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Abstract

Air-drying of banana slabs has been investigated and the influence of experimental parameters such as temperature, relative humidity and slab thickness has been studied. This was in part re-investigated because of inconsistencies in previous studies, particularly in relation to derived water diffusion coefficients. In addition, it is shown that harvest season and hence initial moisture content has a very marked influence on the drying kinetics. By contrast banana maturity (ripeness) has little influence on the kinetics despite there being significant differences in morphology and chemical composition between green and ripe bananas. The effect of these two variables on the drying kinetics has not previously been studied.

Keywords

Banana Dehydration, Air-drying, Fruit Maturity, Slab thickness, CMMB

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AIR-DRYING OF BANANA: INFLUENCE OF EXPERIMENTAL PARAMETERS, SLAB THICKNESS, BANANA MATURITY AND HARVESTING SEASON

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ABSTRACT:

Air-drying of banana slabs has been investigated and the influence of experimental parameters such as temperature, relative humidity and slab thickness has been studied. This was in part re-investigated because of inconsistencies in previous studies, particularly in relation to derived water diffusion coefficients. In addition, it is shown that harvest season and hence initial moisture content has a very marked influence on the drying kinetics. By contrast banana maturity (ripeness) has little influence on the kinetics despite there being significant differences in morphology and chemical composition between green and ripe bananas. The effect of these two variables on the drying kinetics has not previously been studied.

Keywords: Banana Dehydration; Air-drying; Fruit Maturity; Slab thickness.

INTRODUCTION

Previous work on drying banana has focused predominantly on atmospheric drying with air-drying being the most common method applied. In this method, both heat transfer and mass transfer simultaneously occur. The removal of water in a foodstuff during drying occurs via two mechanisms: migration of water within the foodstuff and evaporation of moisture from the foodstuff into the air. The former is considered as the most common moisture migration during drying, and has been used to explain the drying kinetics of banana (Mowlah et al. 1983; Garcia 1988; Sankat et al. 1996).

Modelling of the drying kinetics of banana has been studied previously. Mowlah and co-workers (1983) applied Fick's law of diffusion to predict drying behavior of banana. The predicted drying time fitted well with experimental data. A one-parameter empirical mass transfer model for drying banana was proposed by Mulet and co-workers (1989). In this model, a drying constant was used as a function of process variables (temperature, dimension of samples, humidity). This model was applied to the drying of four fruits namely, apple, pear, kiwi fruit, and banana. Wang et al (1998) used a diffusion model, in which the effects of both heat and mass transfer were taken into account. Their results showed that the most intensive heat and mass transfer occur in the transition region, where capillary flow and vapour diffusion play an important role. A variable diffusion model was proposed by Garcia (1988). In this work, banana slices and foam were dried using microwave and air ovens. The report showed that mass transfer by the vapour diffusion mechanism was intensified in microwave drying.

The effects of drying conditions and drying methods on the quality of the final product have also been reported. Krokida and Maroulis (1999) examined the effect of microwave and microwave- vacuum on increased product porosity and colour changes. They showed that microwave drying increases elasticity and decreases viscosity of product. Krokida and co-workers (1998a) studied the effect of freeze-drying conditions on shrinkage and porosity of banana, potato, carrot, and apple. They found that final porosity decreased as sample temperature increases. These authors (1998b) also examined the effect of drying conditions on color change during conventional and vacuum drying those fruits. Rate of color changes was found to increase as temperature increased and air humidity decreased. Other workers (Robinson 1980) investigated the improvement of banana dehydration and used the results in designing a commercial banana drying plant .

Generally, drying of foods is characterised by two separate phases: the constant rate and the falling rate periods. For a high-moisture food, prior to drying, the surface of the food is saturated with water. The drying rate is thus constant for a period of time until the migration of moisture to the surface is not sufficient to keep it in a saturated state, assuming the composition of the drying air does not change. The constant rate period ends and the moisture content at this point is referred to as the critical moisture content. The falling rate period then starts, and the drying rate falls monotonically to the end of the process. Fruit with a high amount of free water and fruit with a skin such as plum, grape, apple, apricot, peach, and pear usually undergo a constant rate period during drying if the drying temperature is not too high.

