Drying characteristics and quality of bananas under infrared radiation heating

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Abstract: Hot air (HA) drying of banana has low drying efficiency and results in undesirable product quality. The objectives of this research were to investigate the feasibility of infrared (IR) heating to improve banana drying rate, evaluate quality of the dried product, and establish models for predicting drying characteristics. Banana slices of 5 mm and 8 mm thickness were dried with IR and HA at product temperatures of 60 ℃, 70 ℃ and 80 ℃. Banana drying characteristics and changes in residual polyphenol oxidase (PPO), Hydroxymethylfurfural (HMF), color, moisture content (MC) and water activity during the treatments were investigated. Results showed that significant moisture reduction and higher drying rates were achieved with IR drying compared to HA drying in the early stage. The drying data could be fitted to the Page model for accurate prediction of MC change for IR and HA drying with mean R^2 of 0.983. It was noted that enzyme inactivation occurred more quickly with IR than with HA drying. A unique response of PPO under IR and HA drying was revealed. IR heating of banana inactivated PPO within the first 20 min of drying at 60 ℃, 70 ℃ and 80 ℃, while PPO was first activated before inactivation at 60 ℃ and 70 ℃ drying with HA. The highest HMF content occurred in banana slices with 5 mm thickness dried with IR at a product temperature of 80 ℃. It is therefore recommendable to dry banana with IR at product temperature of 70 ℃ or below to preserve the product quality. These findings are new and provide more insight in the application of IR heating for drying banana for improved drying rate and product quality.

Keywords: drying, banana, infrared radiation, hot air drying, enzyme inactivation
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1 Introduction

Banana, a high sugar tropical fruit grown worldwide, is quite susceptible to quality deterioration during conventional hot air (HA) drying[1-4]. Due to low thermal conductivity of the high sugar containing banana, heat transfer to the inner sections of foodstuffs in the falling rate period is limited during conventional heating, which renders low energy efficiency and lengthy drying time. Owing to the high sugar contents, banana drying normally requires high temperatures and prolonged drying time, which adversely affect its flavor, color, texture, nutrients, and rehydration capacity. As processors continue to grapple with lack of low-cost and energy efficient drying technology, the demand for the dried banana and co products shows a steadily increasing

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trend[5-9]. There is a need to develop alternative banana drying technology which can insure energy efficiency during dehydration and at the same time provide products with high quality.

Infrared (IR) heating is gaining interest in the food industry as an energy efficient drying technology. The IR emitters can have efficiencies as high as 80%-90% and greater heat transfer rates than convective heating[10]. Because IR heating does not need a medium to transfer the heat, the energy transfer is highly efficient and could result in reduced energy cost and drying time compared to HA drying of banana[7,11,12]. IR heating for dehydration of fruits, vegetables, and other agricultural products[13] has also indicated promising results. Investigation[14] on the application of infrared radiation to vacuum drying of Cavendish banana slices revealed promising results in terms of higher drying rates and better product quality. In another study[15], low-pressure superheated steam coupled with far-infrared radiation was recommended as the best drying condition, though the operating IR temperature was moderately high at 80℃. There are also reports on the use combined IR radiation and cryogenic freeze drying to improve the dried product quality[16]. It is important to realize that while freeze drying provides best product quality, the cost related to freeze drying alone is very high for an industrially sustainable processing. However, the cost related to IR assisted freeze drying could be significantly reduced by optimizing the time of freeze-drying. Practical research addressing the relationships among various process parameters and finished product quality, particularly for banana drying with infrared, has not been addressed.

Product color is one of the most important sensory attributes of food products, and many food producers utilize the psychological effect of color to enhance their products[17]. The browning of banana is considered to be one of the main causes of quality loss during handling, processing and storage. The mechanism of browning for many fruits can be of enzymatic or non-enzymatic origin[18]. Maillard browning is a non-enzymatic reaction that causes browning in fruits during drying. It is a chemical reaction between amino acids and reducing sugars, usually requiring the addition of heat[19]. Under less acidic conditions (pH > 5), the reactive cyclic compounds (Hydroxymethylfurfural (HMF) and others) are polymerized quickly to dark-colored, insoluble material containing nitrogen. It is generally difficult to ascertain whether the mechanism is enzymatic or non-enzymatic unless the enzyme is first inactivated. However, very few studies have been done to determine the contribution of either enzymatic or non-enzymatic browning to the overall browning. Nimmol et al.[15] studied the effects of using a combination of low-pressure super-heated steam - far infrared radiation (LPSSD-FIR) and vacuum - far infrared radiation (VACUUM-FIR) to determine the drying characteristics of bananas. Although the banana slices were dried in a shorter time than with convective drying, their color was dark. They attributed the cause of browning to only non-enzymatic browning but did not consider enzymatic browning; neither did they specify the type of non-enzymatic browning.

The main objective of this research was to investigate the potential of using IR heating to improve the drying rate and quality of banana. The specific objectives were: (1) Study the drying characteristics of banana during IR and HA drying; (2) Determine the impact of IR drying on product quality; (3) Study the contribution of both enzymatic and non-enzymatic browning to the overall browning in banana dried with IR; and (4) Develop models to predict the drying characteristics of banana dried with IR heating. IR dried banana was compared with that from HA drying as a control.

2 Materials and methods

2.1 Materials

Cavendish bananas (*Musa* spp. AAA group) cv.“Grand Nain” Chiquita brand at commercial maturity were purchased from General Produce Co. (Sacramento, CA). At purchase, the bananas had been ripened with ethylene gas and were at color stage 2.5 according to the Dole color Chart (Dole Castle & Cook, Inc). They were then stored at a controlled temperature of 18°C until they reached color stage 4 (a peel color more yellow than green). The moisture content (MC) ranged from 73.5% to 76.6% on a wet basis.

