Received: 2 March 2018 | Revised: 18 October 2018 | Accepted: 11 January 2019
DOI: 10.1111/jfpe.13020

WILEY Journal of Food Process Engineering

ORIGINAL ARTICLE

Thin layer drying kinetics of Banana var. Monthan (ABB): Influence of convective drying on nutritional quality, microstructure, thermal properties, color, and sensory characteristics

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Funding information
Indian Council of Agricultural Research, Grant/Award Number: IXX12448; National Research Centre for Banana

Abstract

Banana with good amount of resistant starch (RS) offers greater benefit to human health. Studying the dehydration mechanism of the raw banana slice is very important for subsequent processes and quality of the product. Thus the study was aimed to investigate the influence of varying temperatures viz., 45, 55, and 65°C in a convective dryer on thin layer drying kinetics and to infer their influence on the rheological properties coupled thermal and sensory quality. Time for reducing the moisture content from the initial 71.2 ± 0.2% to a final 4.66–6.13% was found to be 270, 210, and 150 min for the drying temperatures 45, 55, and 65°C, respectively. Moisture ratio decreased exponentially with an increase in drying time. Page and logarithmic models obtained highest r^2, lowest chi-square values and least root mean square error and better reflected drying mechanism of banana slices. Improved rehydration ratio (1:2.4) and RS content (36.26%) was observed with the drying temperature of 55°C. Higher water absorption capacity (WAC) was observed in 55°C (4.86%). Swelling power of the flour was maintained to 4–6% till 70°C but it reached to 22% with the increase in temperature to 90°C. Thermal properties and microstructure of flour differed significantly with the temperatures. The lower value for whiteness index with low temperature drying reflected the better drying than at higher temperatures. Dehydration at 55°C was superior with nutrients like ascorbic acid. The banana flour had the rod shaped starch granules and traces of protein in its surface as evidenced. Irregular spherical shape, surface dents, and shrinkages were observed in powders dehydrated with high temperature (>65°C). Equilibrium relative humidity (ERH) studies revealed that 13.27 and 15.23% were the danger and critical point, respectively, for the banana flour. Descriptive sensory scores of the banana flour endorsed that dehydration at 65°C was found superior to other temperatures.

Practical applications

Banana flour offers greater potential to increase the resistant starch (RS) content in the food products besides adding minerals and basic nutrients. Drying process should retain the characteristics of fresh fruits by minimizing the cellular and structural changes during the drying. Mathematical modeling offers scope to set the variables which are influencing the drying of banana slices. The dried banana flour could be a replacement or supplement for various formulations. With the better physical properties like swelling capacity and enthalpy along with high RS, banana flour allow the formation of low bulk, high-fiber products like pasta, noodles, and healthy functional foods with improved sensory descriptors. Banana flour-based enterprises could be started in places where banana is cultivated and large sum of produced bananas are getting wasted due to poor postharvest management.

1 | INTRODUCTION

Banana, a crop of tropics, contributes 16% of total fruit production in the world, is the second most produced after citrus. India is the largest producer of banana in the world with a production of approximately 30.86 million tons from an area of 0.8 million hectares (www.nhb.gov.in). Out of this, only 3–4% of banana is processed and exported in puree form, rest is being consumed in fresh which leads to the loss of one-fifth of the produced quantity (Kumar, Shiva, Mayil Vaganan, & Uma, 2018). The demand for processed foods enhanced with the increasing urbanization, purchasing power, and change in food habits. Food processing industries are favoring bananas due to its higher content of total soluble solids, sugars, bioactive compounds like phenols, flavonoids, carotenoids, and minerals like potassium and magnesium with low acidity (Alkarkhi, Ramli, Yong, & Easa, 2011; Kumar et al., 2018; Zhang, Whistler, Bemiller, & Hanaker, 2005). However, the potential of using the banana for processed food is yet to be unleashed. Human health could be improved with the regular consumption of green banana flour (Martinez, Ayerdi, Agama, Goni, & Bello, 2009). Banana could be used as a functional food for the reduction of cholesterol, constipation, and colon cancer. With its good amount of resistant starch (RS; 17.5%) and nonstarch polysaccharides (14.5%), it could be used for the modulation of glycemic index, diabetes, and weight management by resisting starch hydrolyzing enzymes in the stomach (Sankat, Castaigne, & Maharaj, 1996; Waliszewski, Apari´ Cio, Bello, & Monroy, 2003). Moreover, unripe banana flour could be a source of antioxidants like carotenoids, polyphenols like dopamine, serotonin, and norepinephrine, flavonoids like gallocatechin, epicatechin, and catechin (Teixeira, Ciacco, Tavares, & Bonezzi, 1998; Zhang et al., 2005).

Studying the dehydration mechanism of the raw banana slice is important for subsequent processes and quality of the product. Mostly drying process is targeted to produce quality products with the minimum cost and maximum throughput, and to optimize these factors consistently. Many studies were conducted to assess the effect of various factors on quality of dried banana (Teixeira et al., 1998; Waliszewski et al., 2003). Several studies on thin layer drying of various fruits and vegetables were carried out to elucidate the drying mechanisms and factors like size, shape, air velocity, relative humidity, and temperature associated with it (Akanbi, Adeyemi, & Ojo, 2006; Akpinar & Bicer, 2005; Doymaz, 2004; Freire, Barrozo, Sartori, & Frieire, 2000; Hossain & Bala, 2002; Karim & Hawladar, 2005; Sun & Woods, 1994). Very few researchers attempted to elucidate the impact of dehydration on quality of the products (Krokida & Marinos-Kouris, 2003; Kumar, Kanwat, & Choudhary, 2013) and to advance the efficiency of the dehydration mechanism. Therefore, this study was aimed to investigate the influence of varying temperatures in a convective dryer on thin layer drying kinetics of banana slices and to infer their influence on the rheological properties coupled with rehydration, nutritional quality, microstructure, thermal properties, and sensory quality of the banana slices or powder.

2 | MATERIALS AND METHODS

2.1 | Raw material and preparation

The experiment was conducted with var. Monthan (ABB), a common cultivar used for culinary purpose as a vegetable. The outer peel was removed manually using sharp knife and the banana cut into circular shape of 40 mm in diameter and 4 mm thickness using dicer. Then, the slices were blanched in water (1:3 ratio) containing 0.05% potassium meta bisulphite (KMS) and 0.1% citric acid in the vessel for 3 min at 60°C to arrest the enzymatic browning and to make the slices soft to felicitate smoother drying. After completion of blanching the slices were rinsed in cool distilled water for 30 s, wiped with tissue paper, and shade dried for 10 min to get complete removal of adhered water from the surface of the blanched banana slices.