The drying rate during the falling rate period is caused by the concentration gradient of moisture inside the food matrix. The internal moisture movement results from a number of mechanisms such as liquid diffusion, capillary flow, flows due to shrinkage and pressure gradients (Lyderson 1983).

Due to the complexity of food, drying can occur simultaneously by different mechanisms. Therefore, modelling the drying process, and predicting the drying behavior under different conditions is necessary to have a better understanding of the mechanisms of drying at play. Fick's law of diffusion has been used to describe the drying kinetics of fruit during the falling rate period. Modelling the drying of banana has been reported by several authors using Fick's law of diffusion (Mowlah et al. 1983; Garcia 1988; Sankat et al. 1996).

Most studies (Mowlah et al. 1983; Garcia 1988; Mulet et al. 1989) of dehydration of banana have focused on the validation of a particular model, under a limited range of drying conditions. The effect of temperature on the drying kinetics was of most interest in these studies. In addition, there were some inconsistencies in the derived diffusion coefficients (Mowlah et al. 1983). Although our prime interest has been the effect of pre-treatments such as osmotic dehydration on subsequent air-drying [Nguyen and Price unpublished data] the gaps and inconsistencies in the current literature as far as understanding drying kinetics of banana, led us to re-investigate the matter. In particular, it was hoped that a simple model with a single falling rate period giving a good fit to experimental data for a wide range of conditions could be obtained. Therefore the aim of the current work was to investigate the effect of drying conditions on the drying kinetics over a wide temperature range (30 - 70^{o}C) and to look at the effect of slab thickness. In addition, the influence of banana maturity, and different harvesting seasons was also studied to confirm the effect of morphology on the drying kinetics.

EXPERIMENTAL METHOD

Materials: Fresh Cavendish banana were bought from commercial sources in Wollongong, Australia. They were grown in North Queensland, Australia from a single supplier. Bananas were stored at room temperature. Ripe bananas (bright yellow) and green bananas were used in drying studies. Experiments were repeated in different months from January to November in order to examine the effect of various harvesting seasons on drying kinetics.

Drying Procedures: Bananas were peeled, weighed and cut into cylindrical pieces of thickness 1 or 2 cm. Three hundred grams of ripe bananas, without any treatment, were used in each experiment. Drying experiments were carried out using a laboratory-scale system. (Sabarez et al. 1997) It consisted of a dehydration unit and an online data-logging data system. The drying chamber was equipped with heating, ventilation, and a humidifying system. The humidifying system was used to control the humidity during drying. The fluctuation in RH% that occurred during the experiments was better than ± 5%**.** Fruit was placed on a stainless steel mesh tray, which was suspended from an electronic balance. The balance output to a computer-based data acquisition system recorded automatically the mass change, temperature, and humidity of surrounding air as a function of drying time. This system is illustrated in Figure 1.

Drying experiments were carried out at 10^{o}C intervals between 30 and 70^{o}C. The air velocity was set at a constant 1 m/s. All experiments were repeated at least three times. All drying experiments were continued until a constant mass was obtained for at least four hours.

Moisture Content Determination: Initial moisture contents of banana were determined by vacuum drying at 60^{o}C, for 48 hours over magnesium sulfate desiccant. The initial moisture contents were determined for bananas grown at different times through out the year. Three replications were done. The average value was used to interpret data. The initial moisture contents were expressed on a kg/kg dry basis.

RESULTS and DISCUSSION

Moisture Content of Banana: The average initial moisture content of Australian fresh banana during experiments from March to November was 74.7±1.3 % on wet basis or 2.96 kg/kg DM. This value agreed well with reports from the literature. (Wills et al. 1986; Sadler 1993) Higher moisture content for banana harvested in January was 77.8 ±1.4 % on wet basis or 3.5 kg/kg DM. This value also agreed with results from other authors (Mowlah et al. 1983; Beck et al. 1985; Sankat et al. 1996; Prabha et al. 1998).

