The air drying behaviour of fresh and osmotically dehydrated banana slices

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Summary Ripe banana, cut to 10 mm thick slabs were osmotically treated in sugar solutions of 35, 50 and 65° Brix for 36 h. The initial moisture content fell from a value of 3.13 kg H_2O DM to 2.19, 1.63 and 1.16 kg H_2O kg^{-1} for treatment in the three solutions, respectively. These slabs, with Total Soluble Solids (TSS) contents of 26, 34 and 39° Brix, respectively, as well as freshly cut but untreated slabs (15° Brix) were air dried in a cabinet type tray drier to near equilibrium conditions at fixed temperatures from 40 to 80°C and at a constant air speed of 0.62 m s^{-1}. Drying was found to occur in the falling rate period only for both banana types and two drying constants K_1 and K_2 were established for a first and second falling rate period of drying. Increasing the drying air temperature significantly enhanced the drying rate and the K-values, except at 80°C when the rates fell, possibly because of case hardening of the slabs. Reducing the slab thickness also improved the drying rate, but increasing the air speed to 1.03 m s^{-1} did not have any profound effect. As the sugar content of the banana slabs increased through the osmotic treatment, drying rates fell. Calculated apparent moisture diffusivities at 60°C ranged from 34.8×10^{-10} m^2 s^{-1} (fresh slab) to 8.8×10^{-10} m^2 s^{-1} for dried (39° Brix) slabs. The moisture diffusivity was significantly lowered as the moisture content dropped in drying and with increased levels of sugar. Previously osmosed and then air dried banana slabs showed appealing colour and texture compared to the fresh banana.

Keywords Drying rate, moisture diffusivity, osmotic concentration, quality.

Introduction

Osmotic dehydration is described as the partial dehydration of fruits through the process of osmosis which essentially involves immersing fruits for a given period of time in a sugar solution. Water loss to the extent of 30–50% of the fruits' initial weight is attainable and this is dependent upon the strength of the sugar solution. While water diffuses from the fruit to the solution, there is simultaneous movement of sugar from the solution into the fruit. After this initial osmotic step, a conventional drying method such as hot air drying is necessary to produce a variety of shelf-stable, dried fruit products all of which have special characteristics as a result of this pre-treatment. Ponting (1973) noted that the two effects of sugar which aid in producing a high quality product by prior osmotic dehydration are namely:

(1) it is a very effective inhibitor of polyphenoloxidase, the enzyme which catalyses oxidative browning in many cut fruits and,

(2) it prevents the loss of volatile flavouring constituents during dehydration, even under vacuum.

Jackson & Mohammed (1971) stated that the removal of water in the prior osmotic step is of secondary importance compared to the beneficial effects obtained by coating and impregnating the

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fruit with the osmotic agent, as the subsequent air drying times for fresh and osmosed fruit slices did not differ greatly.

The osmotic process therefore appears very suitable as a pre-treatment prior to air drying of fruits, and in particular the banana. It has been reported and often observed that banana tissue which is damaged (after peeling, slicing, etc.) darkens very rapidly because of enzyme oxidation of dopamine and other polyphenols (Weaver & Charley, 1974). Studies on the mass transfer phenomena during the osmotic dehydration step have been conducted principally with apples and other temperate fruits, with some studies on tropical fruits such as pineapples (Beristain *et al.*, 1990) and papaya (Levi *et al.*, 1983 & Heng *et al.*, 1990) also reported. On the other hand little has been reported on the subsequent air drying behaviour of fruit slices which were previously osmosed. Islam & Flink (1982a) noted that changes in the composition of food material during the osmotic concentration step can subsequently influence air drying behaviour and found that drying rates and water diffusion coefficients (D) were lower for osmosed samples of potatoes compared to non-osmosed, i.e. $D = 8.72 \times 10^{-10}$ m^2 s^{-1} for 7 mm thick non-osmosed potato slice and 4.48×10^{-10} m^2 s^{-1} for osmosed (60% sucrose solution) potato slice at 65.5°C. Rahaman & Lamb (1991) reported that the air drying rates of previously osmosed pineapple slices were significantly decreased because of the presence of the infused sucrose and that the effective diffusion coefficient for water during the air drying step decreased with the increased solids content of the slices.

In this study, the principal objective was to examine in a comparative manner the air drying behaviour of banana slices which were previously osmosed in sugar (sucrose) solutions and that of fresh slices. While bananas represent one of the world's most traded fruits, principally as fresh fruit, commercial processing of banana through sun drying, spray drying or drum drying although long since reported (Von Loesecke, 1950) is not very evident in the producing countries such as the Eastern Caribbean Islands. Low cost techniques for banana processing are desirable, and osmotic dehydration followed by air drying which may involve the use of solar driers, appear an attractive possibility.

Materials and methods

Drying experiments

Fully ripened (yellow) but firm bananas of the Cavendish variety were mechanically sliced using a Hobart slicer into longitudinal, 10 mm thick slabs, peeled and then osmotically pre-treated for 36 h at room temperature (25°C) in one of three sugar (sucrose) solutions, i.e. 35° Brix, 50° Brix or 65° Brix. To these solutions, as recommended by Hope & Vitale (1972), was added 0.25% SO_2, using sodium bisulfite. After the osmotic treatment, slabs were lightly rinsed to remove excess sugar solution, drained and then placed in single layers on pre-weighed drying trays. Fresh banana slabs of 10 mm thickness were prepared and both fresh and osmosed slabs were air dried at a fixed temperature in a cross flow cabinet drier (Proctor and Schwartz Inc., Philadelphia, USA) with drying trays quickly and periodically weighed (0.5 h interval for the first 3 h of drying) during the drying process. In all the drying runs, trays were replicated and from the two values of tray weights, average values of the banana moisture content as a function of time were determined. These values were used to construct the drying curves.

To evaluate the effect of the air dry bulb temperature on the drying process, five temperatures of 40, 50, 60, 70 and 80°C were used, with the air speed in the drier being fixed at 0.62 m s^{-1}. At the end of each drying run and when the tray weights appeared to be fairly constant with time (drying lasted 72 h and 30 h at 40 and 80°C, respectively) drying was stopped and the residual moisture in the dried banana slices was determined by the oven drying (100°C for 24 h) method.