2.2 | Drying experimentation

The blanched banana slices were dried at temperatures of 45, 55, and 65 ± 2°C using laboratory scale electrical cabinet drier (NSW-143, Universal oven, Delhi). The dryer was equipped with heating, ventilation, temperature controller with a thermocouple, and a humidifying system. It consisted of an axial flow fan blowing air with the flow rate of 0.12 to 0.16 m/s into a drying chamber. The blanched banana slices were placed in a single layer on perforated trays (4.0 Kg/m^2) and kept in the drying chamber. The loss of moisture was recorded, using a top loading compact digital weighing balance at every 30 min interval till the end of drying as suggested by Kumar et al. (2013). The dried samples were collected from a tray, cooled to room temperature, and packed in 250 g HDPE bags for subsequent evaluation of physicochemical characteristics, rehydration, and sensory parameters. The dehydrated slices were ground in a commercial pulverizer for 120 s and then sieved using 60 mesh sieve (ASTM: 60; 250 μm), collected, cooled, and stored in a HDPE bags at room temperature for further analysis.

2.3 | Drying kinetics study

As reported by many researchers, thin layer drying models are categorized into three namely theoretical, semi-theoretical, and empirical to describe the thin layer drying of food products (Doymaz, 2004, Midilli, Kucuk, & Yapar, 2002). Among the semi-theoretical drying models, exponential, page, modified page, Henderson and Babis, Thompson, and the Wang and Singh model are frequently used (Ojediran & Raji, 2010). The selected models and their equations are as mentioned below.

Lewis	MR = exp(−kt)
Henderson and Babis	MR = aexp(−kt)
Page	$MR = \exp(-kt^n)$
Modified page	$MR = \exp(-(-kt)^n)$
Logarithmic	MR = aexp(−kt) + c
Two-term exponential	MR = aexp(−kt) + (1 − a)exp(−kat)
Wang and Singh	$MR = 1 + at + bt^2$

$$MR = (M - Me)/(Mo - Me) \quad (1)$$

Where MR is dimensionless moisture ratio, M is the moisture content of the product at each moment, M_o is the initial moisture content of the product, and M_e is the equilibrium moisture content.

The best model describing the thin layer drying of banana slices was chosen based on goodness of fit, that is, with the highest r^2 and lower values for chi-square and the least root mean square error (*RMSE*) with the nonlinear least square regression analysis (Doymaz, 2004; Ertekin & Yaldiz, 2004).

The drying rate of sample was determined using the equation

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

Where M_t, and M_{t+dt}, moisture content at t and moisture content at $t + dt$ (kg water/kg dry matter), respectively, t is drying time (min), dt is the time interval between two consecutive measurements.

The geometry of the banana slices was considered as slab, though it was a cylinder with the dimension of 40 mm × 4mm for mass transfer studies. Higher surface area on the cut face was considered than peripheral area as moisture diffusion would be more through a cut surface and minimum through peripheral area. As drying proceeded, the moisture content of the material decreased and the mechanism of drying changes, which was controlled by the liquid diffusion mechanism as described by Ficks second law. Fick's unidirectional diffusion model could be considered (Chinnan, 1984) for a plate of thickness 2 L having the uniform initial water or solids amount, subjected to dehydration at constant conditions

$$MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{2n-1}\ x\ \exp\left(-(2n-1)^2\frac{\pi^2 D_{ew} t}{4L^2}\right) \tag{3}$$

Where D_{ew} is the effective diffusivity of water (m^2/s), t is the time (s), L is the slab half thickness (m), MR is the moisture ratio, SR is the solid ratio, m_e is the moisture content at equilibrium (g water/ g dry solid), s_e is the solid content at equilibrium (g).

The above equations were modified and represented in linear form by Falade, Igbeka, and Ayanwuyi (2007)

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{ew}}{4L^2}t \tag{4}$$

Anomalous diffusion model (Equation 5) as reported by Simpson, Ramírez, Nuñez, Jaques, and Almonacid (2017) and Ramírez, Astorga, Nuñez, Jaques, and Simpson (2017), was also used for modeling the water diffusion and compared with Fick's model.

$$MR = \frac{8}{\pi^2}e^{-D_{ew}\frac{\pi^2}{4L^2}t^{\alpha}} \tag{5}$$

The temperature dependence of D_{ew} was examined by the following Arrhenius-type equation (Wu, Orikasa, Ogawa, & Tagawa, 2007):

$$D_{ew} = D_0 exp\left(\frac{E_a}{R.T}\right) \tag{6}$$

where, k_0 frequency factor or the Arrhenius constant, R universal gas constant (8.3145 J/mol.K), T is the absolute temperature (K) and E_a activation energy kJ/mol. Higher activation energy implies that a smaller temperature change is sufficient for the degradation of a specific compound. By plotting D_{ew} versus 1/T, the activation energy was calculated.

2.4 | Rehydration characteristics

Rehydration ratio (RR), the coefficient of rehydration (COR), and percent of water (PW) assimilated by the rehydrated samples were calculated (Ranganna, 2002). Five grams of the dried slices were boiled in 150 mL distilled water and 2% salt solution for 15 min. Excess water from the slices was removed by blotting the slices using absorbent paper. Triplicate observations were taken and the mean value was considered.

2.5 | Water solubility and absorption capacity

Water solubility index (WSI) and the water absorption capacity (WAC) of the banana flour was performed using the method of Polesi and Sarmento (2011). One gram (*W*1) of sample, mixed with 10 mL of distilled water. It was kept in a water bath at 30°C with continuous shaking for 30 min and then centrifuged at 5,000 rpm for 10 min. The supernatant was placed in hot air oven (105°C) for drying and the weight of the dried supernatant was noted (*W*2). Weight of the wet sediment was also noted (*W*3).

$$\text{WSI}\ (\%) = \frac{W2}{W1} \times 100 \tag{7}$$

$$\text{WAC}\ (\%) = \frac{W3}{W1 - W2} \times 100 \tag{8}$$

2.6 | Swelling power

The swelling power (SP) of banana starches was performed using the method of Polesi and Sarmento (2011). Sample of 0.5 g (*W*1) was dispersed in water (20 mL) and the suspension was heated to different temperatures including 50, 60, 70, 80, and 90°C in a water bath for 30 min with vigorous shaking for every 5 min, respectively. The starch gel was then centrifuged at 3,000 rpm for 15 min. The weight of the sediment (*W*2) was used to calculate the swelling power.

$$\text{SP}\ (\%) = \frac{W2}{W1 \times (100 - \text{WSI})} \times 100 \tag{9}$$

2.7 | Color index

Color measurements were carried out on the surface of the banana flour using chromometer (Model CR 400 Minolta co Ltd., Japan) on the basis of *L** (0 [black] to 100 [white]), *a** (−a [greenness] to +*a* [redness], and *b** (−b [blueness] to +*b* [yellowness]). The flour was kept in the glass plate and the measurement was performed through a diaphragm (Alkarkhi et al., 2011). The whiteness index (WI) and yellowness index (YI) was calculated.