Commercially, banana is dried to less than 20 % final moisture content, (Bowrey et al. 1980; Robinson 1980) or down to 14-15 % final moisture content (on dry basis) (Garcia 1988). This corresponded to 69.7% mass loss (20% final moisture content) or to 71.2 % mass loss (14 % final moisture content) in this work. At such a level of moisture content, dried banana has a shelf life at least 6 months (Robinson 1980).

In this study, the relative humidity was controlled and kept relatively constant during the drying runs. Humidity during drying was reproducible for different runs of banana from different months and it did not vary significantly during a run**.** In most cases the standard deviation of three replications was not over 3 % (Except at 30 ^oC), as shown in Table 1.

Modelling the Kinetics of Air-Drying of Banana : In order to describe the drying behavior of banana, and predict it under different drying conditions, it is necessary to model the drying process. Drying of banana predominantly follows a falling rate profile. Mass transfer during this period is caused by liquid diffusion or capillary flow. The former is commonly used to describe drying behavior in the falling rate period of fruit and vegetables. The rate of diffusion is governed by moisture concentration gradient as the driving force. Fick's law of diffusion is widely used to model the drying behavior for this period.

Fick's second law of diffusion can be expressed as:

$$dW/dt = D*d^2W/dL^2 \qquad [1]$$

Where W = moisture content at time t

L = distance (m) in the direction of diffusion (or thickness)

D= liquid diffusivity. (m^2h^{-1})

If the external mass transfer resistance is negligible, mass transport occurs in one dimension, and initial moisture content is assumed to be uniform in slabs. A well-known analytical solution for [1] was given by Crank (1975) for an infinite slab drying (Brennan et al. 1976) from one face:

$$\frac{(W-Wt)}{(Wo-We)} = 8/\Pi^2 [\exp\{-Dt (\Pi^2 /4L^{2)} \} +1/9\exp\{- 9Dt(\Pi^2 (Wo-We) /4L^2) + \ldots\}] \quad [2]$$

For long drying (Brennan et al. 1976; Perry et al. 1997) times, [2] can be reduced to:

$$Wr = \frac{(W - We)}{(W_o- We)} = 8/\Pi^2 [\exp \{-D.\ t (\Pi^2 /4L^{2)}\}] \quad [3]$$

Where,

We = Equilibrium moisture content (dry basis)

Wo = Initial moisture content (dry basis)

If moisture loss occurs from both sides, L = half of thickness of slab.

Both equations [2] and [3] ignore the initial thermal transient.

Equation [3] can be rewritten as:

$$Wr = A\ e^{-Kt} \quad [4]$$

Where K is a drying constant (h^{-1}), Wr is removable moisture ratio, t is drying time (h), and A is a constant.

The values of K, and D may be obtained from the slope of the plot ln (Wr) versus drying time according to equation [3] and [4)] respectively. This plot should be a straight line. To apply equation [3] the most important quantity is the equilibrium moisture content. A number of empirical equations exist in the literature for calculation of equilibrium moisture content in banana such as the Henderson's equation (Garcia 1988) and the Guggenheim, Anderson and de Boer (GAB) equation (Mulet et al. 1989).

However, in the present work, wide variations in calculated equilibrium moisture content were obtained from these equations. This is mainly because the range of conditions under which the equations were derived differed from the conditions employed in the present study. In addition, most sorption isotherm data reported for banana were for low temperatures (e.g. 25^oC (Iglesias et al. 1982; Lomauro et al. 1985; Mulet et al. 1989; Ratti et al. 1996), 35^oC, and 45^oC (Iglesias and Chirife 1982)). Therefore, an empirical method for estimating equilibrium moisture content was used in this study. In this method, equilibrium was obtained when drying rate is zero, i.e. when $dW/dt = 0$. The values of equilibrium moisture contents were determined by the point on the plots of dW/dt versus W when the graph cuts the moisture axis. This approach can be applied as the drying occurred over a long time, when equilibrium could be approached. This method was the best available within the time constraints of the project. More time-consuming isotherm measurements were outside the scope of the work. It is interesting to see that the results obtained in this study were very similar to results reported by Sankat and co-workers (1996) with the same range of RH% at each drying condition.