To evaluate the effect of air speed on the drying rate, the drying run at 60°C was repeated with the air velocity increased to 0.82 m s^{-1} and then to 1.03 m s^{-1}. The effect of slab thickness on the rate of air drying was also investigated by drying at 60°C whole bananas, 20, 10 and 5 mm thick fresh slabs and a similar set of whole bananas and fruit slabs but which were previously osmosed for 36 h in a 65° Brix solution.

Apparent moisture diffusivities in osmosed and non-osmosed (fresh) banana slabs dried at 60°C air dry bulb temperature and at an air flow rate of 0.62 m s^{-1} were estimated through a separate air drying run in which whole bananas which had been previously osmotically pre-treated in the three sugar solutions, were sliced into 10 mm thick slabs and then air-dried with similarly sliced but fresh slabs. Finally, % weight loss, colour and texture changes were measured on osmosed and fresh banana slabs when air dried at 60°C at an air speed of 0.62 ms^{-1}. Percent (%) weight loss was calculated on the basis of the slab's initial weight, and colour was expressed through the Hunterlab L and b-values as modulus $\sqrt{L^2 + b^2}$. A Gardner Colorgard (Pacific Scientific, Silver Spring, MD, USA) colorimeter was used to determine the L and b-values. Texture was subjectively rated by four assessors on a scale of 0–100 as follows: 0 – very soft and mushy; 20 – soft and sticky; 40 – soft and chewey; 60 – firm but pliable; 80 – leathery and 100 – hard and tough.

Theoretical methods

For drying of fruits and vegetables in the falling rate period Fick's diffusion equation is widely used to model the drying behaviour (Saravacos & Charm, 1962). The analytical solution to the diffusion equation has been given by Crank (1975) for an infinite slab of half thickness L_0 (m), of initially uniform moisture content M_0, and showing negligible resistance to mass transfer, the surface moisture content during the drying process being the equilibrium moisture content M_e.

Perry *et al.* (1984) noted that for long drying times, this solution can be simplified to a limiting form as follows:

$$M_r = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 Dt}{4 L_0^2}\right] \qquad (1)$$

M_r is called the removable moisture ratio, M is the time dependent variable moisture content of the banana slab (kg H_2O kg^{-1} DM), t is the drying time (h) and D (m^2 h^{-1}) is the apparent moisture diffusivity. Equation 1 is frequently written (Henderson & Perry, 1976) as:

$$\frac{M - M_e}{M_0 - M_e} = A \exp(-Kt) \qquad (2)$$

where K is the drying constant (h^{-1}) and is obtained from the slope of the plot of ln M_r vs. t. Often, and when low values of M_e are expected, the removable moisture in eqn 1 is reduced to $M_r = M/M_0$ (Labuza & Simon, 1970; Yusheng & Poulsen, 1988; Rahaman & Lamb, 1991).

Jason & Peters (1973) noted that this approach may be acceptable at high M-values and in the earlier period of drying, however, as $M \rightarrow M_e$, this may be inadmissible. Values of M_e for fresh and osmosed bananas were therefore predicted from the transient drying data of moisture content vs. time. At equilibrium, the drying rate is zero, i.e.:

$$\text{At } M = M_e, \quad \frac{dM}{dt} = 0 \qquad (3)$$

From plots of near equilibrium, final values of $\frac{dM}{dt}$ vs. M, and through regression analyses, M_e values were determined as the point where the graph cuts the M axis. This approach is valid if long drying times are employed and drying is approaching an equilibrium state, conditions met by these experiments. Other researchers have used mathematical approaches to predict M_e using extrapolation techniques (Jason & Peters, 1973; Hayakawa, 1974 & Marousis *et al.*, 1989) and this is an improvement upon finding the M_e asymptote through graphical inspection.

The apparent moisture diffusivities D during air drying at 60°C of fresh and osmosed banana slabs, initially 10 mm thick were estimated at various moisture contents ($M_r < 0.6$) by the method described by Perry *et al.* (1984) and also used by Del Valle & Nickerson (1968) for estimating D during the drying of salted fish. For a given value of M_r (M is therefore known), the theoretical value of (Dt/L_0^2) is calculated from eqn 1. At the same value of M_r, the predicted experimental value of t is obtained from the linear regression relationship of the drying data, i.e. ln M_r vs. t. Then D is obtained from

$$D = \frac{(Dt/L_0^2)_{the}}{(t/L_0^2)_{\exp}} \qquad (4)$$

where subscripts 'the' and 'exp' refer to theoretical and experimental values, respectively.

Results and discussion

The osmotic pre-treatment

The moisture content of fresh, fully ripened banana slabs averaged 3.13 kg H_2O kg^{-1} DM and after the 36 h osmotic dehydration pre-treatment, this value fell to 2.19, 1.63 and 1.16 kg H_2O kg^{-1} for immersion in the 35, 50 and 65° Brix solutions, respectively. These moisture values represent average losses in initial fruit weight at room temperature (25°C) of 6.3, 24.2 and 36.8% in the three solutions, respectively, and show the strong influence of the sugar concentration on water loss. Hope & Vitale (1972) noted that banana slabs when immersed in a 67° Brix solution for 18 h with gentle, occasional agitation can lose about 40% of their original moisture. The loss in weight of the slabs was accompanied by an increase in sugar content, as average TSS values of the osmosed banana slabs as measured by a Bausch and Lomb refractometer were 26, 34 and 39° Brix, respectively, when immersed in the three sugar solutions of increasing concentrations. These values can be compared to an average TSS value of 15° Brix for the fresh, ripe untreated banana slab. The net effect of water loss and sugar gain by the banana slabs in the osmotic pre-treatment resulted in shrinkage. From an initial slab thickness of 10.0 mm, slabs osmosed in 35, 50 and 65° Brix solutions shrunk to average values of 9.0, 6.0 and 5.0 mm, respectively.

The physical and chemical changes in the fruit slabs during osmosis cause differences in the drying rate, drying time and moisture diffusivity in the subsequent air drying process when compared to fresh fruit slabs.