2.8 | Thermal analysis

Differential Scanning Colorimetry (DSC 6000 Perkin Elmer, USA) was used to study the thermal properties of banana powder dehydrated at varying temperatures (Tribess, Hernandez-Uribe, & Méndez-Montealvo, 2009). Flour sample (10 mg dwb) was prepared using water through micro syringe (20 μL) in the DSC pans, sealed and kept at room temperature for 24 hr to ensure equilibration of the sample. Heating rate of 10°C/min was used to scan the samples from the temperature of 30 to 150°C. Curves raised out using the Universal Analysis 2000 3.9A software, to know the gelatinization temperature (Tp) and transition enthalpy (Δ*H*).

2.9 | Microstructure studies

Scanning Electron Microscope (SEM, Model.JSM-6360 LV, JEDL, Japan) was used to elucidate the surface characteristics of the dehydrated banana slices. Thin films were prepared on a grid coated with carbon using a small amount of the sample. Microporous structure was observed using electron beam at a resolution of the particle size of 20–200 μm.

2.10 | Chemical properties

The samples were analyzed for the moisture content was determined by gravimetric method by drying the sample in a hot air oven at 80 ± 5°C and expressed as per cent (Ranganna, 2002). The TSS (°Bx) and titratable acidity and sugar was determined as per the standard procedures (Sadasivam & Manickam, 2008). Total starch were determined by anthrone method as per the standard procedure with little modification (AOAC, 1996). Sugar extracted samples was resuspended with distilled water and 52% perchloric acid. Color intensity was read using UV spectrophotometer at 630 nm. The starch content was calculated as glucose*0.9. The amylose content was determined by suspending 100 mg sample with 1 mL absolute ethanol and 10 mL 1 N NaOH and incubation for overnight. It was measured colorimetrically using UV spectrophotometer at 590 nm.

2.10.1 | RS estimation

The RS content was determined as per A.O.A.C.2002.02 (Mc Cleary & Monaghan, 2002). In brief, samples (100 ± 5 mg) in screw-cap plastic tubes (50 mL) were suspended with 4ML pancreatic α amylase containing amyloglucosidase. Vortex mixer was used to mix the contents (Remi Cyclo Mixer, 101). Samples were incubated on continuous shaking water bath for 16 hr at 50°C (Julabo SW22) and were washed with 4 mL absolute ethanol and centrifuged at 8,000 rpm for 15 min. Second and third washings was carried out with 2 ml of 50% ethanol and centrifuged. Supernatant was taken for the non RS determination using GOPOD (Glucose oxidase peroxidase) reagent and measured calorimetrically using UV spectrophotometer (Lab India, UV 3200) at 510 nm.

Residues were added to 4 mL of trismaleate/0.1 M NaOH (pH 6) containing 0.02% sodium azide, amyloglucosidase (4 U/mL, Sigma Aldrich® A 7255), α-amylase (300 U/mL, Sigma Aldrich® A-3176), and pepsin (500 U/mL, Sigma Aldrich® P-7012). The tubes were shacked, covered, and incubated at 37°C for 16 hr under stirring. After incubation, 8 mL of 99% ethanol were added and centrifuged for 10 min. Rinsing was repeated with ethanol and allowed to make pellets. Approximately 2 *M* KOH was used to suspend the pellet and stirred using magnetic stirrer (REMI 2MLH). Before incubation in water bath at 50°C for 30 min, solution having sodium acetate buffer with amyloglucosidase was added. GOPOD reagent was used to determine the RS content. D-glucose was used as a reference standard and RS content was expressed in percentage.

2.11 | Sensory evaluation

Quality attributes of banana flour was determined with descriptive sensory score. The prepared dough was presented for sensory evaluation for consistency, flavor, mouth feel, off flavor, taste, and over all acceptability. Loose flour was also kept to judge some sensory descriptors like texture, color, using 20 untrained panelists aged 18–55, using nine point hedonic scale of 1 to 9 (1 = dislike extremely, 9 = like extremely). The panelist evaluated the samples identified with unique codes in a balanced sequential order. They were asked to bring the container to their noses remove the container lid, and recorded the aroma. Subsequently the panelists were asked to evaluate the color and appearance and later to take a taste evaluation to assess the flavor and off-flavor attributes. Wheat flour was provided as reference standard.

2.12 | Equilibrium relative humidity study

To ascertain the packaging requirement of dehydrated fruits slices and the powder, the equilibrium relative humidity was determined by Wink's Weight Equilibrium method (Kumar et al., 2013). Ten grams of dehydrated samples were weighed in small aluminum dishes and were exposed to different relative humidity ranging from 10 to 100% at room temperature (25–30°C) in desiccators containing saturated salt solutions of different salts. The gain or loss in weight of the product under each humidity was determined at 1 day interval till attaining equilibrium. The critical and danger points were assessed and equilibrium moisture curve was plotted to find the equilibrium moisture content for the banana slices.

2.13 | Statistical analysis

The data obtained in the present study was subjected to completely randomized block design (CRBD) analysis using an analysis of variance (ANOVA). All experiments were performed in triplicate and the mean values with *SD*s were reported. Duncan's multiple range test was used to establish the multiple comparisons of the mean values at 95% confidence level (p = 0.05). A statistical program SAS (Ver JMP 10.0) was used to perform the statistical calculations and to perform the modeling of the drying conditions. Drying kinetics and moisture ratio value were plotted against time in the MS Excel (Microsoft office ver 2010). Sensory values were analyzed statistically using ANOVA and the mean value for each descriptor for various treatments was plotted in spider chart using MS Excel.

3 | RESULTS AND DISCUSSION

3.1 | Drying behavior of banana slices

Time for reducing the moisture content of banana slices from the initial 71.2 ± 0.2% to a final 4.66–6.13% was found to be 270, 210, and 150 min for the drying temperatures 45, 55, and 65°C, respectively. The influence of temperatures on banana slices during drying is shown in Figure 1a. It was observed that the moisture-time relation was nonlinear in this study and the moisture content of banana slices decreased over the period in continuous rate irrespective of drying temperatures during the initial period. Figure 1b illustrated the experimental drying rate (kg water/kg dry matter/hr) of banana slices as a function of moisture removal (kg water /kg dry matter) and it was

