing any peel or unwanted solid material, the pulp was finally poured into the tray. The pulp was made into a thin layer, thinner than 5 mm for tray drying.

4. Soaked Paddy - Required amount of paddy was soaked into a pan containing sufficient water at room temperature. Soaking was done for 3 hours. Next paddy was filtered to drain the water and once again put in sufficient water in a pan at room temperature. Paddy was heated to a temperature of 100°C for duration of 15 minutes. Once again paddy was kept overnight soaked in

water at room temperature. Next day paddy was filtered again to drain the water and placed in the aluminum tray for thin layer drying, paddy layer thickness being not more than two grains thick.

5. Banana Slices - Ripe bananas bought were properly washed and the peels were removed. Thin slices were cut into less than 8 mm thickness and distributed evenly in a thin single layer on the tray. Drying was carried out on the slices.

## 2.2 Methodology

The moisture content was calculated on a dry-basis using Equation (1).

$$MC_i = \frac{m_i - m_f}{m_f} \times 100 \quad (1)$$

where,  $MC_i$  is the dry-basis moisture content (g (100 g)<sup>-1</sup> d.b) at  $i$ th time interval;  $m_i$  is the sample weight at  $i$ th time interval and  $m_f$  is the final mass of dry solid in the sample. For further calculations, fractional moisture content and drying rate ( $dX/dt$ ), were calculated according to Equations (2) and (3) (Geankoplis, 2003).

$$X_i = \frac{MC_i}{100} \quad (2)$$

$$DR = \frac{dX}{dt} = \frac{X_{i-1} - X_i}{t_i - t_{i-1}} \quad (3)$$

where,  $X_i$  is moisture fraction (g of water/g of dry solid) at  $i$ th time interval;  $dX/dt$  is drying rate (g of water g of dry solids<sup>-1</sup> min<sup>-1</sup>) between ( $i-1$ )th and  $i$ th time intervals and at mean moisture fraction of  $(X_{i-1} + X_i)/2$ .

To compare drying behaviors of samples having different initial moisture contents, the moisture ratio was calculated to normalize moisture content at the  $i$ th interval with initial moisture contents, as given below by Equation (4) (Chen et al., 2012).

$$MR = \frac{MC_i - MC_e}{MC_0 - MC_e} \quad (4)$$

where,  $MC_0$  is initial moisture content;  $MC_i$  moisture content at  $i$ th time interval, and  $MC_e$  is the Equilibrium Moisture Content (EMC).

The bone-dry state of material might not have been achieved when it is dried in air of varying humidity and temperatures (60°C-80°C), where only EMCs are reached. EMC depends on type of material being dried, air temperature, and relative humidity. To reach bone-dry

material all free water and bound water (capillary condensation, polymolecular adsorption, and monomolecular adsorption) must be removed. Relative humidity values in the drying chamber would have been lower than the inlet relative humidity but also different for each drying temperature, probably not sufficient to remove all types of bound water (Vega-Gálvez et al., 2009).

Overall liquid diffusion was assessed from the data according to the procedure outlined by Geankoplis (2003). According to the procedure, the drying process of biological materials mostly occurs in the falling rate periods. Fick's second law of diffusion as per Equation (5) (Chen et al., 2012) has been extensively used to describe the drying process and interpret drying data.

$$\frac{\partial MR}{\partial t} = \nabla[D_{eff}(\nabla MR)] \quad (5)$$

In the initial stages of drying, till the critical moisture content is reached, a constant rate of drying was evident. Further drying of products took place during the falling rate period. In considering an appropriate theoretical model for moisture movement during dehydration in the falling rate period, only two approaches are included:

1. Capillary rise mechanism & 2. Diffusive transfer of water vapour.

Drying experiments were conducted with convective hot air flow in a tray dryer. Dry basis moisture content values were obtained. Size and shape of sample is said to affect the mass transfer kinetics because of variation in specific surface area to thickness ratio but in the study thin layer sample of thickness 3 to 8 mm was used.

Initially plotting the total moisture content (dry basis) with time, a graphical analysis was derived from the recorded data. The equilibrium moisture content values were estimated first. Next all the values of  $X$  i.e. free moisture content (dry basis) were obtained after subtracting the equilibrium moisture contents from the total moisture content values. A rough estimation was done by closely analyzing the slopes of the obtained curves. The largest slope of the curve over the maximum time interval was identified. From the equilibrium value i.e.  $X_c$ ,  $R_c$  values were identified.

$$R_c = -(W_s/A)(dX/dt) \quad (6)$$

Equation (6) gives  $R_c$  from the constant rate slope of free moisture content vs. time of drying.