Drying behaviour

Typical air drying curves for fresh and osmosed banana slabs at the minimum and maximum air dry bulb temperatures of 40 and 80°C, respectively, are shown in Fig. 1. The differences in initial moisture content reflect the varying degrees of water loss in the osmotic pre-treatment, as previously reported. The strong influence of drying air temperature is readily observed, as there is a very rapid decline in moisture at 80°C compared to drying at 40°C. However, both sets of curves show some convergence after 10 and 25 h of drying at 80 and 40°C, respectively, and as equilibrium conditions are approached.

This observed convergence and the predicted values of equilibrium moisture content M_e (asymptotes of the drying curves) indicate that M_e values are very dependent upon the drying air conditions, falling as the air dry bulb temperature is increased and as the relative humidity is decreased. This is demonstrated in Table 1 by the mean values given at each temperature. Notwithstanding the above, the mean values based upon sugar content show that banana slabs with the highest levels of infused sugar, i.e. 39 and 34° Brix also have a slightly higher level of

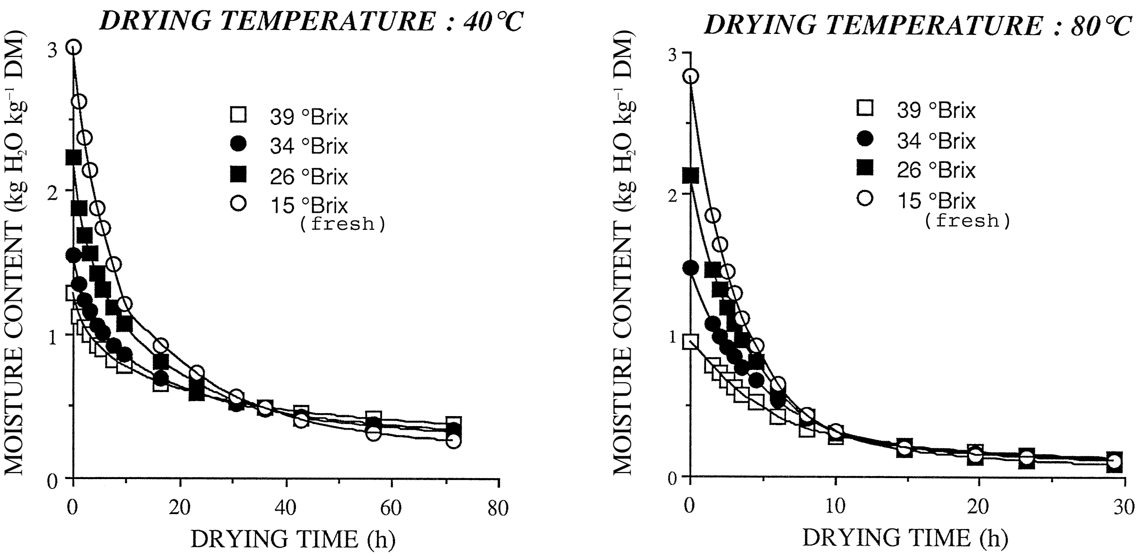

Figure 1 Drying curves for fresh and osmosed banana slabs.

Table 1 Equilibrium moisture contents of air dried fresh and osmosed banana, predicted from the transient drying data

Drying air condition (°C)			TSS content of slabs (°Brix)				Mean TSS
DB[1]	WB[2]	RH[3]	15° fresh	26° osmosed	34° osmosed	39° osmosed	
			Equilibrium moisture content (kg H_2O kg^{-1} DM)				
40	22	18	0.23	0.26	0.28	0.32	0.27
50	24	10	0.16	0.23	0.26	0.22	0.22
60	26	6	0.11	0.16	0.22	0.19	0.17
70	28	4	0.13	0.08	0.18	0.16	0.14
80	31	3	0.09	0.06	0.09	0.09	0.08
Mean			0.14	0.16	0.21	0.20	

[1]Dry bulb temperature. [2]Wet bulb temperature. [3]Relative humidity (%).

equilibrium moisture, a behaviour consistent with a humectant product. Equilibrium moisture contents were predicted from near equilibrium values because of the lengthy drying times required for the slabs to achieve equilibrium, constant weights, this time for example, exceeding 3 days for drying at 40°C.

The drying rate curves for the air drying of both fresh and osmosed banana slabs under all conditions, show drying to occur in the falling rate period. Figure 2 shows drying rate curves at the air drying temperatures of 40 and 80°C. These rates were calculated from the drying data for each drying run, i.e. from the moisture content change which occurred in each time interval for weighing. Drying rates were highest at the beginning of drying when the moisture content was the greatest, with fresh (non-osmosed) slabs therefore displaying the highest initial drying rates. This initial rate is therefore dependent upon the level of osmotic pre-treatment. In the early period of drying there is an rapid decline in the drying rate for all types of slabs. After this period of rapid decline in the drying rate, and below a certain critical moisture content in the falling rate period (e.g. 1.0 kg H_2O kg^{-1} at 40°C), the drying rate curves continue to decline, but more gradually and in a near linear fashion to equilibrium conditions. In fact below this critical moisture content, the differences in equivalent drying rates between fresh and osmosed slabs become small and obscure (Fig. 2). However, closer examina-