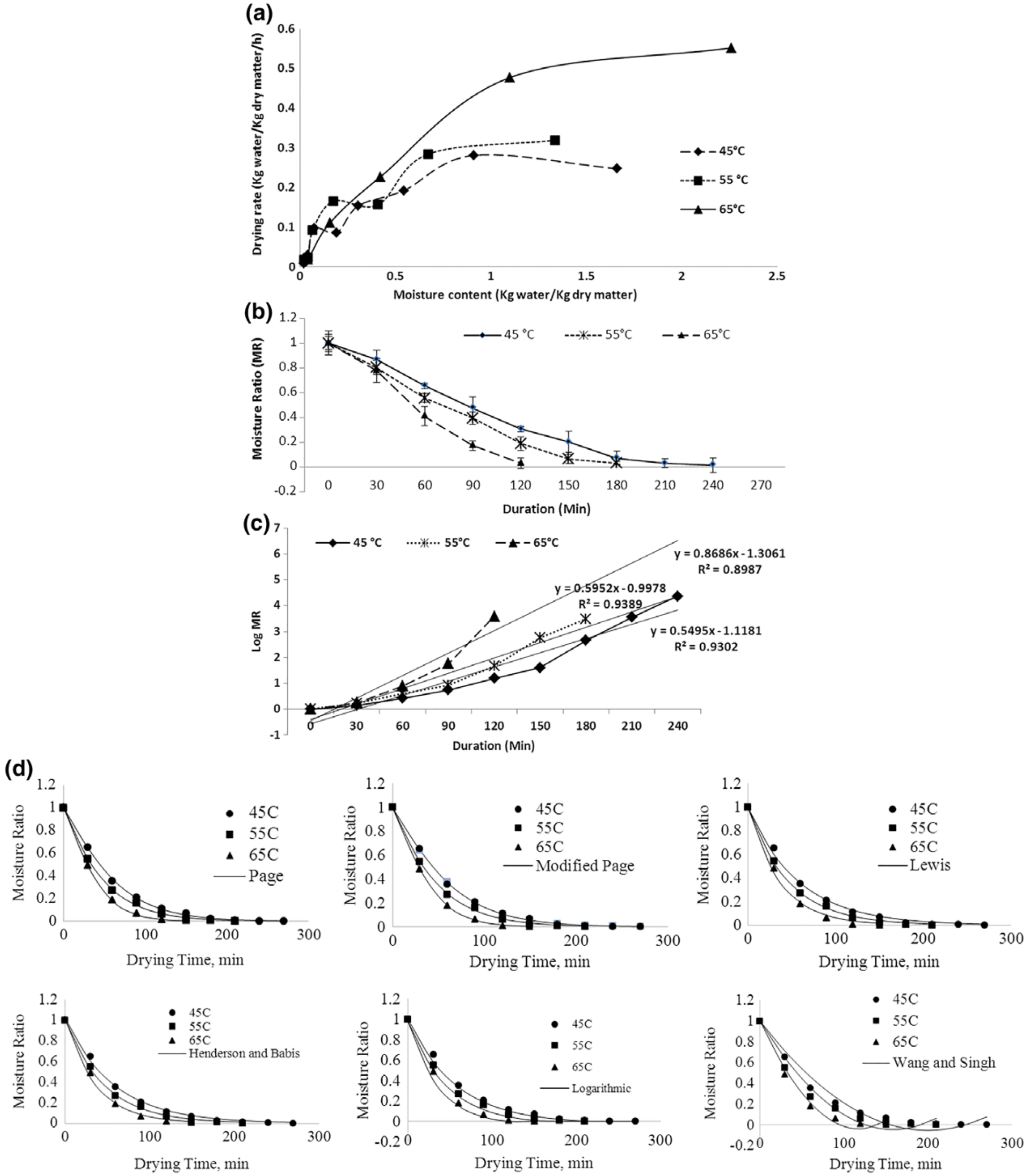

FIGURE 1 (a) Drying rate of banana slices as the function of moisture removal with different temperatures; (b) Influence of drying temperature on moisture ratio pattern on banana cv. Monthan (ABB) slices; (c) Logarithmic pattern of moisture ratio as expressed against of drying with varying temperature; (d) Various model equations to fit the observed values of drying with varying temperature with the predicted value

inferred that smooth diffusion controlled air drying behavior was observed with the samples. Generally, dehydration in a convective dryer, characterized by a constant rate until the movement of water is not enough to continue it in a saturated state followed by the falling rate of drying as the composition of the drying air did not change (Akanbi et al., 2006; Chinnan, 1984). Similarly, in the present experiment, the falling rate period of drying started after the minor constant period and continued till the end of the process. More surface area coupled with the thin layer of slices helped in the faster removal of water and, thus, a falling rate period as opined by Akpinar and Bicer (2005). The study clearly indicated that water movement was mainly governed by diffusion of the moisture from the slices. Contrary, drying rate was minimal and more energy was used significantly to remove the moisture from internal tissues during the later part of drying. The difference in drying rate was found with low temperature compared to other temperatures (Akanbi et al., 2006; Hawaldar, Uddin, Ho, & Teng, 1991; Ojediran & Raji, 2010). The analysis of the moisture variation during drying showed that there was a significant difference ($p \le 0.05$) among temperatures. Other than diffusion, capillary flow and shrinkage coupled flow of water also influenced the internal

TABLE 1 Influence of drying temperature on physical characteristics of dehydrated banana slices (dwb)

Parameters	45°C	55°C	65°C	$p \le 0.05$*
Moisture	4.66 ± 0.11 a	5.52 ± 0.08ab	6.13 ± 0.22bc	0.85
Drying ratio	3.44 ± 0.09c	3.22 ± 0.01a	3.32 ± 0.07b	0.34
Rehydration ratio	2.1 ± 0.01b	2.4 ± 0.02 c	1.8 ± 0.01a	0.03
WAC (%)	4.05 ± 0.31ab	4.86 ± 0.12 c	3.94 ± 0.13a	0.04
WSI (%)	4.01	3.99	4.04	NS
Color				
L^*	58.65 ± 1.52bc	61.42 ± 1.64c	55.93 ± 1.95a	3.38
a^*	−2.25 ± 0.04a	−2.19 ± 0.11a	−0.99 ± 0.05b	0.23
b^*	9.84 ± 0.95a	11.15 ± 0.73 b	13.18 ± 1.01 c	0.87
Whiteness index	195.02 ± 2.47 a	222.90 ± 3.69 b	268.05 ± 2.14 c	10.45
Yellowness index	23.97 ± 0.87a	25.94 ± 1.34 a	33.66 ± 1.96b	3.34
Differential scanning calorimetry (DSC)				
Ti (°C)	68.82 ± 0.14a	69.41 ± 0.18bc	70.13 ± 0.07c	0.23
Tp (°C)	73.34 ± 0.09a	77.21 ± 1.02b	78.76 ± 0.84 bc	1.97
Tf (°C)	80.27 ± 1.13 a	85.58 ± 1.04 b	87.39 ± 0.97 c	2.16
ΔH (J g^{-1})	10.08 ± 0.04 b	10.99 ± 0.02bc	11.24 ± 0.05 c	0.09
Chemical parameters				
Acidity (%)	0.44 ± 0.001b	0.37 ± 0.003 a	0.35 ± 0.01 a	0.03
Total sugar (%)	5.62 ± 0.24bc	4.82 ± 0.07 a	5.27 ± 0.19 b	0.31
Total starch (%)	75.48 ± 0.36 c	73.21 ± 0.25 b	70.52 ± 0.43a	0.93
Resistant starch (%)	34.94 ± 1.81 b	36.26 ± 1.76 bc	29.17 ± 0.85a	1.87
Amylose (%)	41.23 ± 1.23bc	42.41 ± 1.87 c	38.32 ± 0.54 a	1.73
Protein (%)	3.24 ± 0.07 b	3.85 ± 0.04 c	2.12 ± 0.04 a	0.21
Fat (%)	0.79 ± 0.01 b	0.77 ± 0.03 b	0.61 ± 0.03a	0.09
Ash (%)	2.89 ± 0.04a	2.23 ± 0.06 b	1.76 ± 0.16 c	0.73
Ascorbic acid (mg/100 g)	54.26 ± 1.76 b	53.87 ± 2.19b	44.09 ± 1.46 a	21.13
NEB (OD @ 420 nm)	0.15 ± 0.007 a	0.18 ± 0.003 a	0.24 ± 0.005 b	0.04
Sodium (mg)	22.53	23.64	21.61	NS
Potassium (mg)	1,087.31	1,074.36	1,081.44	NS
Calcium (mg)	33.66	35.81	34.49	NS
Phosphorous (mg)	91.24	94.24	92.28	NS
Magnesium (mg)	75.44	77.55	78.57	NS