All values of  $X$  i.e. moisture content (dry basis), lower than the critical moisture content value i.e.  $X_c$  were used to calculate the moisture ratio ( $MR$ ),  $X/X_c$ . The natural logarithm values of the moisture ratio were calculated. These values were analyzed against time. The use of the Equation (7) is based on a constant moisture diffusivity assumption for each temperature, which predicts a *linear behavior* for the dependence of logarithmic dimensionless moisture ratio versus drying time during the falling rates condition.

$$\frac{X}{X_c} = \frac{8}{\pi^2} \exp\left[-\frac{D_{eff}\pi^2}{4\delta^2} t_f\right] \quad (7)$$

$D_{eff}$  is the overall liquid diffusion coefficient ( $m^2 s^{-1}$ );  $\delta$  is the half effective depth of the material being dried.

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{D_{eff}\pi^2}{4\delta^2} t_f \quad (8)$$

When the sample shrinkage is negligible, initial moisture distribution is uniform, and constant moisture diffusivity is assumed, a simplified Equation 8 can be used to determine  $D_{eff}$ .

Effective liquid diffusivities are typically determined by plotting experimental drying data in terms of  $\ln(MR)$  versus time. From Equation (8), a plot of  $\ln(MR)$  versus drying time, gives a straight line with a slope ( $S_o$ ).

$$S_o = -\frac{\pi^2 D_{eff}}{4\delta^2} \quad (9)$$

Even though the experimental drying dependence is not strictly linear in a logarithmic scale, assuming a linear fit appears as being quite a successful approximation (coefficients of determination  $R^2$  greater than 0.98 for the samples). This proves that the above-mentioned assumption on the constant value of diffusion moisture for each temperature works reasonably well. From the equation of the straight line the value of the slope

obtained is  $\left[-\frac{D_{eff}\pi^2}{4\delta^2} t_f\right]$  and this is equated with

$$\left[-\frac{R_c'}{2\delta\rho_s X_c}\right] \text{ and hence a new value of } R_c' \text{ is obtained.}$$

[Where  $2\delta\rho_s = W_s/A$ ]. If the value of  $R_c$  obtained from Figure 1 is less than  $R_c'$ , then the drying can be stated to be capillary controlled and the rate of drying is  $R_c$ , as  $R_c$  cannot be exceeded during falling rate period.

On the other hand, if the value of  $R_c'$  is lower than  $R_c$ , then the drying can be stated to be diffusion controlled and hence the slope of the graphical analysis is evaluated against  $-\frac{\pi^2 D_{eff}}{4\delta^2}$ ; thus  $D_{eff}$  is evaluated for the diffusion controlled falling rate of drying.

The relationship between  $\ln(MR)$  and the drying time was found to be non-linear in some of the drying conditions studied. The non-linear relations may be due to reasons like shrinkage in the product, non-uniform distribution of initial moisture etc. (Hawlder et al., 1991). The non-linearity of the curves is also an indication of the variation of moisture diffusivity with moisture content.

If the logarithmic dimensionless moisture ratio versus drying time is not a straight line i.e. ( $R^2$  less than 0.98 for each sample); method of the slopes is adopted to predict the diffusivity values for small intervals of the  $X$  values.

By applying the technique Method of Slopes the diffusivity values are obtained. Diffusivity value is no longer constant for the given sample, but rather the values alter for every small interval of time. So, with the change of the moisture content of the sample as drying continues the diffusion controlled drying has a different diffusivity value.

### 3 Results and discussion

Moisture diffusivity is a complex and system specific function. The effective moisture diffusivity of a food material characterizes its intrinsic mass transport properties of moisture which includes molecular diffusions of liquid and vapor, hydrodynamic flow and other possible mass transport mechanisms (Karathanos et al., 1990). For foods, liquid diffusion is supposed to be the main mechanism of moisture transport in the first falling rate stage of drying while vapor diffusion is supposed to dominate in the second falling rate stage.

The data collected, analyzed and the results obtained have been presented in the following sections. These include the type of drying exhibited by the specimen in the form of their drying curve, the rates of drying, prediction of the constant rate period of drying, the critical moisture content and finally the effective diffusivity of the moisture in the process of drying.