2.2 Infrared dryer setup

A catalytic infrared (CIR) dryer used in this research was equipped with two IR emitters (30 cm × 60 cm) powered by natural gas (Catalytic Infrared Drying Technologies LLS, KS). Wave guards were installed around the emitters to minimize heat loss. A drying tray made of a stainless steel screen was located in between and positioned parallel to the emitters. Banana slices were placed in a single layer on the drying tray and heated from both sides with IR. An automatic data acquisition and control (DAC) system developed in the Food Processing Laboratory (Department of Biological Engineering, University of California Davis) was used to control and continuously record various operation parameters such as gas flow rate, material temperature, emitter temperature and time. The IR dryer was operated in the intermittent mode according to a pre-set product temperature. The schematic diagram of the equipment used in this research is described in our previous publication[20].

2.3 Infrared drying of banana

Banana slices with 5 mm and 8 mm thickness were used in this study. The slices were arranged in a single layer on a drying tray (40 cm × 20 cm by area) at a loading rate of approximately 2.5 kg/m^2 and 3 kg/m^2, respectively. The trays were sprayed with PAM cooking spray (ConAgra Foods Inc., Omaha, NE) to prevent product from sticking. Type K (NiCr–NiAl) thermocouples were inserted at the center of banana slice for each of the studied slice thicknesses. The thermocouples had 0.81 mm diameter and time constant of 1.8 s. For each experiment, a set of four slices were used during temperature measurement and a fifth thermocouple was inserted into another slice and connected to a computer based DAC system to permit programming of emitter cycles for a set product temperature. Prior to starting drying, the IR emitters were pre-heated. Intermittent IR drying tests were conducted with final product temperatures controlled at 60 ℃, 70 ℃ and 80 ℃. The product temperature was recorded continuously with a data logger (21X Micrologger, Campbell Scientific Inc., Logan, UT) during the drying period. The distances from the drying tray to the upper and lower emitters were fixed at 40 cm and 45 cm, respectively, with an average radiation intensity of 4600 W/m^2.

2.4 Hot air dryer setup

About 450 g of banana slice samples were arranged in a single layer on the trays and dried in pre-heated Proctor & Schwartz cabinet dryer (Product code 062, Proctor & Schwartz, Inc, Horsham, PA) at material temperatures of 60 ℃, 70 ℃ and 80 ℃. Air velocity in the dryer was 4 m/s, relative humidity was (50±1)% and temperature of the ambient air was 21.6 ℃.

2.5 Drying models

The drying data was fitted to the Exponential and Page Models to evaluate their suitability to describe the drying process. The two models were chosen because they are widely used for describing drying of most biological materials. Comprehensive modeling of banana drying process under infrared heating will be a subject of another manuscript. Model curves were fitted to the experimental data, and the performance of the model was determined by the determination coefficient (R^2). A higher R^2 indicates a better fit for the model.

The Newton equation[21,22] or Exponential model (Equation (1)) was used because of its simplicity, high correlation to most drying data, and common use in the literature. The drying constant, k (min^{-1}), can be estimated using the model:

$$MR = \exp(-kt) \quad (1)$$

The moisture ratio (MR) was determined using the average MC data collected in the drying experiments and Me (equilibrium moisture) estimated at 5% (d.b.). MR was plotted on a semi-logarithmic axis versus the time (t), and the slope of the fitting line was the value of the constant k, as in the following equation:

$$-\ln(MR) = kt \quad (2)$$

Determination coefficients were also calculated for all drying conditions.

The Page equation is a modification of the exponential model which includes the addition of an exponent, n. It has been used extensively in thin layer drying of agro-products including fruits and vegetables[23]. The Page equation can be written as:

$$\ln\left[\frac{M(t)-M_e}{M_i-M_e}\right] = -kt^n = y(t) \quad (3)$$

It may also be rewritten as:

$$\ln[-y(t)] = \ln(k) + n\ln(t) \quad (4)$$

where the slope of the line ln[-y(t)] vs. ln(t) gives the value of n, while the exponential of the intersection of this line with y-axis gives the value of k[24]. Kashaninejad et al.[25] suggested expressing time in minutes for use in the Page model because if t = 1, n has no effect on t^n. Therefore, in this study, the unit of time is in minute.

2.6 Moisture content

The MC was determined according to AOAC Official Methods of Analysis 1984. Dried samples of 10 g were spread as evenly as possible over the bottom of pre-weighed aluminum dishes of 8.5 mm diameter and dried for at least 6 hrs at (70±1) ℃ under 25-30 mm Hg of pressure in a vacuum oven (Model No. V01218A, Lindberg/Blue, Ashville, NC). Fresh and high-moisture samples were left to dry for 24 hrs. The balance used for weight measurements had an accuracy of 0.01 g (Mettler Toledo, Model XS 6002S, Thermo Fisher Scientific Inc., Waltham, MA). The MC was determined based on the initial and final sample weights (Equation (5)):

$$MC_{db} = \frac{Mi - M_d}{M_d} \times 100 \quad \text{or} \quad MC_{wb} = \frac{M_i - M_d}{M_i} \times 100 \quad (5)$$

where, MC_{db} or MC_{wb} is the MC on a dry basis or wet basis; M_i is the initial mass in gram in the test portion and M_d is the dry sample mass in gram. Three samples from each trial were used for moisture determination, and the average MC was reported on both dry and wet basis. Samples were recovered for MC determination every 20 min during the first one hour and thereafter every 60 min. The samples were kept sealed in Zip Loc freezer bags at ambient conditions for 8 hrs before MC determination using the AOAC Official Methods of Analysis 1984. The procedure of keeping the samples in sealed Zip Loc freezer bags at ambient conditions for 8 hrs ensured that no moisture was gained or lost by the sample at the time of MC determination.

2.7 Water activity

The same samples used for MC determination were used for water activity measurements. High moisture samples were crushed in a laboratory mortar with a pestle, and dried ones were crushed in a blender (Waring, model 51BL31 (7011), Highland Brands, LLC., Columbus, OH). The material was spread over the bottom of a sample cup and placed in an Aqua Lab water activity meter (Model CX-2, Decagon Devices, Pullman, WA). The water activity meter had an accuracy of ±0.003 a_w and temperature ±0.1 ℃.