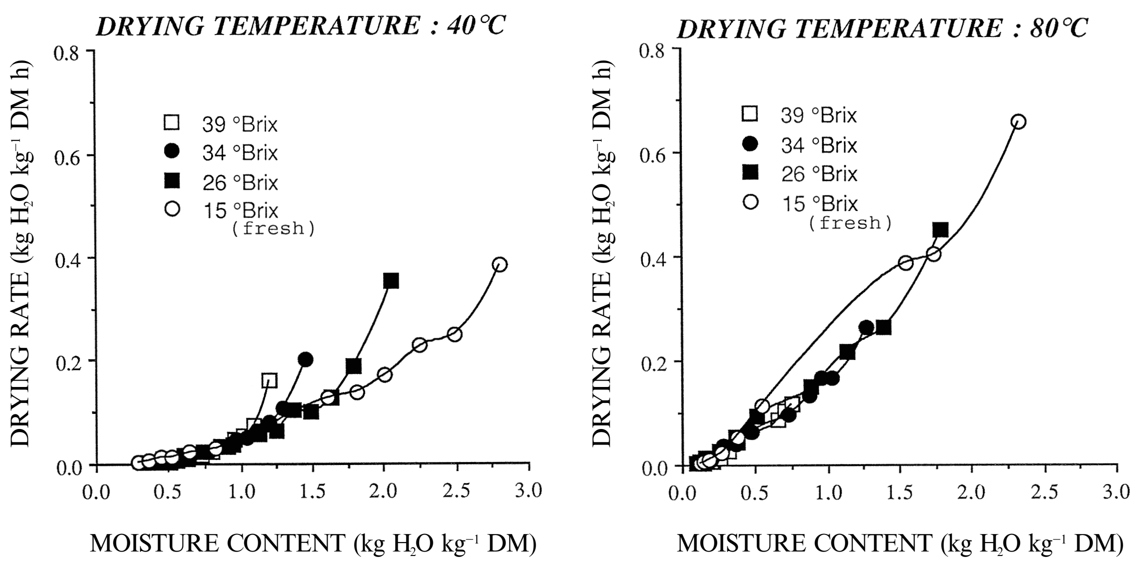

Figure 2 Drying rate curves at 40 and 80°C for fresh and osmosed banana slabs.

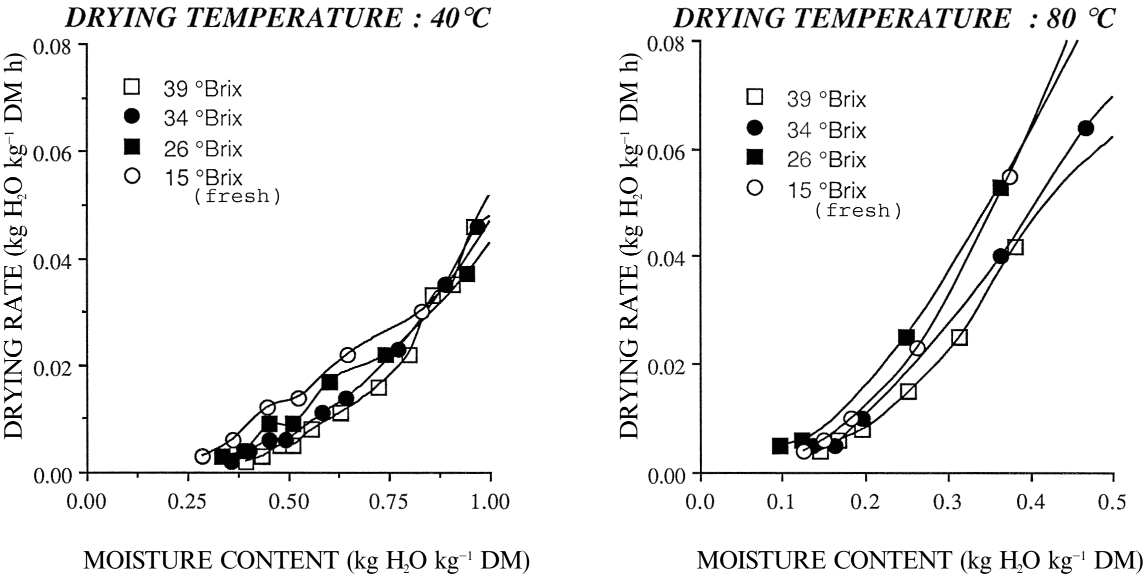

Figure 3 Drying rate curves at 40 and 80°C for fresh and osmosed banana slabs in the later period of drying.

tion of the drying rate data in the moisture content range of 1.0 kg H_2O kg^{-1} to M_e, shows untreated banana (fresh, 15° Brix) or those which are lightly osmosed (26° Brix) having higher drying rates compared to those with the higher sugar contents (Fig. 3). Van Arsdel & Copley (1963) reported that when the drying rates of potato pieces varying widely in sugar content were compared, the drying rate was unaffected to a moisture content near 0.30 kg H_2O kg^{-1}. However, the drying time from M = 0.3 to M = 0.075 kg H_2O kg^{-1} was longer, the higher the sugar content. Fresh, untreated banana slabs showed higher drying rates or water removal rates compared to osmosed slabs, because of the lower physico-chemical, water/sugar interaction in the fresh

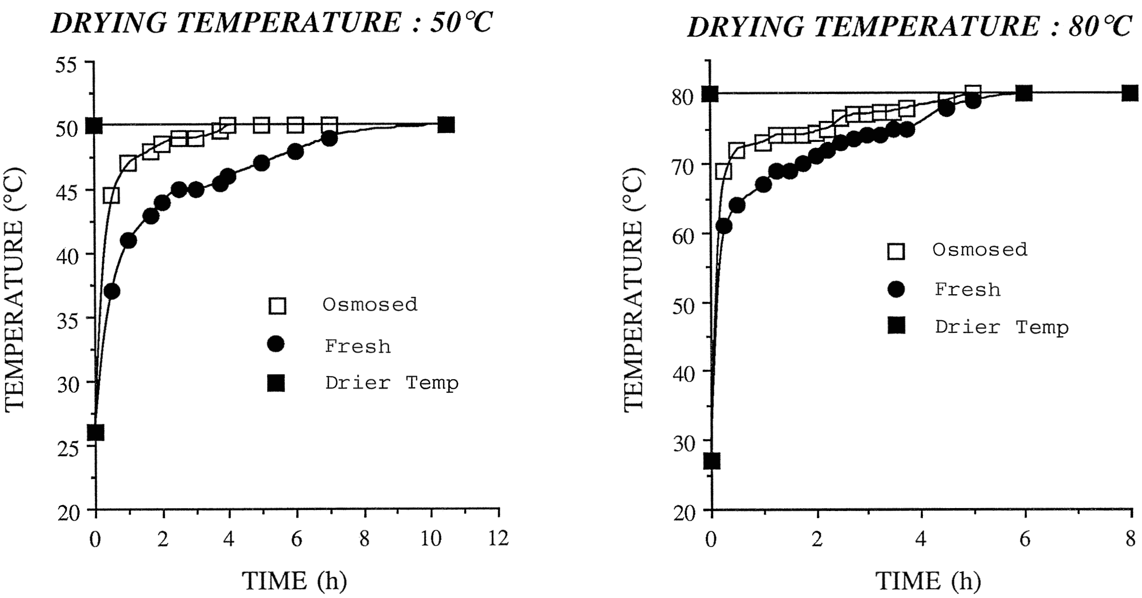

Figure 4 Temperature rise during drying near the surfaces of fresh and osmosed slabs at drier temperatures of 50 and 80°C.

product because of lower sugar content (Marousis *et al.*, 1989). This water binding capacity of sugar in foods is frequently referred to as humectancy. (Fennema, 1985).