*Mean in the same row with different letters varies significantly at $p \le 0.05$ using Duncan's Multiple Range Test.

movement of moisture and extended the drying time at the end hours of drying (Kumar et al., 2013). Moisture ratio decreased exponentially with an increase in drying time (Figure 1c). In general, superior drying ratio was obtained with the banana slices, dried in 55°C followed by 65°C (Table 1). Lower temperature resulted in lesser drying ratio than other drying temperatures. The better result of cabinet drying with 55°C was due to optimum temperature coupled with low RH and constant air flow as expressed by Hawaldar et al. (1991), Kumar et al. (2013), Sahin and Dincer (2005) on dehydration of farm produce.

Effective diffusivities were calculated by fitting the experimental data using unsteady state diffusion equations (Equations 5 and 6) and the values are shown in Table 2. α value showed that the diffusion during drying of banana slices was super diffusion since the values were greater than one ($\alpha > 1$). The calculated diffusivities with Fick's law were increasing from 3.79×10^{-8} m^2/s to 6.23×10^{-8} m^2/s while varying the drying temperature 45–65°C. Similarly, the calculated diffusivities with Anomalous model were increasing from 1.61×10^{-8} m^2/s to 8.89×10^{-9} m^2/s while varying the drying temperature 45–65°C. The increase in drying temperatures had increased the effective diffusivities of moisture significantly. The time required for reaching equilibrium moisture content had decreased with the increase in temperature, which ensured that the diffusion was the most likely physical mechanism governing the moisture movement. Many researchers have reported similar results while dehydration of different fruits and vegetables like jenipapo (Andrade, de Barros Neto, No´Brega, Azoubel, & Guerra, 2007); apricot (Khoyi & Hesari, 2007); and eggplant (Wu et al., 2007). As compared to Anomalous model, Fick's model had predicted the diffusivity with better coefficient of determination (Table 3).

The activation energy (E_a) of moisture diffusion in banana slices was calculated as 22.035 kJ/mol (Supporting Information Figure S1). Similar activation energy were reported for various crops like carrots as 28.36 kJ/mol (Doymaz, 2004); Soybean as 28.80 kJ/mol (Kitic & Viollaz, 1984); Green bean as 35.43 kJ/mol; Red chili as 41.95 (Gupta et al. 2017); and in dates with the range of 29.05–44.02 kJ/mol.

TABLE 2 Calculated diffusivity with varying temperature under different models

	Fick's model			Anomalous model			
Temperature (°C)	D_{eff} (m^2/s)	R^2	*SSE*	D_{eff} (m^2/s)	α	R^2	*SSE*
45	3.79E-08	0.986	0.013	1.61E-08	1.478	0.963	0.038
55	4.35E-08	0.979	0.024	2.39E-08	1.316	0.958	0.037
65	6.23E-08	0.977	0.019	8.89E-09	1.502	0.953	0.036

3.2 | Comparison and selection of drying model

Selected models were fitted with the experimental data, to describe and predict the drying behavior of banana under different drying conditions. The model coefficients and the goodness of fit parameters obtained from nonlinear regression for the selected models are given in Table 3. The Coefficient of determination (*R*) and *RMSE* revealed values were ranged between 0.97–0.99 and 0.012–0.043, respectively. Lowest chi-square values were recorded with all the selected models for the drying temperature of 55°C, which revealed that the smoother diffusion of moisture at 55°C than other temperatures used for drying banana slices compared the experimental and predicted moisture ratios with all the tested models (Figure 1e). Page and logarithmic models had resulted in the highest r^2 and least *RMSE* and chi-square values at all temperatures and these models could be selected as better models to reflect the drying mechanism of banana slices. Kumar et al. (2013) also found that page model was one of the best models for elucidating the drying behavior of bamboo slices. From the result it was assumed that, in banana drying, the least suitable models were two-term exponential model and Wang and Singh model, nonetheless these models may be better for drying other produces which have different dehydration properties. In principle, using a simple model with few variables offers significant advantages rather than complex models, as reported by Sankat et al. (1996) while modeling the drying of fresh banana. The power index "*n*" in the equations play a vital role in the prediction than the constant "*a*" as it was reflected through fitting of all the drying models. Kumar and Sagar (2014) on mango, Kumar et al. (2013) on bamboo, and Doymaz (2004) on apple also showed the importance of model selection for better drying of commodities.

3.3 | Rehydration characteristics

Rehydration ratio (RR), the coefficient of rehydration (COR), and percent of water (PW) assimilated by the rehydrated samples were presented in Figure 2a. The slices dried at 55°C recorded better rehydration than other temperatures. Lewicki (1998) argued that practically irreversible changes would have occurred with dehydration and rehydration could not be simply a reverse process. In the present study, the addition of salt in the rehydration medium resulted in better regaining of the structure, RR, COR, and PW irrespective of the temperature of drying as reported by Kumar et al. (2013) and Lewicki

TABLE 3 Fitted models and its regression coefficients along with the goodness of fit parameters

Model	Temperature (°C)	*k*	*a*	*b*	R^2	Adj. R^2	*RMSE*	χ^2
Page	45	0.0084	1.1667		0.9994	0.9993	0.0090	8.08E-05
	55	0.0155	1.0777		0.9990	0.9988	0.0122	1.49E-04
	65	0.0105	1.2460		0.9999	0.9999	0.0049	2.36E-05
Modified page	45	0.0166	1.1659		0.9994	0.9993	0.0090	8.08E-05
	55	0.0209	1.0779		0.9990	0.9988	0.0122	1.49E-04
	65	0.0259	1.2467		0.9999	0.9999	0.0049	2.36E-05
Lewis	45	0.0171			0.9957	0.9957	0.0222	4.09E-04
	55	0.0214			0.9982	0.9982	0.0150	2.24E-04
	65	0.0273			0.9952	0.9952	0.0271	7.31E-04
Henderson and Babis	45	0.0174	1.0210		0.9961	0.9957	0.0222	3.15E-04
	55	0.0215	1.0060		0.9982	0.9979	0.0160	5.90E-05
	65	0.0276	1.0110		0.9954	0.9943	0.0297	5.15E-04
Logarithmic	45	0.0162	1.0390	−0.0250	0.9977	0.9971	0.0182	5.90E-04
	55	0.0189	1.0410	−0.0320	0.9977	0.9971	0.0182	5.90E-04
	65	0.0246	1.0480	−0.0425	0.9983	0.9971	0.0210	5.19E-04
Two term exponential	45	21.1500	0.0008		0.9956	0.9951	0.0237	3.95E-04
	55	6.7420	0.0032		0.9981	0.9978	0.0164	1.59E-04
	65	11.3600	0.0024		0.9952	0.9940	0.0305	2.47E-04
Wang and Singh	45		−0.0105	2.63E-05	0.9658	0.9615	0.0661	4.37E-03
	55		−0.0132	4.15E-05	0.9668	0.9613	0.0692	4.71E-03
	65		−0.0176	7.45E-05	0.9873	0.9841	0.0494	2.40E-03