Estimated parameters of diffusion model: The equilibrium moisture contents for all drying conditions obtained in this study are summarized in Table 2. The results of equilibrium moisture contents agreed well with data in the literature (Brekke et al. 1970; Sankat et al. 1996). Applying equation [3] by plotting the natural logarithm of removal moisture ratio (Wr) versus time, the value of rate constant (K), and thus the diffusion coefficient D could be determined from the slope of the straight line.

$$\text{Slope} = -\Pi^2 D/ 4L^2 = K \qquad [5]$$

Where L = the thickness of the slab, if drying occurred only on one large face. In this study, drying occurred on two faces, as slabs were placed on a mesh tray. In this case L = half thickness.

Figure 2 shows the plots of ln Wr versus time for banana (1cm) dried at different temperatures. The linear plots of ln Wr versus time indicate that D was independent of moisture content. (R^2 = 0.99 for all temperatures.). Increased D with increased temperature was observed. Values of constant rates and diffusion coefficients obtained from different drying conditions are summarized in Table 3. The temperature dependence of the moisture diffusivity was described with an Arrhenius type equation: $D = D_o \exp(-Ea/RT)$ [6] where Ea is activation energy (kJ/ mol).

Values of lnD at different temperatures were plotted versus 1/T for slabs of 1 and 2 cm. Good linearity was obtained in both cases. From the slope of these lines, activation energy was derived. The values of $E_{\mathbf{a}}$ were 39.8 (±4.6) kJ/mol, and 34.7 (± 0.073) kJ/mol for 1 cm, and 2 cm slabs respectively.

Testing and evaluation of the model: In order to evaluate this model for predicting drying behavior of banana, experimental drying curves of banana at 30°C, 50°C, 60°C, and 70°C for 1 cm slabs were compared with those obtained by the diffusion model. In the model, the fitted values of D, K for the semi-log plots were used to generate the model drying curves. The two curves were compared statistically across the entire drying period. Figure 3 represents the comparison of the changes of experimental and predicted moisture content during drying at 60°C. At all temperatures studied the deviation between experiment and predicted moisture content was generally 1-2% at any time point.

These results and the deviations of D and K show that the diffusion model can be used successfully to predict the mass transfer during the falling rate period of drying banana for a wide range of drying temperatures. An extremely good fit was obtained for drying at 60^{o}C and 70^{o}C. This agreed with expectations, because at high temperature, the rate of moisture loss was very rapid at the beginning. At this stage the evaporation of moisture from the surface controlled the rate of drying. The faster the surface moisture was deleted, the sooner the drying rate was controlled predominantly by internal diffusion.

The drying time at all temperatures also agreed very well between predicted and experimental data. The difference in drying time to a particular moisture content between the model and experimental data was 10-15 min or less for all drying temperatures from 30^{o}C to 70^{o}C.

In summary, the diffusion model gave the good fit with the experimental data. The values of moisture diffusion coefficients or constant rates, which were yielded from this model, were useful to explain the effects of different drying conditions on drying behaviors of banana. There are several significant advantages in a simple model with few variable parameters, over previous reports (Sankat et al. 1996) to model the drying of fresh banana. Not least of these is that for the temperature range used here, it was possible to use only one falling-rate period of drying to describe the process.

Effect of drying temperature on drying kinetics: Bananas were dried at 10^{o}C intervals from 30^{o}C to 70^{o}C to investigate the influence of temperature on drying kinetics. The effect of temperature on drying rate was seen clearly from the results of water diffusivity in Table 3. Increasing temperature resulted in significant improvement of rate of mass loss, especially the initial rate. Total drying time was reduced significantly with increasing temperature. The initial drying rate and the drying time needed to obtain a 70 % mass loss (wet basis) at different drying temperatures are shown in Table 4. The drying time of banana at 70^{o}C was twice as fast as that at 60^{o}C, three times compared to 50^{o}C, four times that at 40^{o}C and 10 times that at 30^{o}C. Decreased drying time of around 10h with increasing 10^{o}C was observed within this temperature range, except for the large difference for case of drying at 30^{o}C.