Thermocouples inserted just below the surfaces of the slabs during air drying, monitored the temperature rise in the slabs. Figure 4 shows the temperature rise in the osmosed (39° Brix) and fresh slabs, for the 50 and 80°C air dry bulb temperature runs. In both cases, the temperatures at the surfaces rose steadily towards the set, drying air temperature, with no apparent equilibration seen near to the corresponding air wet bulb temperatures (24 and 31°C, respectively). Surface temperatures of fresh slabs were somewhat lower than those of osmosed slabs within the first few hours of drying because of the higher cooling effect of evaporation from the surfaces of the higher moisture, fresh slabs.

Both the drying rate curves and the steady temperature rises of the slabs' surfaces indicate that air drying of both fresh and osmosed banana slabs occur in the falling rate period. If a constant rate period does exist, it is very short and insignificant. Mowlah *et al.* (1983) noted that the falling rate period constitutes the major proportion of the overall drying time of banana slices, although they did report a constant rate period of 0.37 kg H_2O kg^{-1} h^{-1} for blanched, banana dices. Blanching of bananas and the disruption in the natural state of the tissues, particularly if severe rupturing occurs, will likely affect the drying

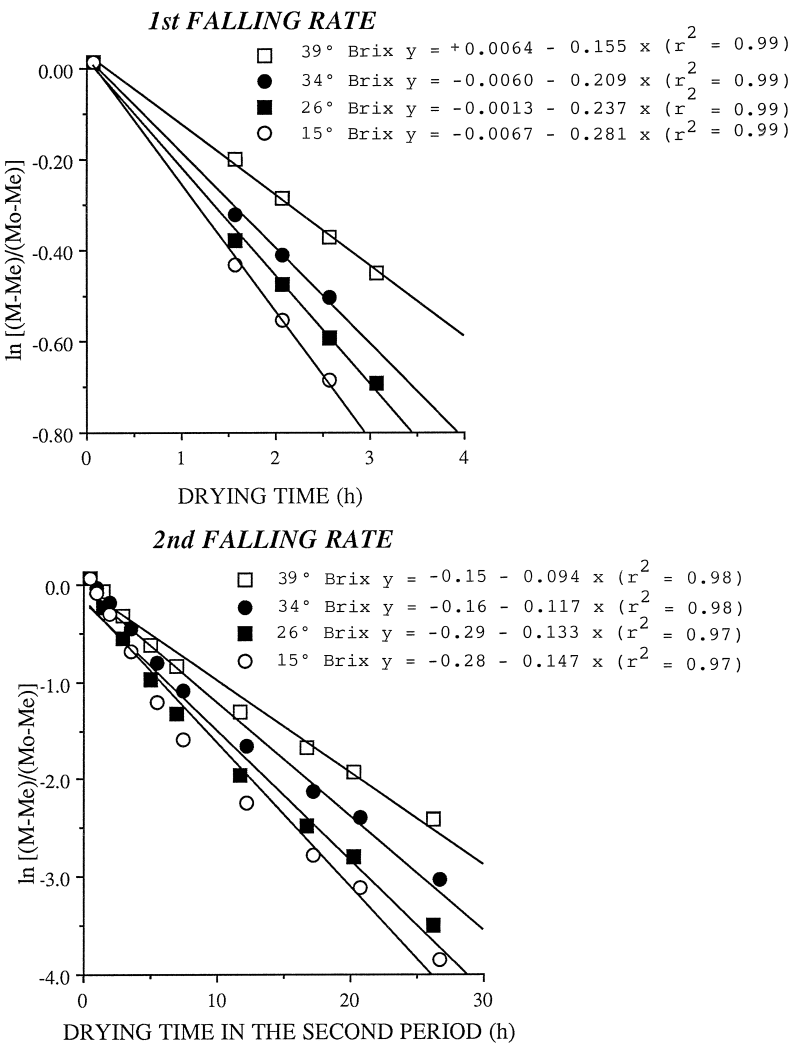

Figure 5 First and second falling rate drying curves at 80°C for fresh and osmosed banana slabs.

Table 2 Drying constants, K_1 and K_2, during the air drying of fresh and osmosed banana at various temperatures

Drying air temperature (°C)	TSS content of slabs (°Brix)				Mean TSS
	15° fresh	26° osmosed	34° osmosed	39° osmosed	
	Drying constant (h^{-1})				
		1st falling rate period K_1			
40	0.122	0.136	0.096	0.081	0.109
50	0.187	0.221	0.202	0.185	0.199
60	0.192	0.218	0.168	0.187	0.192
70	0.277	0.200	0.194	0.221	0.223
80	0.281	0.237	0.209	0.155	0.220
Mean	0.212	0.202	0.174	0.166	
		2nd falling rate period K_2			
40	0.053	0.044	0.037	0.032	0.042
50	0.104	0.073	0.084	0.061	0.085
60	0.145	0.123	0.103	0.071	0.111
70	0.242	0.181	0.110	0.140	0.168
80	0.147	0.133	0.117	0.094	0.123
Mean	0.138	0.111	0.090	0.080	

characteristics, compared to unblanched, natural bananas.