R^2: Co- efficient of determination, *RMSE*: Root mean square error, χ^2:Chi-square value.

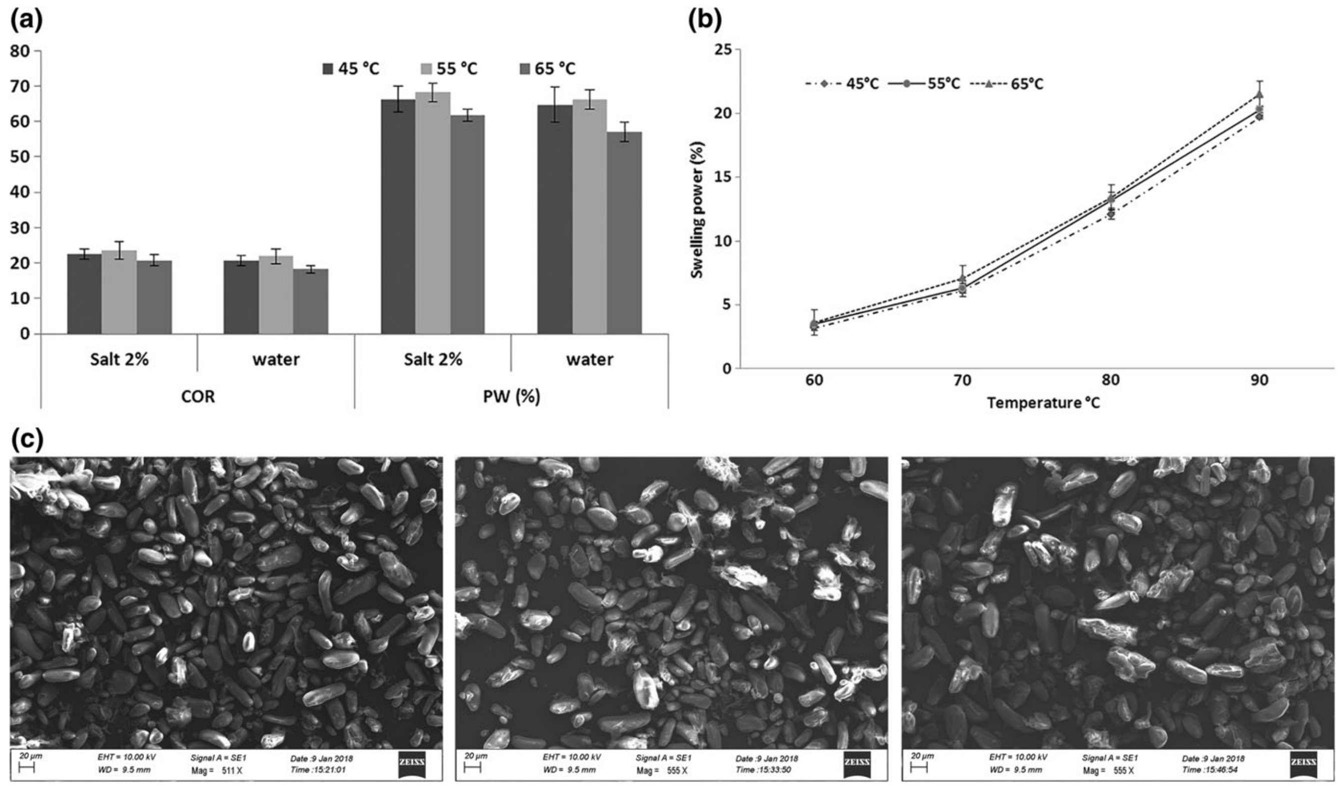

FIGURE 2 (a) Influence of temperature on rehydration characteristics of banana slices; (b) Influence of temperature on swelling power of banana flour; (c) Influence of temperature on surface morphology of banana flour

(1998). At 45°C, rehydration ratio (Table 1) was comparatively poor due to enhanced drying hours which led to the disintegration of the structure. Higher rehydration with 55°C was due to the porous structure of banana, thus, facilitating higher rehydration ability. It was observed that the material almost regained its original shape after rehydration at 55°C as COR and PW were recorded higher at 55°C followed 45°C. Dehydration temperature beyond 65°C modified the internal structure of tissues led to poor rehydration. This was because of higher damage to cell wall at very high temperature, consequently, reduced water absorption capacity. Besides, casehardening (rigid layers) on the outer perimeter with higher temperature further reduced the rehydration of tissues (Kumar et al., 2013). The study thus concluded that dehydration at optimum temperature was prerequisite for superior reconstitution of dried products.

3.4 | Water absorption, solubility, and swelling capacity

In this study, the highest WAC was observed in 55°C (4.86%) when compared with 45 (4.05%) and 65°C (3.94%; Table 1). Change in molecular structure with 55°C, increased the water absorption capacity which led to an easy movement of starch components. The whole process was due to the intrinsic gelatinization and retrogradation of banana powder where the removal of starch is noticed (Govindasamy, Campanella, & Oates, 1996). The solubility parameter is used as an indicator of the destruction of components. Generally low solubility values were reported for banana (Kayisu & Hood, 1981) and plantain flour (Pérez-Sira, 1997). Distribution of molecular weight, the degree of debranching, length of branches and the confirmation of the molecules along with the ratio of amylose and amylopectin play a very vital influence on the interaction between water and starch. However, the water solubility index among the drying temperature was not significant. The swelling power of banana starches was directly correlated to increase in temperature (Figure 2c) with the decreased protein and fat content under the higher temperature of drying. In the present study, the swelling power increased linearly with the increase in temperature, irrespective of the drying condition for the flour. The change in swelling power was also noticed as the higher temperature of drying resulted in more swelling than other temperatures (Pérez-Sira, 1997). In theory, swelling power actually measures the firmness of the bonds in the crystalline part of the starch granule which ultimately demonstrated easiness of cooking the starch or banana powder. Normally, the starch granules with more crystalline areas and stronger bonds swell less in cold or hot water as it forms a low viscosity paste with higher retrogradation (Govindasamy et al., 1996).