2.8 Color measurements

Samples were taken every 20 minutes during the first hour and thereafter every one hour of drying for immediate color measurement. Color was measured using a Minolta CM-200 reflectance colorimeter (Minolta, Japan) to obtain L^*, a^* and b^* values. The reported color values were the measurement averages of 15 slices per sample in four different locations of each slice. The total color change was then determined using the following equation[26]:

$$\Delta E = \sqrt{(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2} \quad (6)$$

L_o^*, a_o^* and b_o^* are initial color values; L^*, a^* and b^* are final color values.

2.9 Polyphenol oxidase (PPO) measurement

Determination of residual PPO was based on the method reported by Anthon and Barrett[27]. Enzyme inactivation curves were generated for each drying method under different treatment conditions. Also, enzyme inactivation kinetics at different product temperatures was determined according to first order reaction rate equation:

$$Log(A / A_o) = (-k / 2.303)t \quad \text{or}$$

$$Log(A) = Log(A_o) - \frac{kt}{2.303} \quad (7)$$

where, A_o (10^5 units) is the initial enzyme activity; A is the activity after heating for time t; k is the rate constant.

2.10 Hydroxymethylfurfural

Investigation of HMF as an indicator of Maillard browning in dried banana was based on the method of Meydav and Berk[28]. The amount of HMF was determined by the following equation:

$$\text{HMF (mg/L)} = \frac{(\text{A440 sample - A440 blank}) \times 126.1}{(\text{slope of standard curve}) \times 1000 \times \text{V}} \quad (9)$$

where, A440 is absorbance of sample and blank read at

440 nm; 126.1 is the molecular weight of HMF and V is the volume (mL) of banana supernatant added. In this study, weight, on a dry basis, substitutes for the volume, and therefore HMF is reported in mg/kg d.b. or ppm.

2.11 Statistical analyses

Duplicate experiments were conducted for each of the temperature settings, 60℃, 70℃ and 80℃, and two drying methods, IR and HA. For each experiment three sample replicates were used. Data for water activity, PPO, and overall color change was analyzed statistically using SAS (Statistics Department, UC Davis). Post-hoc tests were performed using the Turkey-Kramer adjustments for multiple comparisons. Data was considered significantly different when $P < 0.05$.

3 Results and discussion

3.1 Product temperature profiles during IR and HA drying

Figure 1 (a) and (b) show that all the three targeted drying temperatures were reached in less than 9 min with IR and more than 90 min with HA (Table 1). Boudhrioua et al.[29] found that product temperatures of 5 mm thick banana slices reached drying air temperatures after about 120 min. Results in this study agreed with what was obtained during IR and HA drying of onions[30] in which product temperature increased faster with IR heating than HA. The faster rise in product temperature was due to higher rate of heat delivery with IR than HA. There were more fluctuations in product temperature with IR than HA due to fluctuations in IR heating in response to the pre-set intermittent mode of IR heating temperature which was controlled by the DAC system.

Table 1 Times required to reach targeted temperatures for different thicknesses of banana slices under infrtared (IR) and hot air (HA) drying

Product temperature	Time to reach targeted temperature/min			
	5 mm, with HA	5 mm, with IR	8 mm, with HA	8 mm, with IR
60 ℃	108	2	119	4.0
70 ℃	112	4	132	6.6
80 ℃	92	8	215	8.2

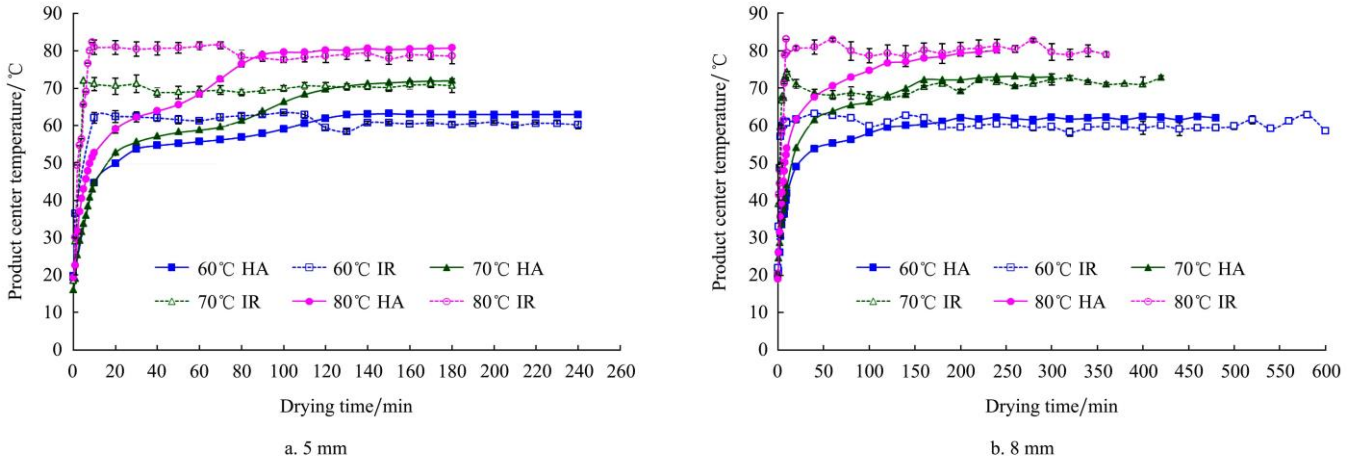

Figure 1 Changes in temperature of banana slices during drying with IR and HA for 5 mm (a) and 8 mm (b) slice thicknesses

In the early stage of IR drying, specific heat capacity of the product was relatively high due to high MC. As drying progressed, the MC decreased, hence specific heat decreased. Less heating energy is required to increase the temperature of a substance with low specific heat capacity than one with high specific heat capacity. Low specific heat meant that the product temperature was more sensitive to the emitter being on and off. Therefore, in effort to maintain the pre-set product temperatures, the gas supply was shut off for the bottom emitter but the basic heat supplied by electric heating was maintained. This successfully prevented excessive increase in product temperature and insured appropriate on and off cycle time as reported in our previous research[13].