Drying constants

Linear regression analyses of the drying data (ln M_r vs. t) did not generally produce a very good fit because of some deviation from linearity after a certain time had elapsed. The drying curves were therefore broken into two linear sections, corresponding to two diffusion controlled drying rate periods as proposed by Jason & Peters (1973). The break point separating the first and second periods of drying was found to occur after 2–3 h of drying in all the runs. This approach is illustrated in Fig. 5 which shows the 1st and 2nd falling rate periods of drying at 80°C, as well as the regression equations. The drying time given in the 2nd falling rate period (Fig. 5) refers to the time of drying only from the commencement of this period. Drying constants K_1 and K_2 were therefore established (eqn 2) from the slopes of the lines, and the r^2 values obtained ranged from 0.96–1.00. Some curvature in the points is noted in Fig. 5 (2nd falling rate period) and this is indicative of a variable, possibly moisture dependent diffusivity. Table 2 shows the K_1 and K_2 values obtained for the various drying air temperature conditions, and these values can be used to describe the average drying behaviour of the samples during the respective periods.

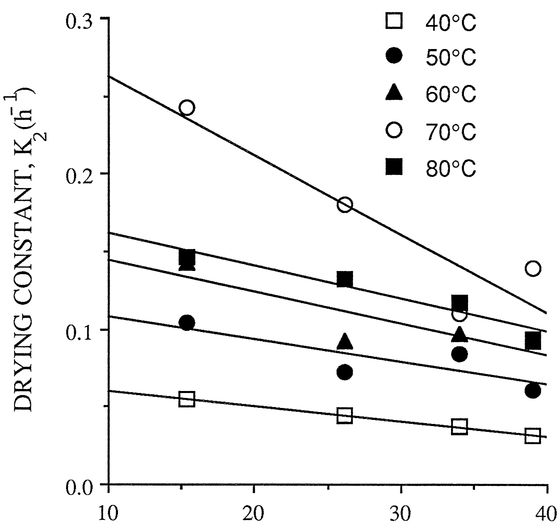

Figure 6 The effect of sugar content on the drying constant K_2 at various drying air temperatures.

Increasing the air temperature had a marked effect on the drying rates of fresh banana slabs (Fig. 6), increasing as the air temperature is raised. This is borne out by the K_1 and K_2 values (Table 2) which generally increase with temperature. As the sugar content of the slabs is

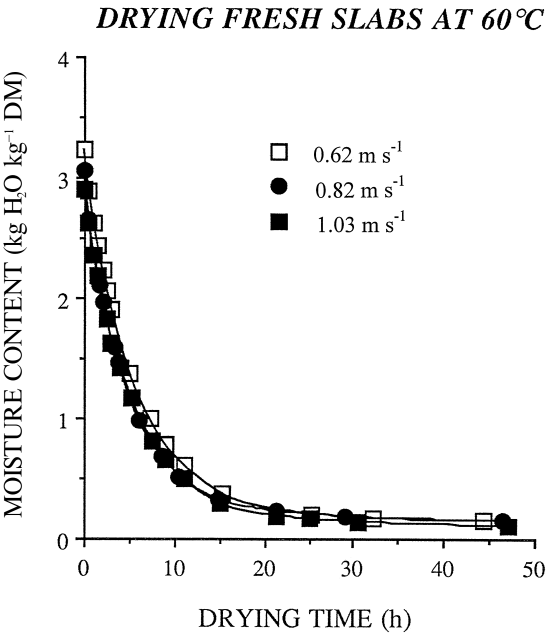

Figure 7 The effect of air velocity on the drying behaviour of fresh banana slabs dried at 60°C.

increased, and particularly at 34 and 39° Brix, the positive effect of air temperature on the drying rate and the drying constants is not as pronounced. These effects are seen in Fig. 6. At 80°C in particular and in the later period of drying (2^{nd} falling rate), drying constants were generally less than at 70°C even for fresh (15° Brix) slabs. Drying air temperatures above 70°C therefore do not seem to be beneficial, probably because of case hardening of the slabs.

Overall mean values of the drying constants (Table 2) clearly show decreasing K_1 and K_2 values as the sugar content rises in the slabs. This effect is more pronounced in the second period of drying (Fig. 6), a period in which the slabs were shrinking, becoming denser and tougher and the resistance to internal moisture movement is increased. Marousis *et al.* (1989) noted that the incorporation of sugars into starchy materials will in general decrease water diffusivity, mainly because of the reduction in the porosity of the material. The water binding, hygroscopic nature of the infused sugar will also increase internal resistance to moisture movement (Rahaman & Lamb, 1991) and differences in the hydrophllic constituents of foods can therefore affect their drying rates.

The drying rates of both fresh and osmosed banana slabs are remarkably slow, compared to other fruits and vegetables. Saravacos & Charm (1962) reported single K-values at drying air temperatures of 61–65°C of 1.53 h^{-1} for 3 mm thick, sliced blanched potatoes, 2.12 h^{-1} for