**Palm candy solution:** - The ratio of palm candy

crystals to water is 1:10 (w/w). The solution turned more viscous as drying took place. A point came when the solution lost its flow ability characteristics owing to increased viscosity. As drying continued, the moisture front receded from the surface with time. The surface of the solution turned into a hard layer, due to formation of sugar crystals. Further as the material dried up, the layer of the crust on the surface thickened. As analysis showed, drying was mainly capillary controlled and some predictions could be made about the moisture movement from the solution. As there was a continuous mass transfer of moisture from the solution with drying in progress and the crust formation was initiated, the movement of moisture vapour in form of bubbles created fine passages throughout the mass of the solution for their movement. These fine passages actually behaved as capillaries distributed in the entire mass of the dried solution. So, in the later period of falling rate, the movement of moisture took place through these capillaries to the surface. Figures 2, 3, 4 present the moisture content (d.b.) vs. time; drying rate vs. moisture content (d.b.) and unaccomplished moisture ratio vs. time curves of palm candy drying process, respectively. In Figure 2 for all curves shown, the initial slant straight lines are indicative of constant rates of drying. Once the lines deviate from the straight portions and the free moisture content approach zero value, the falling rates of drying predominate. In Figure 3 the drying rates peak at very high moisture contents or at the initial conditions. After attaining the maximum rate values for a very short duration, as evident from the figure, there is an unsteady decline of the drying rates, which are called the falling rates or unequal moisture migration between the inside and outside of water body in the food.

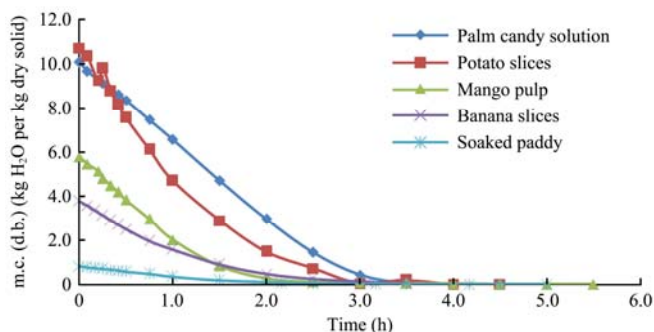


Figure 2 Moisture content (dry basis) vs time for various food samples

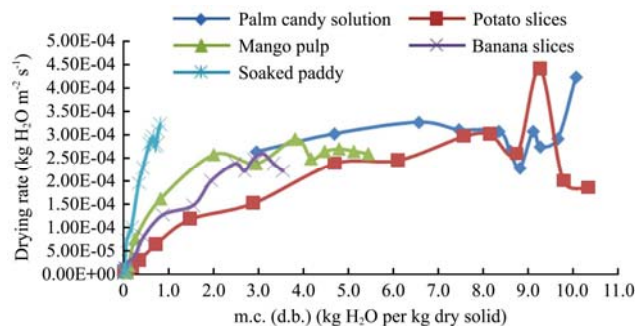


Figure 3 Drying rate vs moisture content (dry basis) for various food samples

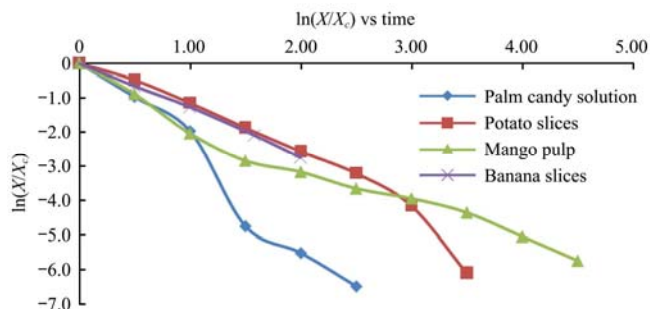


Figure 4  $\ln(X/X_c)$  vs time for food samples

Figure 4 depicts the logarithmic moisture ratio as function of drying time, post constant rates of drying. The curves or the lines in Figure 4 start from a value of zero for logarithmic moisture ratio, indicating first free moisture content equal to the critical free moisture content values. Figure 4 dwells only on the falling rates periods. Capillary or diffusion-controlled drying predominates during the falling rates regimes.

**Potato slices:** - Analysis of the data showed that capillary drying was predominant. As the drying took place in the constant rate period, the moisture was being removed from the surface itself. But in the falling rate period the moisture front from the surface started travelling to the interior due to the concentration difference. The structural orientation of the potato slice allowed formation of capillary pore spaces. The solute molecules did not cause any hindrances to fine capillary formations. Thus the drying is capillary controlled in the falling rate period (Figures 2, 3 and 4).