During drying with HA, heating was continuous at constant temperatures hence less fluctuation occurred. In general, there was a rapid increase in temperature at the beginning, more for drying at 80℃. The rapid temperature increase was followed by a gradual increase

until the target product temperature was attained. Afterwards the product temperature remained constant until the end of each drying cycle. For each targeted drying temperature, thinner slices (5 mm) heated faster than the thicker ones (8 mm) at the beginning of drying.

Figure 2 shows product center and surface temperature profiles during drying with IR for banana slices with 5 mm (a) and 8 mm (b) thicknesses. During the initial stage of drying, there was a rapid increase in surface temperature as expected with a corresponding increase of the product center temperature. At all drying temperatures, the surface temperatures fluctuate more than center temperatures. This could be due to automatic switching on/off of the IR emitters which was controlled based on the product center temperature. Swasdisevi et al.[31] observed similar temperature fluctuations during vacuum-infrared drying of bananas. Since the surrounding air is almost at room temperature, the surface cools down faster than the center during the off mode. The surface cooling could also be due to the fact that as the water evaporated it removed heat from the banana surface in terms of the heat of vaporization.

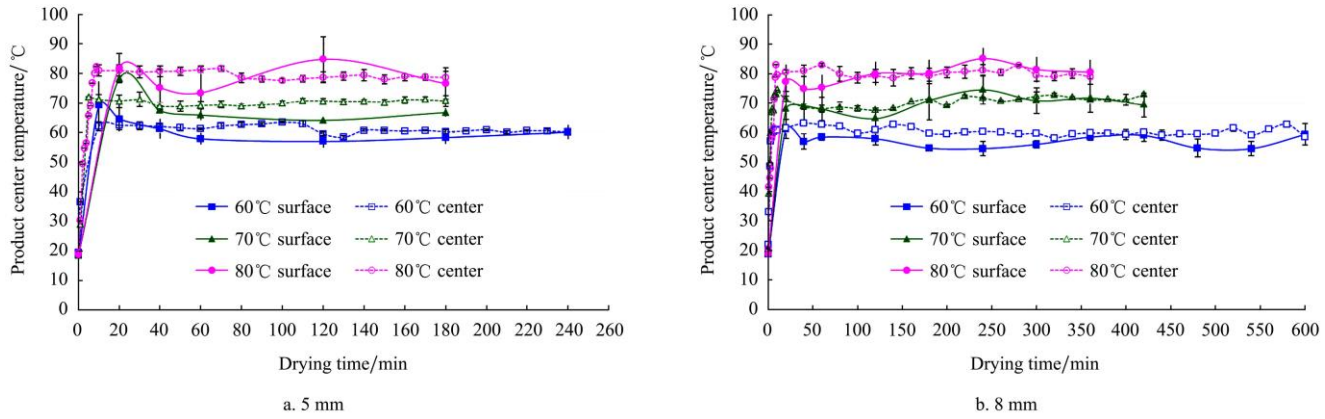

Figure 2 Changes in center and surface temperatures of banana slices during drying with IR for 5 mm (a) and 8 mm (b) slice thicknesses

The average surface temperatures at 60 ℃ in 8 mm and 70 ℃ in 5 mm slices were about 5 ℃ below the set temperature after 150 min and 60 min of heating, respectively. This could have been due to the prolonged time of the off mode as MC deceased. However, the fluctuations were mostly around the set temperatures which are consistent with results of Swasdisevi et al.[31], although their set temperature was surface controlled.

3.2 Drying rates

The changes in MC of the banana slices with respect to the drying period are shown in Figure 3. In the early drying stage, MC decreased more rapidly with IR than with HA. This was due to the high drying rates in the early stages, especially with IR (Figure 4). Similar studies with carrots and potatoes showed a higher rate of drying with IR than with HA throughout the drying process[32]. The HA drying plots appeared to be more linear, representing a more consistent removal of moisture during drying. A similar trend was seen in studies with onions[13,30].

IR heating increased the rate of moisture movement towards the surface. However, slow evaporation of moisture from surface, due to weak convective currents, slowed down the drying rates, unlike in HA drying where the convective flow of air removed the moisture from the surface, which resulted in increased mass transfer[32].

During banana drying with IR and HA for 5 mm and 8 mm thick slices, no constant rate drying period was observed (Figure 4 a and b). Vega et al.[33] reported that in the hot-air drying process of products of vegetal origin, the constant rate period was not observed, and there was a marked falling rate period due to the quick moisture removal from the samples. However, opposite observation was reported by Maskan[34] who stated that a short constant rate period during the drying of high MC products was observed by using lower drying temperatures such as 40-50 ℃. The consistency of our results with the report by Vega et al.[33] could be because during IR and HA drying the product temperatures were at 60 ℃, 70 ℃ and 80 ℃ in our study.