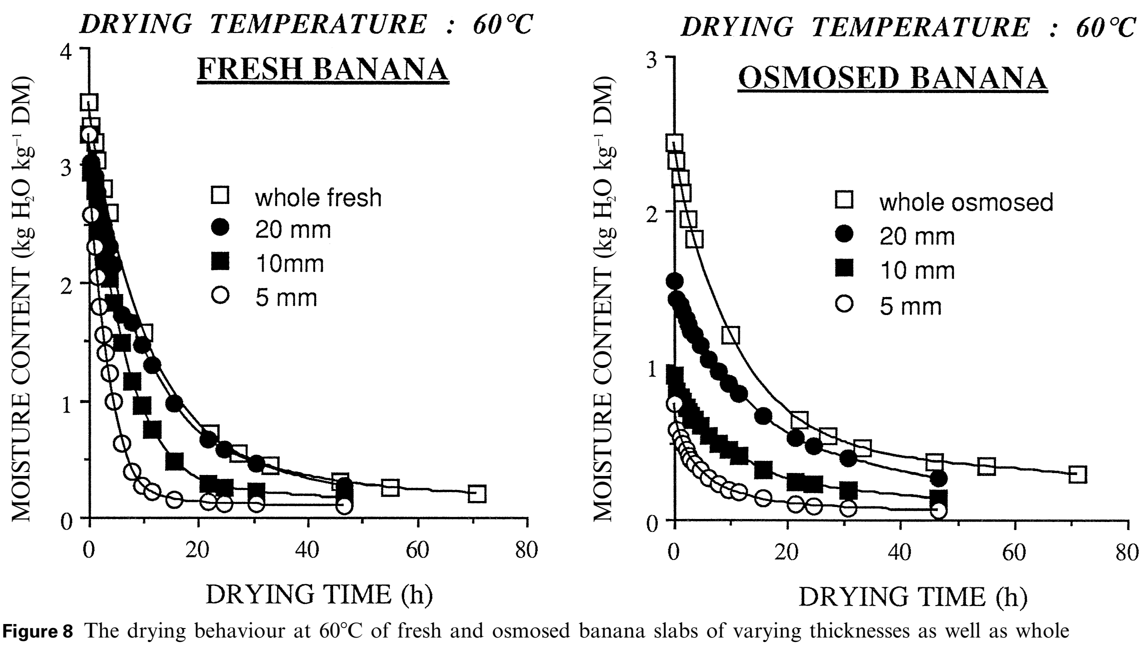

Figure 8 The drying behaviour at 60°C of fresh and osmosed banana slabs of varying thicknesses as well as whole bananas.

12 × 12 × 6 mm diced apples, 0.95 h^{-1} for 6 mm thick pear slabs, 0.35 h^{-1} for peach halves and 0.3–0.4 h^{-1} for seedless grapes dried in a single layer. These values can be compared to the 60°C K_1 and K_2 values found in this study for the 10 mm thick, fresh banana slab of 0.192 h^{-1} and 0.145 h^{-1}, respectively.

Increasing the air velocity from 0.62 m s^{-1} to 0.82 m s^{-1} and finally to 1.03 m s^{-1} did not markedly influence drying behaviour. However, a small improvement in the drying rate (Fig. 7) was observed when fresh slabs were dried at higher air speeds. For the lower initial moisture, osmosed slabs, the effect of air speed could be considered insignificant. Mean K_1 and K_2 values found for the osmosed slabs at 0.62, 0.82 and 1.03 m s^{-1} were 0.191, 0.222 and 0.206 h^{-1} for K_1, respectively, and 0.099, 0.114 and 0.94 h^{-1} for K_2, respectively. In the drying process, two resistances to moisture movement, internal and external, can be considered, with the internal resistance to moisture migration being the dominant, rate controlling mechanism in the falling rate period. Saravacos & Charm (1962) and more recently Yusheng & Poulsen (1988) both noted that air velocity did not significantly influence drying in the falling rate period, but they were working at higher air velocities (1.02–3.10 m s^{-1}) compared to this study. Islam & Flink (1982b) noted that in natural convection drying, air velocities are low, generally below 1 m s^{-1}, and under such circumstances drying occurs with significant external mass transport resistances. It would therefore appear from these observations, that an air flow velocity of 0.82 m s^{-1} represents a threshold level above which any external resistance to moisture movement in the drying of banana slabs is of little consequence.

Figure 8 shows drying curves at 60°C and 0.62 m s^{-1} for whole and sliced bananas (5, 10 and 20 mm), dried fresh or after osmotic pretreatment in a 65° Brix solution. Slab thickness significantly affected the drying rate, with the 5 mm thick slabs showing the fastest rate of moisture content reduction. When the drying constants were evaluated, the dependence of K_1 and K_2 on the slab thickness L_0 is clearly seen (Table 3). Whole bananas, 30 mm in diameter when fresh and 25 mm in diameter after osmosis, showed a very similar drying behaviour to the 20 mm thick slabs. In the Caribbean, whole ripe bananas are frequently sun or solar dried to produce banana figs and their drying behaviour is therefore of practical interest. These results on slab thickness again demonstrate the internal, rate controlling nature of the drying process. As given by eqns (1) and (2), $K \propto L_0^{-2}$ or as proposed by Vaccarezza & Chirife (1978), $K \propto L_0^{-n}$ where n may be calculated and compared to the expected theoretical value of 2. They found $n = 1.80$ for sugar beet slabs which was raised to 1.96 when a correction factor based upon heat transfer effects was introduced. Yusheng & Poulsen (1988) found $n = 1.83$ for potato slabs and Alzamora *et al.* (1980) reported $n = 1.69$ for avocado slabs. In this study for fresh banana slabs, whose thicknesses were firmly established compared to osmosed slabs where considerable shrinkage occurred before drying, values of $n = 0.78$ ($r^2 = 0.97$) and $n = 0.70$ ($r^2 = 0.94$) for the first and second falling rate periods of drying were calculated. This discrepancy has been previously commented upon, with the existence of external mass transfer resistances and low air velocities being the reasons attributed to values of n being lower than 2 (King, 1968; Vaccarezza & Chirife, 1978 & Islam & Flink, 1982a). As previously noted, at an air velocity of 0.62 m s^{-1} under which these trials were conducted, this appears to be a distinct possibility.

Table 3 The effect of slab thickness on the drying constants of fresh and osmosed banana at 60°C

Slab thickness (mm)	Drying constants (h^{-1})			
	Fresh		Osmosed	
	K_1	K_2	K_1	K_2
5	0.279	0.180	0.224	0.105
10	0.141	0.138	0.145	0.072
20	0.098	0.072	0.088	0.064
Whole	0.086	0.052	0.084	0.065

Moisture diffusivities

When the apparent moisture diffusivities D were calculated using eqn. (4), for drying at 60°C of fresh and osmosed banana slabs (air speed = 0.62 m s^{-1}) with all slabs 10 mm thick before air drying, the results were quite revealing. Calculated diffusivities ranged from a high of 34.8 × 10^{-10} m^2

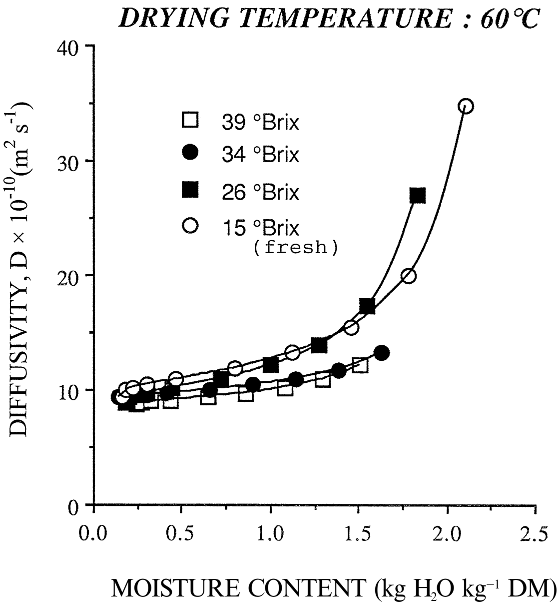

Figure 9 The changes of the moisture diffusivity in banana slabs of increasing sugar content in the drying process at 60°C.