**Mango pulp:** - After analysis it was determined that drying in case of mango pulp was diffusion controlled in the falling rate period. Mango is a fruit and is renowned for its sweetness, which is due to the presence of high molecular weight dissolved solute molecules. The molecules are bulky and large in size. The structural orientation supports the analysis that drying is diffusion

controlled in case of mango pulp. As the moisture receded from the surface (Figure 2), the movement of the moisture from the interior followed a tortuous path before finally diffusing out of the pulp. The path is typically complex and critically oriented. There are regions having different temperatures in the path of the moisture movement. A temperature gradient existed between the top and the bottom layers. This caused the moisture to constantly change in phase. The moisture was in the form of water in the cooler regions and turned into vapor in the warmer sections and finally diffused out of the pulp. The natural logarithm values of the moisture ratio in case of mango pulp being dried were calculated. These values were analyzed against time (Figure 4).

The use of Equation (5) is based on a constant moisture diffusivity assumption for each temperature, which predicts a linear behavior for the dependence of logarithmic dimensionless moisture ratio versus drying time.

The slope of the graphical analysis is evaluated against  $-\frac{\pi^2 D_{eff}}{4\delta^2}$ ; thus  $D_{eff}$  is evaluated for mango pulp for the diffusion controlled falling rate of drying (Figure 5).

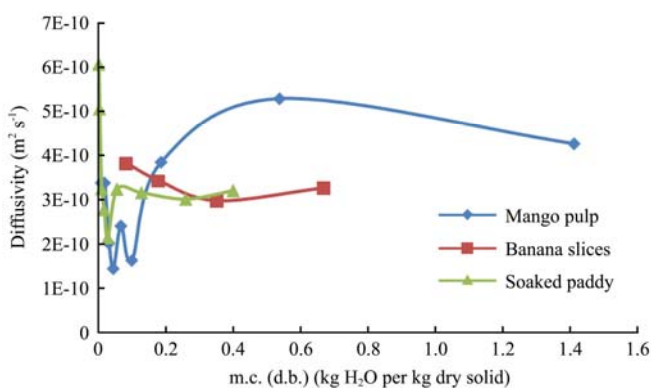


Figure 5 Diffusivity vs moisture content (d.b.) for food samples

**Banana slices:** - Analysis of the data showed that drying was diffusion controlled in the falling rate period (Figure 4). This result can be explained as banana being a fruit, it contains larger proportion of sugar in the ripened stage. Moreover, banana slices were slimy and this made the material lack high permeability. Hence the moisture movement met with hindrance and diffused out of the slices following the tortuous wended paths (Mowlah et al., 1983).

Similarly, the natural logarithm values of the moisture ratio in case of banana slices were calculated. These values were analyzed against time (Figure 4).

The slope of the graphical analysis is evaluated against  $-\frac{\pi^2 D_{eff}}{4\delta^2}$ ; thus,  $D_{eff}$  is evaluated for banana slices for the diffusion controlled falling rate of drying (Figure 5).

**Paddy:** - Cracking takes place, developing fissures due to thermal stress during drying. These fissures allow easy migration of internal moisture. Data analysis showed that paddy exhibited relatively long constant rate drying period as the sheath, inherent on rice grains prevents slow moisture migration typical of falling rate period (Figure 3). The grains of paddy are extremely rigid and hard in structure, especially when we consider moisture movement phenomenon. The outer husk makes the movement of moisture even more difficult. The paddy in the interior is itself a hard material. Paddy treatment was carried out in specific way, ultimately leading to parboiling of the paddy thus gelatinizing the starch content. This altered the interior of the grain and made it more homogenous and of higher viscosity, leading to the moisture movement following diffusion mechanism (Figure 5).

### 4 Conclusions

The study conclusively established that for syrupy consistency of palm candy solution and porous potato tissues capillary drying was predominant during the falling rate periods. For the other three produce, namely mango pulp, banana slice and soaked paddy the falling rates of drying were all diffusion controlled. Moisture diffusivity in these three commodities varied considerably as the produce temperature approached the drying air temperature during the last stages of drying (Table 1).

**Table 1 Values of the constant drying rate  $R_c$  and diffusion coefficient  $D_{eff}$  for the samples**

Sample	$R_c$ (constant drying rate) (kg H <sub>2</sub> O m <sup>-2</sup> h <sup>-1</sup> )	$D_{eff}$ (effective diffusivity) (m <sup>2</sup> s <sup>-1</sup> )
palm candy solution	2.986×10 <sup>-4</sup>	-----
potato slices	2.5×10 <sup>-4</sup>	-----
mango pulp	2.44×10 <sup>-4</sup>	3.655×10 <sup>-10</sup>
banana slices	2.00×10 <sup>-4</sup>	3.428×10 <sup>-10</sup>
paddy	2.805×10 <sup>-4</sup>	4.10×10 <sup>-10</sup>

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