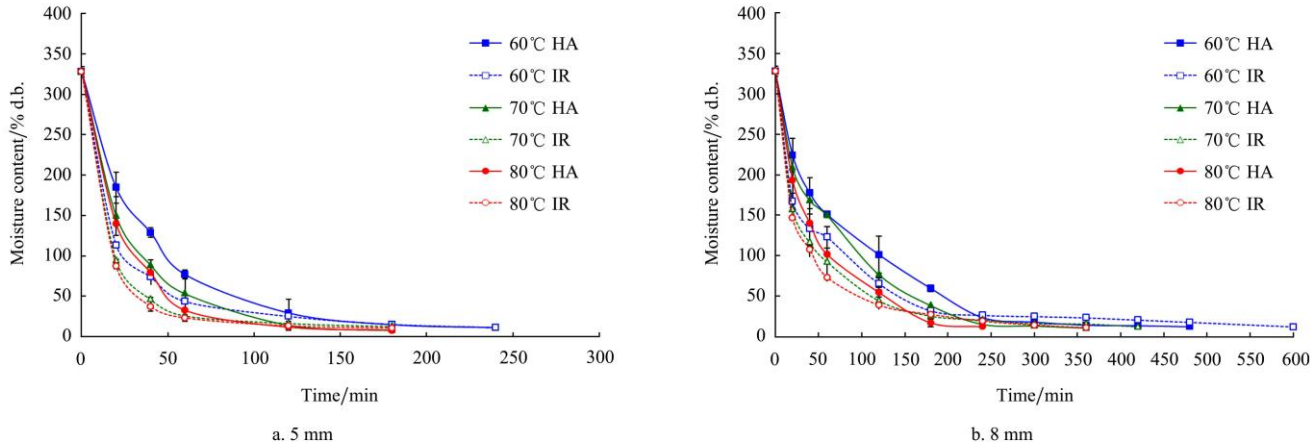

Figure 3 Changes in moisture content of banana slices during drying with IR and HA for 5 mm (a) and 8 mm (b) slice thicknesses

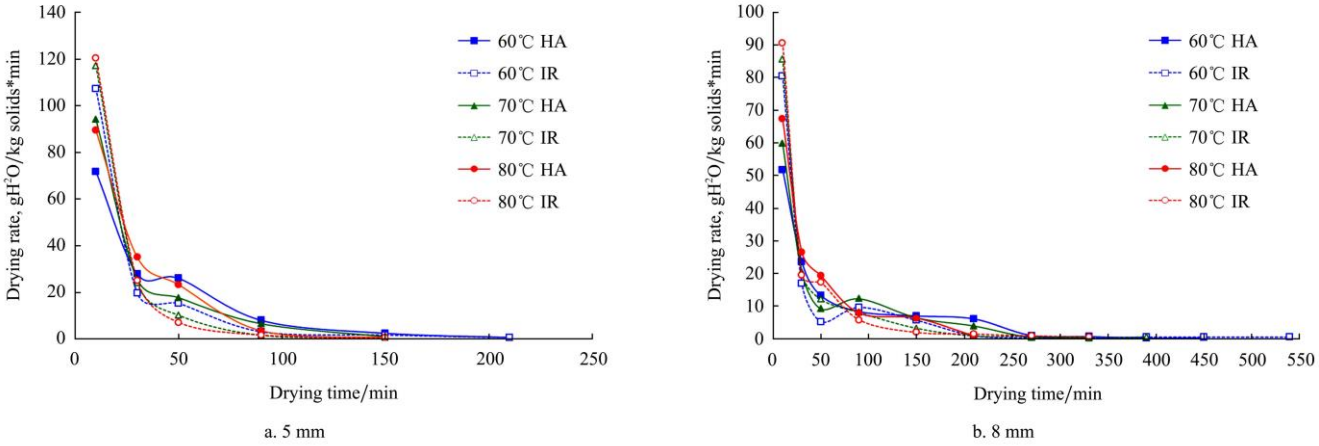

Figure 4 Changes in drying rates of banana slices during drying with IR and HA for 5 mm (a) and 8 mm (b) slice thicknesses

3.3 Drying models

Table 2 summarizes the drying characteristics including constants and correlation coefficients for the studied drying models at the different conditions. The Page model clearly fitted experimental data better than the Exponential model under the studied IR drying conditions with coefficient values of R^2 nearly unity. Therefore, the Page model could be used for predicting moisture change of bananas under the tested conditions. The values of R^2 of the Exponential model for IR dried bananas were in the range of 0.214 to 0.662, which indicates the model may not be appropriate for describing the drying characteristics of the bananas during drying with IR.

A higher drying constant demonstrates a higher drying rate. The values of drying constant k of the Page model is higher during IR than HA drying for similar drying temperatures, whereas the values of k of the Exponential model showed no apparent differences. However, both models showed that higher temperatures

Table 2 Constants in Page and Exponential models during IR and HA drying of banana at various temperatures and product thicknesses

Drying condition	Drying constant K (Exponential model)	Drying constant K (Page model)	Drying exponent (Page model)	Correlation coefficient (Exponential/ Page)
	min^{-1}	min^{-1}	n	R^2
60 ℃, 5 mm, HA	0.019	0.054	0.797	0.945/0.994
60 ℃, 5 mm, IR	0.020	0.237	0.517	0.559/0.993
60 ℃, 8 mm, HA	0.009	0.037	0.765	0.921/0.985
60 ℃, 8 mm, IR	0.008	0.140	0.520	0.576/0.976
70 ℃, 5 mm, HA	0.029	0.067	0.822	0.978/0.998
70 ℃, 5 mm, IR	0.034	0.335	0.483	0.214/0.953
70 ℃, 8 mm, HA	0.013	0.036	0.806	0.974/0.981
70 ℃, 8 mm, IR	0.011	0.146	0.547	0.662/0.991
80 ℃, 5 mm, HA	0.035	0.083	0.795	0.948/0.986
80 ℃, 5 mm, IR	0.037	0.357	0.485	0.256/0.952
80 ℃, 8 mm, HA	0.017	0.047	0.797	0.970/0.989
80 ℃, 8 mm, IR	0.013	0.162	0.542	0.750/0.998

resulted in higher drying constant, *k*. A similar trend was also observed by Nishiyama et al.[35] during grain drying and Hofsetz et al.[36] during banana drying. The value of *k* at all drying temperatures was less for 8 mm thick slices compared to 5 mm thick slices.

Under HA drying conditions, both the Exponential and Page models well fitted with the experimental data, although the Page model fitted better. The R^2 values for the Exponential model were in the range of 0.928 to 0.978, and 0.981 to 0.998 for the Page model (Table 2). The experiments of Ceylan et al.[37] with HA drying of bananas also found the Page model to give the best R^2 (0.998). Similarly, Phoungchandang and Woods[38] found the Exponential model fitting well for solar dried whole bananas. Dandamrongrak et al.[39] and Hofsetz et al.[36] found both models fitting well during convection drying of bananas.