3.5 | Impact of drying on color of the flour

The difference in mean $L*$ value (55.9–67.5) indicates a substantial color difference existed with drying temperatures (Table 1). The color of the fresh produce was whiter than the product which was dried under different temperature. The opaque white of the fresh pulp changed to darker with the drying. The lower (45°C) and higher (65°C) drying conditions led to the dark color development in the flour. However, the change was comparatively lesser when the slices were dried with 55°C. Similarly, the $a*$ value for the dehydrated flour also changed significantly. The slices dehydrated under 55°C recorded the value of −2.19 which was comparable to the 45°C where the produce recorded the value of −2.25. The least *a** value was recorded with the higher temperature of drying. The *b** value revealed that with the drying, the pulp opaqueness disappeared, and the product turns yellow. This might have been due to the enzymatic and nonenzymatic browning of slices during dehydration under different processing condition. It was noticed that when the banana was dehydrated, the resultant product was the darker color with intense yellow under vacuum drying. This change in color was attributed to moisture loss, enzymatic and nonenzymatic browning of the produces (Alkarkhi et al., 2011). WI of food produce generally measures consumers' preference for white colors. It indicates the degree of whiteness of the food product thereby indicating the level of discoloration during processing. WI is derived from the combination of lightness and yellow–blue into a single term. YI of food products is used to quantify foods derived from degradation process of scorching, soiling, exposure to light and chemical processing. It is clear in the present study that the lower value for WI with low temperature drying reflected the better drying than at higher temperatures. Similarly the YI value for higher temperature drying showed the demerit of faster drying with higher temperature.

3.6 | Microstructure

There have been reports of structural changes (intercellular space, cell wall), permeability of membrane with varying temperatures in banana slices (Govindasamy et al., 1996; Polesi & Sarmento, 2011). From the scanning electron microscopic studies, it was evident that varying temperature profile has different surface characteristic on banana slices (Figure 2c). Generally, the banana powder has rod shaped starch granules and traces of protein in its surface as evidenced. Irregular spherical shape, surface dents, and shrinkages were observed in powders dehydrated with high temperature (>65°C). This could be attributed to faster drying which resulted in to case hardening of the surface tissues. Higher drying temperature led to quicker wall solidification and dent smoothening could not occur later. Similarly, the dents were more with low temperature (45°C) which was attributed to shrinkage in later stages after initial slow drying. The protein and fat layers were also noticed more with the lower temperature which was supporting the principle of swelling and water absorption capacity of the flour. The grouping of starch and other particles were also more with low temperature as observed under scanning electron microscopy. Zhang et al. (2005) opined that with higher temperature, aggression and binding of the smaller dust of same granules may occur due to the van der wall forces and static electrical effects.

3.7 | Thermal analyses

The differential scanning calorimetry (DSC) of banana powder dehydrated under varying temperatures is presented in Table 1. The peak or gelatinization temperature ranged from 68.82 to 70.13°C, depending on the drying conditions. Similarly, the gelatinization enthalpy (ΔH) varied (10.08 ± 0.88 J g^{-1} to 11.24 ± 0.32 J g^{-1}) and it was significantly influenced by air temperature. The result is similar to the findings of Kayisu and Hood (1981). It was lucid that commercial wheat flour has the lower gelatinization temperature (63.27 ± 0.59°C) and enthalpy (6.57 ± 1.21 J g^{-1}) than the raw banana flour. Concurrent results were found in the literature on various flour and starches (Garci´A-Alonso, Jimenez-Escrig, Marti´N Carro´N, Bravo, & Saura Calixto, 1999; Jambrak et al., 2010). Differences in the amylopectin structure which depending upon the bonding forces of the double helix resulted in the distinction in gelatinization energy of different flour. With the temperature of above 65°C, banana starch is gelatinized accompanied by swelling and case hardening which would decrease the porosity and slowed down the moisture transfer rate (Martinez et al., 2009; Tribess et al., 2009; Waliszewski et al., 2003; Zhang et al., 2005).

3.8 | Influence of drying temperature on chemical constituents

Physicochemical analysis of fresh fruits revealed that the Banana var. Monthan (ABB) is rich in various health-promoting substances and could be a good supplemental candidate for wheat and rice flour for enriching the overall functional quality of the flour-based products. The average fruit weight of the monthan varied between 168.7 and 248.2 g. The variety has good pulp to peel ratio of 1.27–1.37 (Supporting Information Table S1). Fresh banana has more moisture, contributes 64–71% of the weight with lesser TSS value of 3.5–5.1°Bx. Among the carbohydrates (22–28%), starch content is more in raw banana. Fresh fruits have recorded the considerable amount of protein (1.09–1.34%) with the traceable amount of fat (0.36–0.39%). Banana is the richest source of minerals like potassium (440.27 mg/100 g) and magnesium (32.56 mg/100 g) and has the significant amount of calcium and phosphorus (Karim & Hawladar, 2005; Martinez et al., 2009).

The chemical compositions of dehydrated banana with various temperatures are presented in Table 1. The statistically not significant result was obtained with respect to the presence of moisture and acidity content with respect to various temperature. However, higher temperature (65°C) retained more moisture as the surface tends to remove moisture faster than the diffusion of moisture from the inner cell. Ascorbic acid and reducing sugar content was more with 55°C than other drying conditions. Ascorbic acid reduced significantly with the higher temperature compared to other nutrients. Similarly, the protein got denaturized with the elevated temperature and thus recorded the lower value when the product was dehydrated with higher temperature (Kumar et al., 2018).

The debranching of α (1–6) linkage of amylopectin with treatments increased the amylose content so as RS content. In general, the amylose content was higher with 55°C than other temperatures. RS contents of green banana flour produced at each drying condition are presented in Table 1. The results indicated that RS content was significantly influenced by the drying conditions ($p \leq 0.05$). It could be observed that lower temperature decreased the RS content, probably due to the higher drying time, led to more time to reach equilibrium humidity and consequently partial disorganization of the crystalline structure of starch (Polesi & Sarmento, 2011). In contrast, the protein content was more with low temperature drying than the other temperatures. Higher the temperature (>65°C) led to protein denaturation. Compared to fresh fruits, when the fruits were dried, the RS content of the banana got reduced due to the breakdown of the

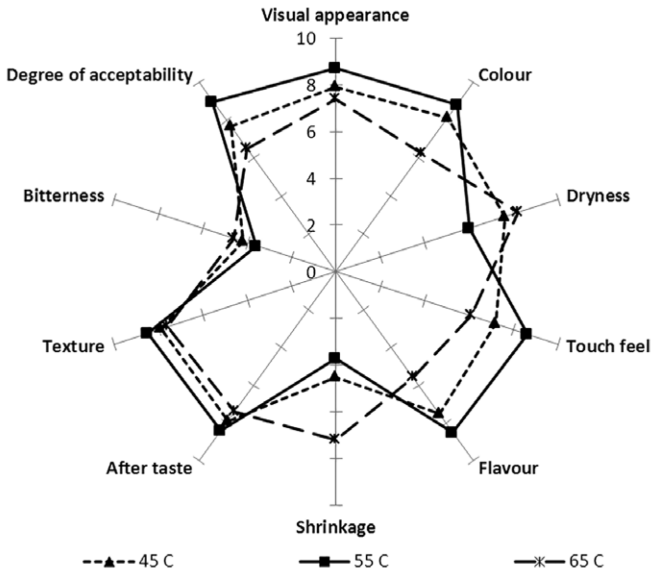

FIGURE 3 Descriptive score of banana flour dehydrated at varying temperatures

amylose structure and disturbance in the crystallinity of the produce. Optimum temperature is, therefore, pre-requisite to get the flour with higher RS content. The reduction of RS content in the banana flour was more pronounced (29.17%) with higher temperature (65°C) of drying due to starch retrogradation than the other temperatures (Ramakrishna et al., 2000).