The influence of sample thickness on kinetics of drying banana: The drying rate in the falling rate period, which is mainly influenced by the moisture gradient in food, (Strumillo et al. 1986) is also thickness dependent. The following section examines the effect of banana slab thickness on the kinetics of drying. Table 5 shows the results of rate constants and diffusion coefficients calculated from the diffusion model for 1 cm and 2 cm slabs dried at different temperatures. From Table 5, the thickness and temperature dependence of D can be seen clearly. The D values for 2 cm slabs were nearly 3 times greater than those for 1 cm slabs at all temperatures. This was not surprising, because the diffusion model assumed that diffusion took place from only one direction from inside to the surface of slabs. This assumption was valid for thin slabs, in which the edge effect (side way diffusion) was negligible. In thick slabs, some side diffusion might occur. Taking this effect into account, the removal of moisture in thick slabs might be enhanced.

In the falling rate period, the concentration gradient in food matrix controls the drying rate and is temperature dependent. This leads to large difference of drying rate difference between 1 cm, and 2 cm slabs within various temperatures, especially at the beginning of drying. The drying rate difference between 1 cm and 2 cm slabs is illustrated in Figure 4, and it can be seen that significant differences of drying rates between 1 cm and 2 cm slabs at all examined temperatures occurred in the early stage of drying (before 3 h). These differences then decreased gradually to the point when the drying rates of 1 cm, and 2 cm slabs were equal. Drying times to obtain equal rates of 1 cm and 2 cm slabs decreased with increasing temperatures.

In the early stages of drying, when the fruit had high moisture content, the removal of water depended on the pathway of water from the internal sites of fruit cells toward the surface areas. This pathway was thickness dependent and drying at high temperature compensated for the influence of thickness and therefore equal rates between thick and thin slabs were obtained faster.

In addition, when drying at a high temperature, a surface hardening effect occurred for the thin slabs faster than in thick slabs, due to quicker initial rate of evaporation of moisture from the surface. This hardening effect slowed down the drying rate in the thin slabs. This in turn made the difference between the drying rate of 1 cm and 2 cm slabs decreased faster at high drying temperature than at the lower ones. This effect also could be helpful to explain why the diffusion coefficients in 1 cm slabs were smaller than in 2 cm slabs.

In summary, edge effects might enhance the removal of moisture from thick slabs. A hardening effect might hinder the transfer of moisture in thin slabs after drying some hours. Both these reasons would explain why the values of D of thick slabs were higher than that of thin slabs.

The effect of initial moisture content of banana on drying kinetics: The initial moisture content of banana harvested at different time was found to vary during this study. Bananas were dried during various months from January to November. The average moisture content (wet basis) of bananas from different months are presented in Table 6. A large difference between the moisture contents of January and March bananas was observed. It is known that the initial moisture content in fruit influences initial drying rate (Sabarez et al. 1997; Sabarez et al. 1999) and thus, the drying time. The initial moisture dependence of drying rates of Australian bananas harvested in January and March was investigated. Table 7 shows the results of initial drying rates and drying time of these samples dried at 40^{o}C and 60^{o}C (Drying to moisture content = 20 % dry basis). The difference in initial moisture contents led to significantly different initial drying rates at both drying temperatures. This was understandable, because the higher the initial moisture content the greater the concentration gradient established and thus, a higher driving force for mass transport would result.

From Table 7, it can be seen that different initial moisture contents resulted in longer drying times for samples dried at 40^{o}C, whereas drying times were nearly the same for two samples dried at 60^{o}C, despite their being a greater initial drying rate for the banana with the higher moisture content. The increase of water diffusivity with increased moisture content has been reported elsewhere (Saravacos et al. 1984;

Sokhansanj et al. 1987). Thus, higher initial moisture content in food resulted in a higher drying rate, as expected. This led to a rapid decrease in moisture content in the fruit, and resulted in the same drying time for both January and March samples at 60^{o}C.

Moreover, high temperature (60^{o}C) accelerated the evaporation of moisture near the surface better than low temperature (40^{o}C), thus drying time could be reduced. The results of drying at 60^{o}C agreed with the reports of Sabarez, Price and co-workers (1997; 2001) for drying plum of different initial moisture contents at 70^{o}C. The authors reported that at this temperature, there was very little difference in drying time between samples with different initial moisture contents. Perhaps, strong temperature dependent diffusivity of water in banana led to the difference between the two temperatures.