The Page model better predicted the drying characteristics for 5 mm thick slices than for 8 mm thick slices. In the 8 mm slices, the predicted data did not fit very well with the experimental data in the middle, especially in the case of HA drying at 80 ℃. A similar trend was observed by Gabel[13] in HA dehydrated onions at 80 ℃.

3.4 Water activity (a_w)

The average temperature of samples during water activity measurements was (23±1.6) ℃. Water activity decreased during the drying process as expected with the decrease in MC. Figure 5 (a) and (b) show variation of water activity with MC during IR and HA drying at different drying times and temperatures for 5 mm and 8 mm thick slices, respectively. A similar trend in the variation of a_w with MC was observed for slice with the thickness of 5 mm and 8 mm under both drying methods.

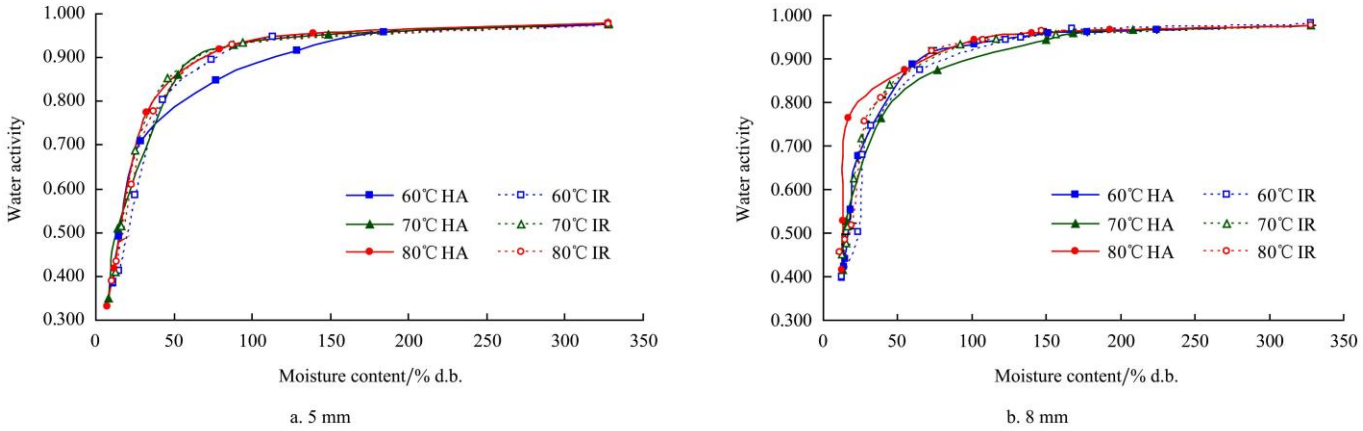

Figure 5 Water activity versus moisture content of banana slices at different drying conditions in 5 mm (a) and 8 mm (b) slice thicknesses

Water activities at 180 min of drying time for all the drying conditions were statistically analyzed. The results at 60 ℃ for 5 mm slices showed no significant ($P > 0.05$) differences in water activity between methods. This implies that 5 mm slices can either be dried with HA or IR to achieve a similar water activity after 180 min of heating. Nevertheless, water activities of the IR dried 8 mm thick slices were significantly ($P < 0.05$) lower than the HA dried ones. Therefore, IR can be considered a more appropriate method to achieve low water activities faster.

At 70 ℃ and the same slice thickness, there were no significant differences in water activity between methods. However, there were significant differences between slice thicknesses with the 8 mm thick slices exhibiting a higher water activity. Therefore to achieve a low water activity faster, it would be more appropriate to use the thinner slice.

At 80 ℃, the final water activity in 5 mm thick slices dried with HA was significantly ($P<0.05$) lower than that of 5 mm thick slices dried with IR and 8 mm thick slice dried with both IR and HA. There could be more case hardening in the case of 5 mm thick slices dried with IR due to the rapid surface moisture removal at the beginning of the drying. However, in the 8 mm thick slices there could be more resistance to mass transfer due to size leading to lower final a_w. Desorption isotherms resulting from the studied drying conditions are all of

Type II, which is typical of many sorption isotherms of foods[40]. This agrees with the findings by Kechaou and Maalej[41] and Phoungchandang and Woods[38].

3.5 Enzyme kinetics

Figure 6 illustrates residual enzyme activities at different drying conditions in 5 mm and 8 mm thick slices. The PPO was inactivated with IR within the first 20 min of drying at each temperature studied for both slice thicknesses. The rapid inactivation of PPO was possibly because the IR energy has wavelengths in the range of 3-6 μm, which matches the region of peak absorption of water and proteins[10]. This makes it possible to achieve rapid heating of high moisture foods such as fresh fruits and vegetables.

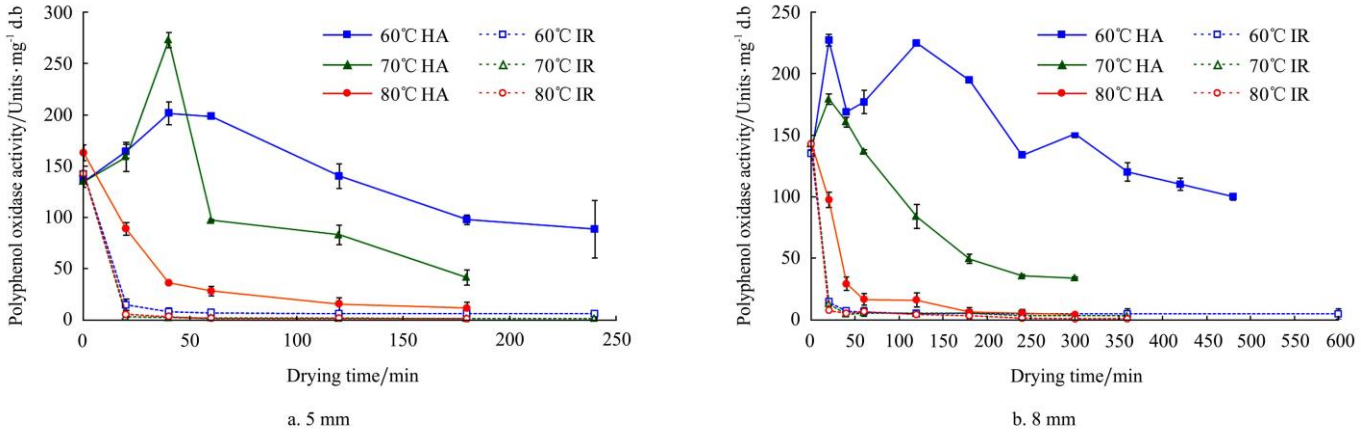

Figure 6 Residual enzyme activity of banana slices at different drying conditions in 5 mm (a) and 8 mm (b) slice thicknesses