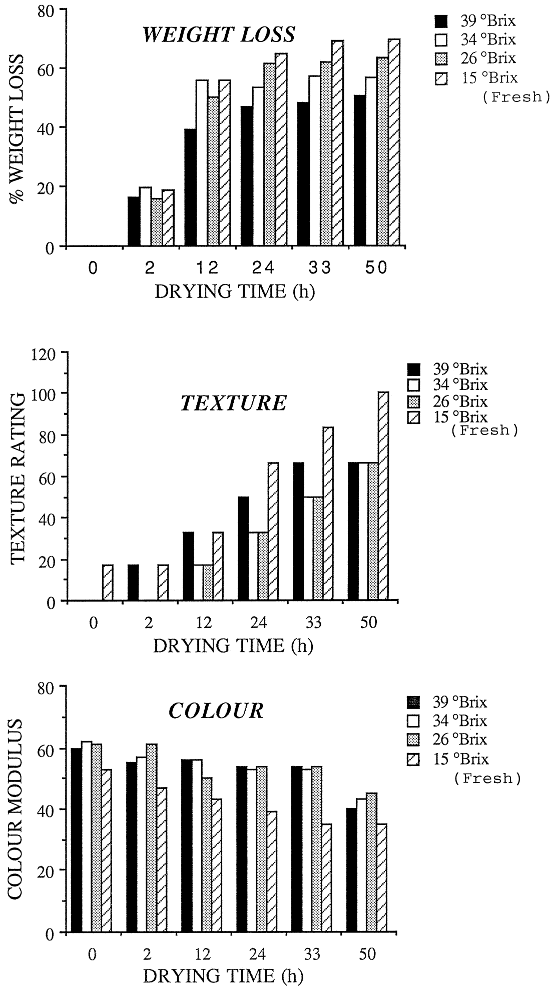

Figure 10 Changes in fresh and osmosed banana slabs during drying.

s^{-1} for fresh banana slabs at a moisture content of 2.1 kg H_2O kg^{-1}, to a low of 8.8×10^{-10} m^2 s^{-1} for 39° Brix banana slabs at a moisture content of 0.2 kg H_2O kg^{-1}. On drying, the 10 mm thick osmosed slabs shrunk to mean thickness of 3.7, 3.4, 3.0 and 1.6 mm for the 39, 34, 26 and 15° Brix samples, respectively. Figure 9 shows that as the moisture content decreased during the drying process, moisture diffusivities also decreased. This is particularly noticeable for the high initial moisture, fresh slab and the 26° Brix slab. This is an expected behaviour since moisture migration becomes increasingly difficult as the physical structure becomes denser and harder during drying. Further, as additional sugar is infused into the slabs in the osmotic pre-treatment, apparent diffusivities also fall. Hence slabs with the highest TSS content of 39° Brix consistently showed the smallest D-values (Fig. 9). Similar results were found by Rahaman & Lamb (1991) who concluded that osmosed pineapple slices containing the most sucrose had the lowest apparent moisture diffusivities (1.62×10^{-10} compared to 12.54×10^{-10} m^2 s^{-1} in the osmosed and non-osmosed samples). Saravacos & Raouzeos (1984) obtained a mean D-value of 5.9×10^{-10} m^2 s^{-1} for a 1:1 starch/glucose gel at 50°C and concluded that the presence of glucose in the gel resulted in a significant decrease in the drying rate and the D-value. Marousis *et al.* (1989) noted that the apparent diffusivities of water in the temperature range 40–100°C in granular starches and starch/sugar mixtures varied in the range $1–100 \times 10^{-10}$ m^2 s^{-1}, depending upon moisture content and temperature. They stated that the incorporation of sugars in starchy materials generally decreased the diffusivity mainly because of the significant decrease of the porosity of the materials.

Product quality

As banana slabs lost weight in the drying process, they became tougher, with this increase in toughness being much more pronounced for fresh banana slabs compared to osmosed slabs (Fig. 10). Osmosed or sugar infused slabs after drying were generally soft and chewy even after 40% weight loss had occurred, whereas fresh, untreated slabs were quite firm in texture. As the colour modulus (Fig. 10) shows, osmosed slabs (with SO_2) maintained a predominantly pleasant yellow/orange colour during the drying process, compared to the fresh untreated slabs which became light to dark brown very rapidly. The addition of sugar through osmosis and the use of an antioxidant like SO_2 can therefore be used for the development of a shelf stable, dehydrated banana product of appealing colour and favourable texture.

Conclusions

This study has shown that both fresh and osmotically pre-treated banana slabs dry in the falling rate period and the solution to Fick's diffusion equation for an infinite slab may be used to model the drying behaviour. Drying was found to occur in two falling rate periods and appropriate drying constants established. Drying rates and constants were very much influenced by the air dry bulb temperature (40–80°C) and the thickness (5–20 mm) of the slabs. Drying at temperatures above 70°C is not recommended as case-hardening may inhibit drying rates. The K-values found show that banana dries much slower compared to many other fruits, principally because of its physical/chemical composition. Air flow rates between 0.62–1.03 m s^{-1} did not markedly affect drying behaviour although below 0.82 m s^{-1} a small decrease was detected in the drying rate of fresh slabs. Increasing the sugar content of the slabs through the prior osmotic step, resulted in decreased drying constants, and the beneficial effect of moisture loss in the osmotic pre-treatment may be lost in the subsequent air drying step because of reduced drying rates. Calculated apparent moisture diffusivities bear this out, as D-values fell with increasing sugar and reduced moisture content. However, the addition of sugar in an osmotic pre-treatment is desirable for the dehydrated banana slab, as together with an antioxidant, this can result in a dehydrated product of good colour and texture.

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