The influence of maturity of banana on drying kinetics: There have been reports of changes in structure (intercellular space, cell wall) (Charles et al. 1973; Marriot 1980; Prabha and Bhagyalakshimi 1998), permeability of membrane, chemical composition (including starch, sugar and water) (Ketiku 1973; Wills et al. 1984; Ni et al. 1993; Prabha and Bhagyalakshimi 1998) between green and ripe banana. It was therefore of interest to investigate the drying kinetics of banana of different maturity. Green banana and ripe ones of the same hand (given six days more to mature) were dried under the same drying conditions (temperature, thickness, and humidity and air velocity). Mass loss of green and ripe bananas as a function of drying time was very similar for all drying temperatures and slab thickness. The values of K, and D (calculated from the diffusion model) of green and ripe samples under different drying conditions are presented in Table 8. The values of K and D are not very different between green and unripe samples indicating little net influence of maturity and hence fruit morphology on the drying rate.

CONCLUSION

Using a simple solution to Fick's diffusion equation for an infinite slab it was possible to model the drying kinetics of drying banana slabs. The deviation between predicted and experimental moisture contents during drying was small and extremely good fits to experimental data was obtained at all drying temperatures. Perhaps, under these drying conditions, very little non-moisture loss was observed.

Temperature dependence of diffusivity followed an Arrhenius type equation with a high correlation coefficient (R^2 = 0.99), and the apparent moisture diffusivity obtained in this work agreed with data reported in the literature.

The difference in drying rates for banana slabs of different thickness showed that drying banana followed mainly the internal moisture transfer of the falling rate period, in which water diffusivity depended upon both temperature and distance.

Initial moisture content varied with bananas of different harvesting seasons. The large difference in initial moisture content (over 5% wet basis) could strongly affect drying rates. However, this effect was only clearly observed at low temperature (40^{o}C). At a higher drying temperature this was not seen, since temperature dependence of diffusivity was stronger than the concentration dependence.

Mass loss under all drying conditions between green and ripe banana was very similar. This showed that mass loss was not influenced much by fruit morphology. However, chemical changes, especially significant rise in the amount of sugar in ripe banana may contribute to reducing the rate of mass loss of ripe banana. This would compensate for the more open structure of ripe banana which be expected to favor an increased drying rate for ripe banana. It is possible these two competing effects counter-balance each other.

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Table 1: Relative humidity ranges of experimental drying of banana at different temperatures.

Temperature (^oC)	30	40	50	60	70
Average of RH%	45.8	27.4	8.9	5.3	2.3
Std. Dev.	8.3	2.3	0.6	1.4	0.7

Table 2: Equilibrium moisture contents of banana at different drying conditions. (In all cases, the standard deviations in the mean We were between 1- 3 % for three replications).

Drying conditions	**Values of W_e** (kg/kgDM)
30 ^oC ,1 cm	0.25
40 ^oC ,1 cm	0.22
50 ^oC ,1 cm, green	0.18
50 ^oC ,1 cm, ripe	0.16
50 ^oC , 2 cm, ripe	0.25
60 ^oC ,1 cm, green	0.08
60 ^oC ,1 cm, ripe	0.095
60 ^oC ,2 cm, green	0.15
60^oC ,2 cm, ripe	0.1
70 ^oC ,1 cm, green	0.07
70^oC ,1 cm, ripe	0.09
70 ^oC , 2 cm, green	0.1
70^oC , 2cm, ripe	0.13

Table 3:

Values of rate constants and of diffusion coefficients of bananas dried at different dying conditions (ripe banana of 1cm slabs). In all cases, the standard deviations in the mean K, and D were between 1-2% for three replications.