Enzyme activity in bananas dried with HA at 60 ℃ and 70 ℃ first increased before it decreased. This implies that there was first activation of the enzyme as a result of the increase in temperature, with subsequent inactivation as product temperatures increased above the optimal temperature for PPO activity. This is consistent with the findings on the characteristics of banana PPO by Yang et al.[42]. Residual PPO was still present on the final products after 180 min of HA drying at both 60 ℃ and 70 ℃. The final residual PPO activity in the HA dried bananas was significantly ($P < 0.05$) higher at 60 ℃ than at all three temperatures with IR and 80 ℃ with HA. This indicates that PPO is stable at 60 ℃ which is consistent with findings in the literature[43,44]. The fluctuating activation and inactivation patterns observed at 60 ℃ with HA could be due to latent PPO[46,47]. Final PPO activity in the 5 mm thick slices dried at 60 ℃ with HA decreased by about 30% compared to that in fresh bananas. At 80 ℃ with HA, there was a gradual inactivation of PPO to almost zero units/mg d.b. at the end of the drying time for both slice thicknesses.

Residual enzyme activities were determined at different temperatures. For the IR experiments, estimates were calculated for the first 40 min of drying (Table 3). Enzyme inactivation occurred more quickly with IR than with HA.

Table 3 Inactivation of PPO during drying of banana slices with infrared radiation (IR) and hot air (HA)

Slice thickness	Drying method	Drying temperature	Reaction rate constant (k) (min^{-1})	R^2
5 mm	IR	60 ℃	0.019	1.000
		70 ℃	0.152	1.000
		80 ℃	0.117	1.000
	HA	60 ℃	0.005	0.945
		70 ℃	0.010	0.866
		80 ℃	0.014	0.966
8 mm	IR	60 ℃	0.081	0.906
		70 ℃	0.085	0.950
		80 ℃	0.147	1.000
	HA	60 ℃	0.002	0.811
		70 ℃	0.008	0.994
		80 ℃	0.017	0.994

3.6 Color kinetics

Enzymatic and non-enzymatic browning normally occurs when agro-products are heated. Both types of browning were expected to have taken place in these experiments since oxygen was present and temperatures were higher than 50 ℃ in both IR and HA dryers.

A higher IR drying temperature induced greater overall color change (ΔE) in dried slices (Figure 7 and Table 4). Product color is a surface phenomenon; therefore product surface temperature (Figure 2) had the most influence on color change.

Table 4 Final overall color change (ΔE) and Hydroxymethylfurfural (HMF) of banana in the dried 5 and 8 mm thick slices

Drying method	Drying temperature	ΔE		Turkey-Kramer (P <0.05)		HMF (ppm)	
		5 mm	8 mm	5 mm	8 mm	5 mm	8 mm
IR	60 ℃	25	28	B	B	0	0
	70 ℃	23	31	B	B	9	9
	80 ℃	37	35	A	AB	970	219
HA	60 ℃	21	39	B	A	0	0
	70 ℃	24	36	B	A	0	0
	80 ℃	26	29	B	B	291	135

A rapid increase in ΔE was observed (Figure 7a) for 5 mm thick slices within the first 20 min of drying, as a result of an increase in surface temperature (Figure 2); after which it stabilized in IR dried bananas. This observation is comparable to that observed with freeze drying of bananas[8]. The increase in ΔE was more gradual at 60 ℃ and 70 ℃ in HA dried slices but more rapid at 80 ℃ and in IR dried bananas. Gradually, ΔE stabilized after 120 min and by the end of drying, and was not significantly (P > 0.05) different within the treatments except at 80 ℃ drying with IR (Table 4). At 80 ℃ drying with IR, ΔE continued to rise to significantly (P < 0.05) higher levels. Products dried at 80 ℃ with IR and HA exhibited high values of HMF. It is therefore not recommended to dry at product temperature of 80 ℃ with either IR or HA. The increase in ΔE in HA dried slices, especially at product temperature of 80 ℃, could be primarily due to enzymatic browning caused by the gradual rise in temperatures since there was an increase in enzymatic activity as shown in Figure 7a. However, the first increase in ΔE in the IR dried slices could have been contributed more by non-enzymatic than enzymatic reactions as a result of the rapid rise in surface temperatures that favor Maillard reactions, but deactivated PPO (Figure 6a).

As shown in Figure 7b, for 8 mm thick slices, there was a rapid increase in ΔE at all temperatures within the first 20 min of drying, but the highest ΔE was at 60 ℃ in HA dried slices. This increase could have been mainly due to enzymatic browning since an increase in residual PPO activity was observed after 20 min (Figure 6b) and remained quite high for most of the drying time. Also, at the end of the drying, HMF was not detected (Table 4). However, at the end of the drying ΔE for IR drying at 60 ℃ was the lowest and also significantly less than that for HA drying at same temperature. IR dried slices at 60 ℃ could have browned as a result of PPO enzyme activity. Since PPO was quickly inactivated (Figure 6b), it had little effect on the product color. Also, HMF was not detected, indicating that non-enzymatic reactions did not contribute much to browning.