Productions of dehydrated products are often influenced by the nonenzymatic browning or the Maillard reaction. Optimum diffusion of moisture with 55°C made the surface moisture to act as a protective layer to minimize color degradation. NEB was higher when the slices were dried under extreme drying conditions. The better quality of the product with 55°C might be due to the prevention of the reaction between amino acid and sugars as these two components are mainly involved in Maillard reaction (Kumar & Sagar, 2014). As discussed in the drying kinetics, due to high moisture in the produce, the surface would be continuously having a layer of moisture during the initial stage of drying in all the temperature level. This probably prevents dehydration of the surface sugar and reduces the rate of the Maillard reaction and lowering the overall color change. However, these formations of moisture layer get delayed over the time with the rise in temperature and the product tends to lose its color. However, the change in color was more pronounced with the higher temperature (>65°C) of drying due to the creation of different temperature profile. This led to case hardening of the slice and more nonenzymatic browning. Mineral content of the banana powder did not change with the difference in drying temperatures. Unlike ascorbic acid which was highly heat labile, the mineral content reflects the intrinsic properties of the produces (Kumar et al., 2013).

3.9 | Sensory evaluation

Sensory attributed plays a vital role in the acceptability of dehydrated products (Figure 3). In the present study, it was observed from various sensory descriptors that products dried at 55°C recorded highest scores for visual appearance (α = 0.08) and color (α = 0.53) at the end of drying. The low-temperature drying (45°C) maintained good color whereas its taste and flavor scored less. Pretreatment with KMS and optimum drying of material under cabinet drier imparted the best color to the dried product (Akpinar & Bicer, 2005). Similarly higher temperature (65°C) imparted a little burnt like the smell and changed the color. Loosing of rigidity and the hydrostatic pressure exerted in the living cell led to the disintegration of tissue and thus texture (Kumar et al., 2013). The texture of dried samples (α = 0.03) was better at 55°C than other temperatures. Better texture score was due to the rapid heat transfer coupled with the loss of moisture which might have facilitated the maintenance of the cell structure (Kumar et al., 2013). Flavor (α = 0.23), aroma (α = 0.14) and overall acceptability of dried product was also highest at 55°C. Drying at a higher temperature may cause serious damage to flavor, color and nutrients of the dehydrated product (Kumar et al., 2013; Kumar & Sagar, 2014). The oxidized phenolic substances with higher temperature attributed to the bitterness of the flour. With high temperature (65°C), degradation of quality components like sugar, acid, and carotenes occurred which led to the generation of off flavors.

3.10 | Moisture absorption behavior

The desorption isotherm of banana powder revealed that the equilibrium moisture content (EMC) increased with an increase in equilibrium relative humidity (ERH). The humidity-moisture equilibrium curves revealed highly hygroscopic nature of fruit powder since the increase in moisture content was steep beyond 50% RH (Figure 4). The critical and danger points 6.27% EMC and 30% ERH for the powders. Similar results have been reported in the literature for the sorption isotherm

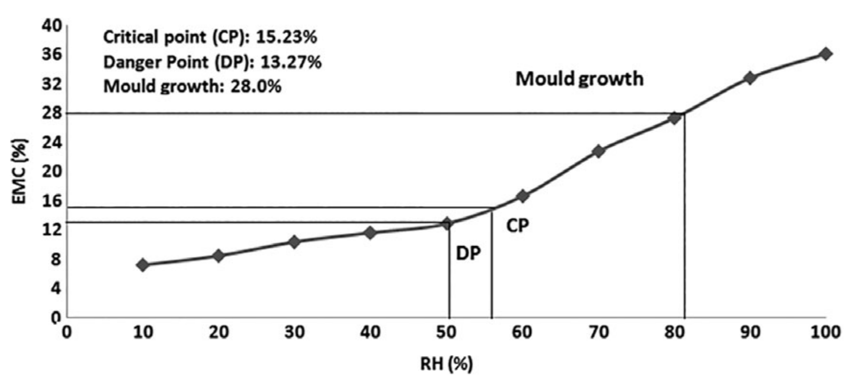

FIGURE 4 Moisture absorption behavior of banana flour dehydrated at 55°C

(Akanbi et al., 2006; Ertekin & Yaldiz, 2004; Kumar & Sagar, 2014). Initially lumping and caking took place resulting from the compaction, thickening of inter particle bridges, reduction of spaces, and deformation of particle clumps with the loss of system integrity with the reduced equilibrium relative humidity.

4 | CONCLUSIONS

It is very important that drying process should have higher dehydration capacity and should retain the characteristics of fresh fruits by minimizing the cellular and structural changes during the drying process. Banana flour offers greater potential to increase the RS content in the food products. The present study suggested that the page and logarithmic model has shown a better fit to the experimental drying of banana slices than other models. The effect of drying temperature on the drying model constants has shown that 55°C temperature was more appropriate for drying of banana slices as it produced the banana flour with maximum nutrient content with the minimum loss to RS content. These results were affirmed with the SEM and DSC studies which revealed that the dehydration of the banana slices with 55°C was optimum to get a better product with minimum structural changes as evidenced by better rehydration, solubility and swelling power. It was evident that the physical properties of high RS banana flour allow the formation of low bulk high-fiber products like pasta, noodles and healthy functional foods with improved texture, appearance, and mouthfeel.

ACKNOWLEDGMENTS

Authors acknowledge the Director, ICAR-National Research Centre for Banana, Trichy, for funding this project. We also acknowledge, National Institute of Technology, Trichy for analyses of sample. The authors would like to thank Miss. S. Kohila, for laboratory analyses. The research was supported by the research grants (IXX12448) from the Indian Council of Agricultural Research, New Delhi, India.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Kumar PS, Nambi E, Shiva KN, et al. Thin layer drying kinetics of Banana var. Monthan (ABB): Influence of convective drying on nutritional quality, microstructure, thermal properties, color, and sensory characteristics. *J Food Process Eng*. 2019;e13020. https://doi.org/10.1111/jfpe.13020