Drying temperatures (^{o} C)	**K (h^{-1})**	**D (m^2/s)*10^{10}**
30	0.046	1.3
40	0.083	2.1
50	0.111	3.2
60	0.208	5.1
70	0.277	7.8

Table 4 Comparison of initial drying rates (kg H_2O/kg DM* h) and drying times to 70% mass loss for drying bananas (1 cm slabs) at different temperatures. (In all cases, the standard deviations in the mean initial drying rates were between 2- 4 % for 3 replications. Errors quoted for the drying times are the standard deviations of the mean for 3 replications)

T(^{o}C)	30	40	50	60	70
Initial drying rate (kg H_2O/kg DM* h)	0.17	0.3	0.39	0.54	0.73
Drying time (min) to 70% mass loss	6000 ± 95	2520 ± 60	1850 ± 75	1320 ± 60	660 ± 60

Table 5: Rate constants and diffusion coefficients of moisture in ripe banana slabs of different thickness dried at different temperatures. (In all cases, the standard deviations of the mean K, D were between 1- 2% for three replications)

Drying conditions		**K (h^{-1})**	**D (m^2/s)*10 ^{10}**
50 ^oC	1 cm	0.11	3.2
	2 cm	0.09	10.8
60 ^oC	1 cm	0.21	5.1
	2 cm	0.14	15.9
70 ^oC	1 cm	0.28	7.8
	2 cm	0.20	22.7

Table 6: Variations of moisture contents with different harvest seasons.

Month	**% MC**
January	77.8 ± 1.2
March	71.4 ± 1.3
Average of other months	74 ± 1

Notes: Errors are the standard deviations of the mean for 3 replications.

Table 7: Drying times and initial drying rates of bananas harvested in January and March. In all cases, the standard deviations in the mean initial drying rates were between 2-3 % for three replications. Errors quoted for drying time are the standard deviations of the mean for three replications.

Temperature	40^oC		60^oC	
Month	January	March	January	March
Initial drying rate (kg H_2O/kg DM*h)	0.53	0.34	0.95	0.63
Drying time (min)	1575 ± 74	1800 ± 46	1020 ± 30	1050 ± 45

Table 8: Rate constants and diffusion coefficients of green and ripe banana dried under different drying conditions. In all cases, the standard deviations in the mean K, D were between 2-3 % for three replications

Drying conditions		**K (h^{-1})**	**D (m^2/s)*10^{10}**
50^o C ,1 cm	green	0.14	3.81
	ripe	0.11	3.21
60^o C ,2 cm	green	0.13	14.75
	ripe	0.14	15.87
70^o C ,1 cm	green	0.30	8.5
	ripe	0.28	7.8
70^oC , 2 cm	Green	0.18	20.15
	Ripe	0.202	22.74

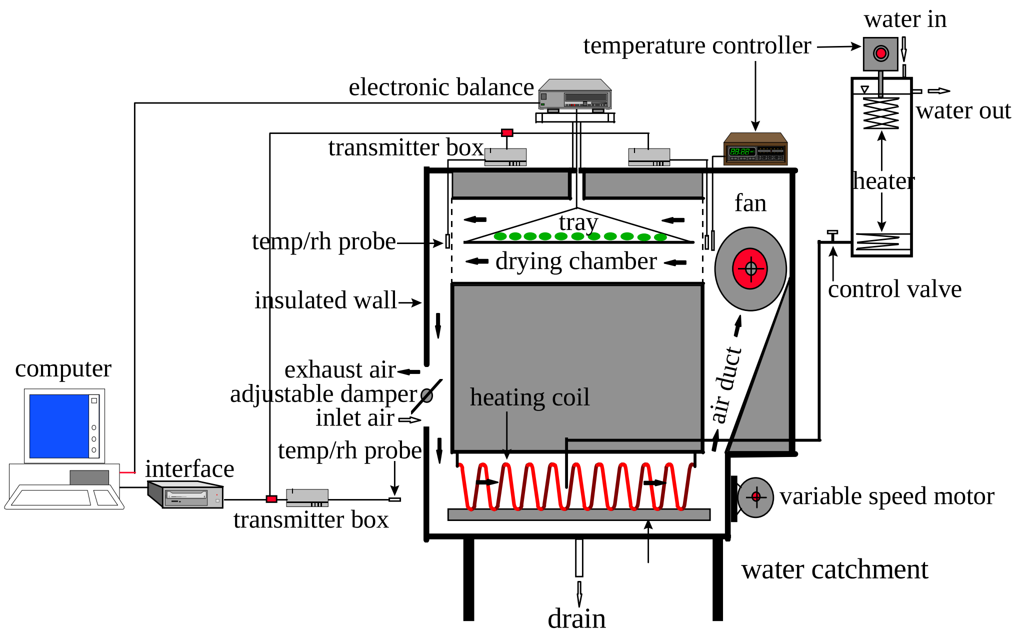

Figure 1: Schematic diagram of the dehydration system

Figure 2:

Plots of ln Wr versus time for 1cm slabs banana versus time at different drying temperatures. (Initial moisture content = 72.6 % wet basis, velocity =1m/s)

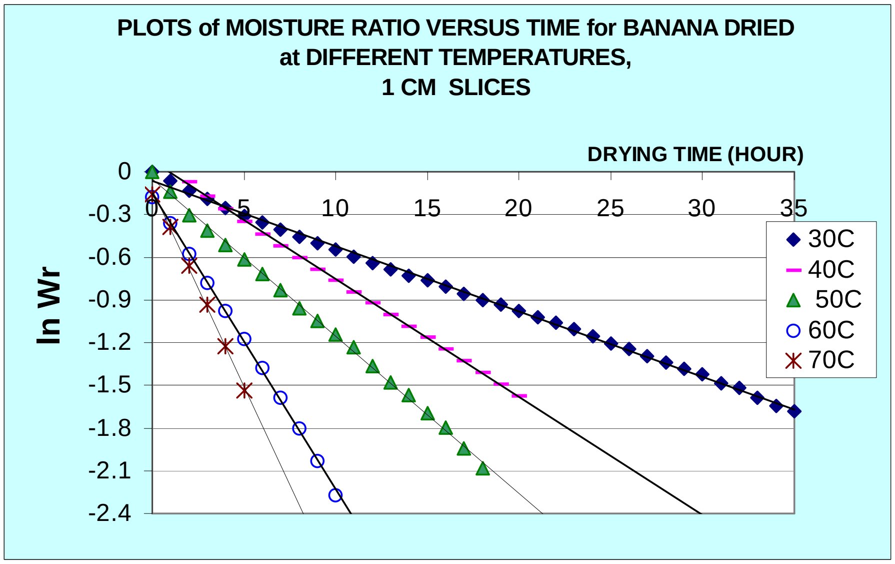

Figure 3: Comparison between experimental and predicted moisture content changes

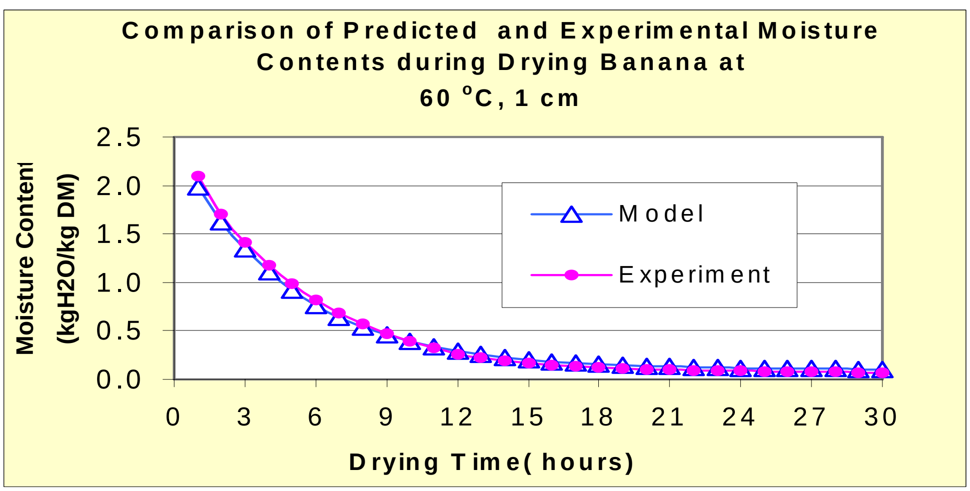

Figure 4: The difference in drying rates between 1 cm and 2 cm banana slabs at various drying temperatures.