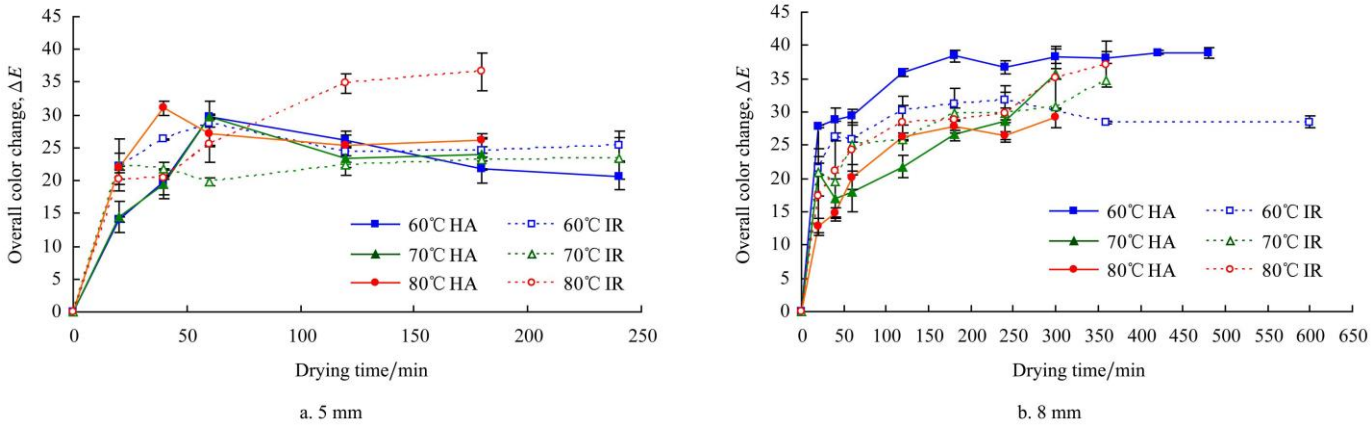

Figure 7 Overall color changes of banana slices at different drying conditions in 5 mm (a) and 8 mm (b) slice thicknesses

During the first 20 min of drying, ΔE was less at 70 ℃ than at 60 ℃ in HA dried slices due to lower enzyme activity at 70 ℃ than 60 ℃ (Figure 6b). However, by the end of drying, ΔE values at 60 ℃ and 70 ℃ HA were not

significantly ($P > 0.05$) different. Although residual PPO at 70℃ HA declined (Figure 6b), the product color continued to change steadily (Figure 7b) meaning that even low levels of enzyme activity were able to cause color change. Although no HMF was observed (Table 4), the possibility of non-enzymatic browning also existed due to the high temperatures. This holds true during final stage of drying when water activity was too low for enzyme activity[48]. However, at the end of the drying at 70℃, ΔE was significantly less with IR than with HA. At 70℃, it was possible that IR dried slices browned as result of PPO, but because it was quickly inactivated (Figure 6b) it had less effect on the product color. Most likely non-enzymatic reactions favored by the high temperature also contributed to browning since color continued to change after 20 min of drying. The low levels of HMF are also an indication of the lack of non-enzymatic browning.

The value of ΔE was the least during the first 20 min of drying at 80℃ for HA dried slices with 8 mm thickness. Initial browning could have been caused mainly by PPO activity. However this is yet to be validated due to the high temperature which could have quickly inactivated the enzyme (Figure 6b). After 20 min of drying, the color continued to change gradually. Therefore, it is most likely that non-enzymatic reactions contributed the most to browning during the rest of the drying period. This was further confirmed by the observation of HMF in the final product (Table 4). In slices dried with IR at 80℃, product surface temperature rose rapidly to 80℃ with IR (Figure 2), providing reasoning for the measured ΔE value to be primarily a result of non-enzymatic browning.

Compared to the control for drying under all conditions, the a* value increased and L* and b* values decreased significantly for IR dried products. These results agree with Krokida and others[8] for air dried bananas, apples, and potatoes. Products dried at 80℃ with IR and HA exhibited the highest a* values, along with low L* values. These are indicators of non-enzymatic browning which was further confirmed by the significant high values of HMF concentrations. In the case of lightness, it was found that all of the drying conditions in this study greatly influenced overall product color. The high temperatures led to higher values of HMF. This agrees with findings of Nimmol et al.[15] who dried bananas using combined low pressure super-heated steam and far-infrared radiation.

Drying temperatures were above 50℃, rendering the possibility that Maillard browning was the primary cause of non-enzymatic browning. More Maillard browning was measured in 5 mm thick slices, under the same drying conditions, than in 8 mm thick slices. This could have been the result of a greater surface area exposed to IR and a faster rate of drying in the thinner slices. The occurrence of caramelization was less likely because temperatures were less than 120℃, the temperature at which caramelization occurs.

4 Conclusions

The study indicated that IR heating has potential to improve drying rate and quality of dried banana. Significant moisture reduction and higher drying rates were achieved with IR drying compared to HA drying in the early stage. Increasing slice thickness to 8 mm from 5mm caused a decrease in drying rate. Using a slice thickness of 5 mm and 60℃ for IR drying was recommended to obtain product with light color and no HMF. IR heating of banana inactivated PPO within the first 20 min of drying at 60℃, 70℃ and 80℃. However at 60℃ and 70℃ drying with HA, PPO was first activated before the inactivation began. The Page model provided the most accurate predictions of moisture change for both the IR and HA drying processes. The exponential model was not appropriate for modeling the IR drying process, especially at low moisture content. Overall, employing the high drying rates, especially in the early stages of drying, to quickly remove moisture from bananas and also inactivate enzymes with IR heating followed by HA drying in the final stages could improve drying efficiency and product quality. Optimization of the process variables is very important for providing recommended process protocols using the infrared drying of banana. Future studies are crucial to further elucidate other quality attributes such as rehydration ratio, shrinkage, pH, microstructure (morphology), total

polysaccharide content as well as spectroscopic profiles of infrared dried banana samples for a comparative assessment of the resultant product quality.

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